DOCTORAL THESIS

MAINTENANCE-RELATED INCIDENTS AND ACCIDENTS

Aspects of Hazard Identification

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Division of Quality and Environmental Management

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*Cuiusvis hominis est errare** *(Cicero)*

**) to error is human*

PREFACE

The research work presented in this thesis has been carried out at both the Division of Operation and Maintenance Engineering and Division of Quality and Environmental Management.

First of all I would like to thank my supervisor Professor Uday Kumar. You welcomed me into your group and have enriched my knowledge in maintenance by valuable discussions. Many thanks are also due to Professor Bengt Klefsjö for most valuable support during my research studies. You believed in me and gave me motivation when I needed it most, even after I left your division.

I would also like to express my gratitude to my colleague and friend, Dr. Peter Söderholm. Peter, I really appreciated our collaboration and fruitful discussions. You always encouraged me and gave me valuable advices when you thought I needed it. My thanks are also due to Adjunct Professor Per-Anders Akersten. I appreciate your ideas and support during the project. Our conversations about research and other matters are greatly valued.

I would also like to acknowledge the help of Professor Håkan Alm for co-writing a paper with me. My thanks are also due to Dr. Rickard Garvare for valuable comments on drafts of this thesis, Dr. Johan Bäckman for access to the BOR database and Jessica Olsson at the Swedish Rail Agency (Järnvägsstyrelsen) for assisting me in getting access to the accident investigations.

Furthermore, I would like to acknowledge the financial support given by the Swedish National Rail Administration (Banverket) and Luleå Railway Research Center (JVTC). I have also received valuable ideas from Ulla Espling, Gerry Kullbrandt, Dr. Per-Olof Larsson-Kråik and Dr. Ulf Olsson.

I would also like to thank my colleagues and friends for enriching moments and some silly larks during this journey. No one mentioned, no one forgotten: you know who you are!

I also would like to say thank you to my parents, Björn & Ingegerd, for their support. You have always believed in me. Finally, I would like to express my gratitude to Anna-Karin. Your devotion and endless patience have enriched my life.

Mattias Holmgren

Luleå, August 2006

ABSTRACT

The satisfaction of stakeholders depends upon the fulfilment of their requirements. Two important stakeholder requirements related to technical systems are dependability and safety. However, system operation will gradually impair its performance leading to potentially hazardous states of the system. Maintenance is all activities aimed at retaining a system in, or restoring it to, a state where it can fulfil the stakeholders' requirements. However, although maintenance is performed in order to ensure dependability and safety, incorrectly performed maintenance may contribute to accidents with extensive losses. Traditionally, human failures have often been appointed as one major cause of these maintenance-related accidents. However, human failures are not completely satisfactory as an explanation for incidents and accidents since there most often are other contributory causes to these failures.

The purpose of this thesis is to explore and describe hazards contributory to maintenance-related incidents and accidents, in order to support continuous risk reduction. To fulfil the stated purpose, two case studies, supported by a literature study, have been performed. One case study focused on documented maintenance-related incidents and accidents within the Swedish railway. The second case study focused on perceived hazards in relation to maintenance execution within the Swedish paper industry.

The railway case study indicates that improper infrastructure maintenance is a major cause of collisions and derailments within the Swedish railway. Furthermore, the study indicates that the three major maintenance-related hazards within the Swedish railway system are: communication errors, information retrieval errors and omitted operations. The study also proposes that it is not good enough to accept human failures, i.e. human error or rule violation, as a root cause of maintenance-related incidents and accidents.

Both case studies show that a major maintenance-related hazard is insufficient communication between different activities associated with maintenance execution. Another common finding from the studies is that incidents manifested during maintenance execution might be caused by hazards in other maintenance-related activities within the maintenance process. In addition, both case studies show that a proposed process model of maintenance is a valuable support in hazard identification.

Keywords: Maintenance, Incident, Accident, Hazard Identification, Railway, Paper Industry

SUMMARY IN SWEDISH

Tillfredsställelsen hos tekniska systemets intressenter beror på hur väl deras krav uppfylls. Två viktiga intressentkrav relaterade till tekniska system är driftsäkerhet och säkerhet. Driften av systemet kommer emellertid att gradvis försämra dess prestanda, vilket leder till riskfyllda systemtillstånd. Underhåll är alla aktiviteter avsedda att bibehålla systemet i, eller återställa det till, ett tillstånd där det kan uppfylla intressentkraven. Trots att underhåll syftar till att säkerställa driftsäkerheten och säkerheten, kan felaktigt utfört underhåll bidra till olyckor med stora förluster. Traditionellt sett har mänskligt felhandlande ansetts som en betydande orsak till dessa underhållsrelaterade olyckor. Trots det är mänskligt felhandlande inte en tillfredsställande förklaring till incidenter och olyckor, då det oftast finns bidragande orsaker till dessa felaktiga handlingar.

Syftet med denna avhandling är att undersöka och beskriva riskkällor som bidrar till underhållsrelaterade incidenter och olyckor för att stödja ständig riskreduktion. För att uppnå det angivna syftet har två fallstudier genomförts, underbyggda av en litteraturstudie. En fallstudie fokuserade på dokumenterade underhållsrelaterade incidenter och olyckor vid den svenska järnvägen. Den andra fallstudien fokuserade på upplevda riskkällor i relation till underhållsutförande inom svensk pappersindustri.

Järnvägsfallstudien påvisar att bristfälligt infrastrukturunderhåll är en betydande orsak till kollisioner och urspårningar inom svensk järnväg. Vidare påvisar studien tre betydande underhållsrelaterade riskkällor inom svensk järnväg, vilka är: kommunikationsbrister, brister vid mottagande av information samt utelämnade arbetsmoment. Studien framställer vidare att det inte är godtagbart att acceptera mänskligt felhandlande och regelbrott som en grundläggande orsak till underhållsrelaterade incidenter och olyckor.

Båda fallstudierna visar att en betydande underhållsrelaterad riskkälla är otillräcklig kommunikation mellan olika aktiviteter associerade till underhållsutförandet. En annan gemensam slutsats från studierna är att incidenter som synliggörs vid underhållsutförandet kan ha orsakats av riskkällor vid andra underhållsrelaterande aktiviteter i underhållsprocessen. Båda fallstudierna visar dessutom att en föreslagen processmodell av underhåll är ett värdefullt stöd vid identifiering av riskkällor.

Nyckelord: underhåll, incident, olycka, riskälleidentifiering, järnväg, pappersindustri

LIST OF APPENDED PAPERS

This thesis includes an extended summary and the following five papers, appended in full.

PAPER I **Söderholm, P., Holmgren, M. & Klefsjö, B.** (2006). A process view of maintenance and its stakeholders. Accepted for publication in: *Journal of Quality in Maintenance Engineering.*

PAPER II **Holmgren, M. & Söderholm, P.** (2006a). A process approach to maintenance-related hazard identification. Accepted for publication in: *International Journal of COMADEM.*

PAPER III **Holmgren, M.** (2005). Maintenance–related losses at the Swedish rail. *Journal of Quality in Maintenance Engineering,* 11(1), 5-18.

PAPER IV **Holmgren, M. & Alm, H.** (2006). Loss causation analysis of accidents linked to maintenance on the Swedish state railways. Submitted for publication.

PAPER V **Holmgren, M. & Söderholm, P.** (2006b). Human failures in maintenance execution within a railway context. Submitted for publication.

LIST OF RELATED PUBLICATIONS

There are some publications that are related to the research area, but are not appended in this thesis.

Holmgren, M. & Akersten, P.A. (2002a). Maintenance related risks – Do they need any further investigation? In proceedings of: *3:d Edinburgh Conference on RISK: Analysis, Assessment and Management*, Edinburgh, Scotland, April 8-10, 2002.

Holmgren, M. & Akersten, P.A. (2002b). The maintenance process: looked upon through risk glasses. In proceedings of: *16th International Maintenance Congress: Euromaintenance*, Helsinki, Finland, June 3-5, 2002, 267-273.

Holmgren, M. (2003). Maintenance Related Losses: A Study at the Swedish National Rail Administration, Licentiate Thesis, Division of Quality and Environmental Management, Luleå University of Technology, Luleå.

TABLE OF CONTENTS

APPENDED PAPERS

1 INTRODUCTION

A brief introduction is given in this chapter in order to introduce the reader to the problem area. Furthermore, purpose, research questions and delimitations, as well as the structure of the thesis, are presented.

1.1 Background and Problem Discussion

Global competition among companies has lead to higher demands on production systems[1] (Miyake & Enkawa, 1999). End customer satisfaction is dependent on the production systems' capability to deliver goods and services that meet certain quality requirements. To do so the systems must be fit for use and thereby fulfil important quality parameters. Two such important quality parameters are dependability[2] and safety. However, operation of the systems will gradually impair their performance, dependability and safety. Wear, dirt, corrosion and overloading are some contributory causes of the degradation[3] of the systems (Clifton, 1974). Therefore, management must determine and implement proper maintenance strategies to ensure the functioning of the systems (Coetzee, 1998). Maintenance is here defined as the combination of technical and administrative actions such as supervision actions intended to retain an item in, or restore it to, a state in which it can perform a required function (IEV191-07-01, 2002). Two examples of maintenance methodologies used in different industries are: Reliability Centred Maintenance, RCM, (Nowland & Heap, 1978) and Total Productive Maintenance, TPM, (Nakajima, 1988). As well as ensuring the functioning of a system, maintenance is also important for the system's impact on

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[1] A system may be seen as a composite entity, at any level of complexity, which consists of personnel, procedures, materials, tools, equipment, facilities, and software (IEC 60300-3-9).

[2] Dependability is here defined as a collective term used to describe the availability performance and its influencing factors: Reliability performance, Maintainability performance and Maintenance support performance (IEV 191-02-03). Reliability is the probability that an item can perform a required function under given conditions for a given time interval (IEV 191-12-01). Maintainability performance 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 (IEV 191-13-01). Maintenance support performance is the ability for a maintenance organisation, under given conditions, to provide upon demands, the resources required to maintain an item, under given maintenance policy (IEV 191-02-08).

[3] Degradation is here defined as an irreversible process in one or more characteristic of an item due to time, use or external cause (SS-EN 13306). Degradation may lead to a Failure or Fault. A failure is the termination of the ability of an item to perform a required function (IEV 191-05-01). A fault is defined as the state of an item that is characterised by the inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to lack of external resources (IEV 191-05-01).

safety and for prevention of incident and accidents[4] (Uth, 1999). However, although maintenance is performed in order to ensure safety, maintenance is sometimes performed incorrectly. This incorrectly performed maintenance may reduce the safety of the systems and thereby contribute to extensive losses[5] (Kletz, 1994). There are a number of accidents, where improper maintenance was one major contributory cause towards disaster. Examples of these from the process industries are the leak from a chemical plant at Bhopal, India in 1984; the Piper Alpha oil platform fire, North Sea in 1988; the disaster at Philips petrochemical plant in Texas, USA in 1989; the explosion and fires at the Texaco refinery at Milford Haven, UK in 1994; and the chemical release and fire at the Associated Octel Company Limited in Cheshire, UK in 1994.

Besides safety aspects, improper maintenance may also cause the system to deteriorate and thereby create quality deficiencies, such as delays and non-conforming products causing economical losses (Ollila & Malmipuro, 1999). However, even though maintenance errors have lead to huge financial losses each year and, worse, resulted in death and injury throughout the world, they receive little attention (Reason & Hobbs, 2003).

There are generally two different kinds of maintenance errors: erroneously performed maintenance and lack of necessary maintenance (Reason & Hobbs, 2003). Erroneously performed maintenance is related to the risk that maintenance personnel will introduce the ingredients for a failure that would not have otherwise occurred. Lack of necessary maintenance is related to the risk that someone will not detect a failure or not perform or fail to complete a necessary maintenance task.

To learn from the past it is necessary to investigate incidents and accidents (Wagenaar & van der Schrier, 1997; Jones et al., 1999; Reinach & Viale, 2006). However, it is not easy to properly investigate incidents or accidents. One way of doing this is to use an accident model, since it outlines the foundation for incident and accident investigations (Leveson, 2004; Sklet, 2004). Hence, even though the risk of maintenance error can never be eliminated entirely, it can be managed more effectively (Reason & Hobbs, 2003). Both maintenance personnel and managers need to understand why maintenance errors occur, and how the risk of error can be managed (Reason & Hobbs, 2003).

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[4] An accident is here defined as an undesired event that causes damage or injury (Harms-Ringdahl, 2001). It is usually the result of a contact with a source of energy above the threshold limit of the structure or body (Bird & Germain, 1996).

[5] The term loss is here defined as an undesired event that affects people or property creating physical or economic harm (Bird & Germain, 1996).

One way to achieve this is to learn from past incidents and accidents through their investigations (Sklet, 2004). Accident investigations are related to different layers of contributory causes. The outer layers deal with the immediate technical causes while the inner layers are related to ways of avoiding the hazards and with the underlying causes, such as weaknesses in the management system (Kletz, 2001). However, often only the outer layers are considered in the investigations and the possibilities to learn from the accidents and prevent them happening again is diminished (Kletz, 2001).

Since the mid-1980s accidents have come to be seen as the consequences of complex interactions rather than simple threads of causes and effects (Hollnagel, 2004). However, progress in accident models has not been matched by advances in methodologies. Hence the understanding of accidents is still approximate and incomplete (Hollnagel, 2004; Leveson, 2004). The unsatisfactory understanding of accidents, together with the fact that they inevitably will occur in the future means that there is an unfulfilled need for better understanding of the nature of accidents (Hollnagel, 2004). There are even those that claim that today's technological systems have become so complex that accidents must be seen as the norm rather than the exception (Perrow, 1984).

To sum up, although the aim of maintenance is to ensure the productivity and efficiency of technical systems, improper maintenance, in the sense of incorrectly performed maintenance or lack of suitable maintenance activities, contributes to deterioration and, even more seriously, cause incidents and accidents. Therefore it is important to identify hazards from occurred incidents and accidents to learn and avoid these hazards in the future. For that matter, in turn, documentation from occurred events should be done in a systematic way and then be an important part of the management system – and last, but not least, used for improvements.

These matters are even more important today, when many organisations outsource or contract out the maintenance of equipment and sub-systems (Campbell, 1995). Outsourcing aims at strengthening the organisation by concentrating its resources and investments on its core competence and activities, and by outsourcing those activities, which are not of strategic importance and where the resources needed are not available within the organisation. The use of specialized contractors may enhance the quality of the maintenance jobs and at the same time lower the maintenance cost.

However, there are several risks related to outsourcing that are of special interest when planning and performing maintenance. In Campbell (1995) the following list is presented:

- Loss of control over a supplier
- Loss of cross-functional communication
- Loss of critical skills or developing the wrong skills

The use of maintenance contractors increases the need for better control, which requires the establishment of suitable management control systems (van der Meer-Kooistra & Vosselman, 2000). Administrator control may be affected by contracted maintenance, especially if proper information about system changes and repair is not communicated (Kletz, 2001).

In the United Kingdom, for instance, several accidents have occurred on the British Rail due to inadequate control of the maintenance contractors. Some quite recent examples are the derailment and collision at Ladbroke Grove in 1999 and the derailment near Hatfield in 2000 (Health and Safety Executive, 2001; 2002).

The development on the Swedish railways followed the one in the United Kingdom. In order to transform the Swedish rail traffic into a safe, competitive alternative for transportation of people and goods the Swedish National Rail Administration (Swedish: Banverket) was restructured in 1988 (Espling & Kumar, 2002). The Swedish National Rail Administration was then divided into one organisation responsible for infrastructure management and a state owned train operator, SJ (Swedish: Statens Järnvägar). Swedish train operations were deregulated and thereby open for competition on a free market (Banverket, 2006). The infrastructure management became responsible for design and construction, as well as track maintenance (Espling & Kumar, 2002). However, track maintenance was still only performed in-house. This situation changed in 2001, when the Swedish National Rail Administration decided to open up their rail maintenance to the free market. Maintenance contractors were invited to participate in the bidding for maintenance contracts for some sections of the track in 2002 (Banverket, 2006).

The Swedish National Rail Administration chooses to use maintenance contractors, despite the initial problems that may occur, see, for instance, problems at British Rail (Health and Safety Executive, 2001; 2002). The main reason is to reduce the cost of track maintenance (Banverket, 2006). However, economical benefits must not affect the safety of the rail system. Safety is still the most prioritized goal for the Swedish National Rail Administration. Despite this, incident and accidents still occur on the Swedish rail network.

When changing maintenance strategies, i.e. switching from in-house maintenance to outsourcing, it is important to identify the contributory causes of past incidents and accidents associated with maintenance when deciding upon new risk reduction activities in order to be truly proactive. Such analysis of past incidents and accidents identifies areas that need special attention so that countermeasures can be implemented for continuous improvements through hazard reduction.

Accordingly, improving the maintenance by continuous hazard reduction would in turn ensure safety. There are also economical benefits in reducing the number of incidents and accidents. Therefore it is most important to identify and understand the hazards linked to maintenance, in order to create possibilities for continuous risk reduction through continuous improvement.

1.2 Purpose of the Thesis

The purpose of this thesis is to explore and describe hazards contributory to maintenance-related incidents and accidents, in order to support continuous risk reduction.

1.3 Research Questions

The purpose of the study thesis has been focusing on the following two research questions:

1. How can methodologies and tools be used for identification of maintenance-related hazards contributing to incidents and accidents?

2. What kind of hazards contribute to maintenance-related incidents and accidents?

1.4 Delimitations

There are two main delimitations made in this thesis. Firstly, the thesis focuses on maintenance of critical technical systems. The reason for studying technical systems is to improve the maintenance execution through continuous risk reduction, in order to avoid casualties and economical losses due to unidentified hazards. This is believed to be important since the complexity and criticality of technical systems has increased dramatically, at the same time as improper maintenance has received too little attention.

Secondly, this thesis has a special focus on railways. One reason to focus on railways is due to the fact that they make use of critical systems where improper maintenance may cause derailments and collisions, which have severe impact on the travellers and also may result in injuries, fatalities and extensive economical losses. Another reason is that even though the railway industry is a mature one, it is faced with new challenges, such as a dynamic business environment and new technologies. A further reason is a pronounced determination from the Swedish

National Rail Administration to identify hazards related to improper maintenance, which facilitated the possibility to study relevant information.

1.5 Structure of the Thesis

The structure of the thesis is presented in Figure 1.1. The thesis consists of five chapters and five appended papers.

The first chapter (Introduction) starts with a description of the background and research problem. Thereafter, the purpose, research questions, delimitations and thesis structure are outlined.

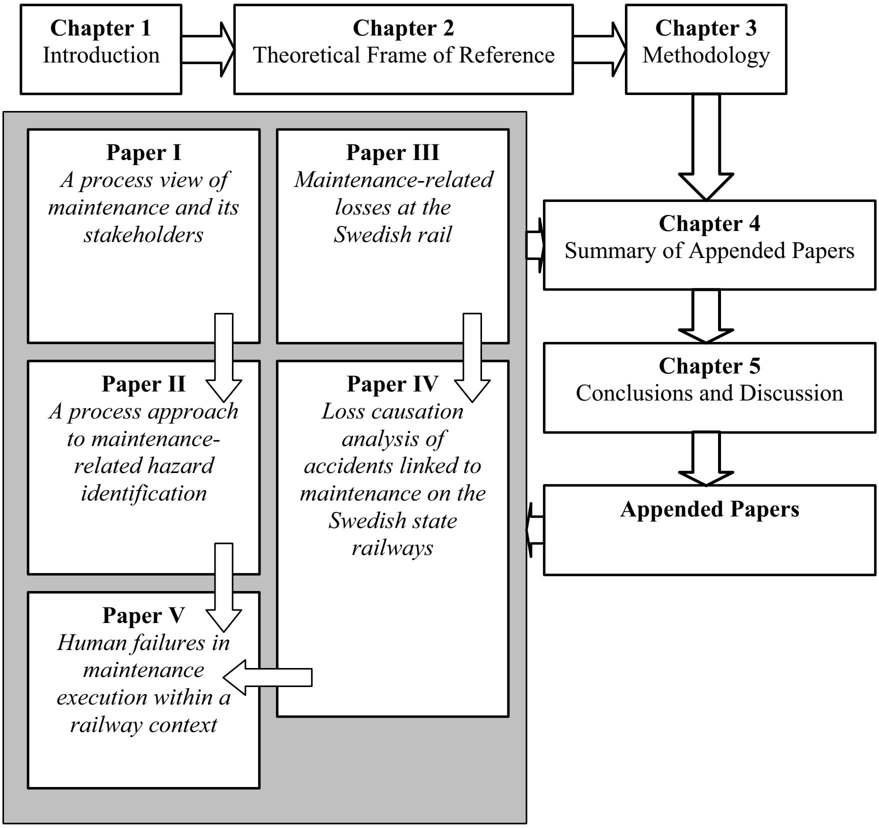

Figure 1.1. The structure of this thesis, including five chapters and five appended papers.

In the second chapter (Theoretical Frame of Reference) the theoretical framework will be presented, including aspects of Maintenance, Quality and Risk Management. Different accident causation models and aspects of accident investigations are also presented.

The third chapter (Research Methodology) includes the chosen research design and different aspects of data collection and data analysis will be presented. Validity and reliability issues of the different studies will also be discussed.

In the fourth chapter (Summary of Appended Papers) the five appended papers are summarized and the main results presented. The relations between the papers and the research questions are illustrated in Figure 1.2.

Paper	RQ 1	RQ 2
I	+ +	
II	+ +	+
III	+	+ +
IV	+	+ +
V	+ +	+ +

Figure 1.2. The relations between the five appended papers and the research two questions. Here "++" means a strong correlation and "+" a weaker correlation.

In the fifth and last chapter (Conclusions and Discussion) the general conclusions drawn from the different papers will be presented in relation to the two research questions and a discussion will be held to comment some aspects of the results. Finally, suggestions for further research work will be outlined.

2 THEORETICAL FRAME OF REFERENCE

This chapter consists of the theoretical frame of reference. Areas important for this thesis are described.

2.1 Maintenance Management

With increasing awareness of the fact that maintenance not only ensures high level of safety at work places, high reliability and availability of plants but also creates value in the business process, maintenance has become a focus of strategic thinking of many companies all over the world (Kumar & Ellingsen, 2000; Liyanage & Kumar, 2003).

With this change in mind set of managers, maintenance discipline has developed into a complex investment activity, rather than being a cost producing activity, due to the insight that efficient maintenance increases the profit of the company (Groote, 1994). Maintenance is multidisciplinary in nature and therefore effective management of maintenance process necessitates application of knowledge from different disciplines cutting across various fields of science (Kumar, 2002). Maintenance may be defined as the combination of technical and administrative actions, such as supervision actions, intended to retain an item in or restore it to a state in which it can perform a required function (IEV 191-07-01, 2002).

Maintenance Management may be described as the activities of the management that determine Maintenance Objectives[6], Maintenance Strategies[7], Maintenance Policy[8] and responsibilities (SS-EN 13306). Thereafter Maintenance Plans[9] and control, including supervision, must be implemented in the organisation. Finally, the adopted methodologies in the organisation, including economic aspects, must be evaluated (SS-EN 13306).

The Maintenance Strategy may be divided into Preventive Maintenance and Corrective Maintenance, see Figure 2.1 for an illustration of the different Maintenance Strategies (SS-EN 13306). Instead of preventing and correcting

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[6] Maintenance Objectives are here defined as targets assigned, and accepted for the maintenance activities which may include availability, cost reduction, product quality, environment preservation, and safety (SS-EN 13306).

[7] Maintenance Strategy is here defined as a management method, used in order to achieve the Maintenance Objectives (SS-EN 13306). Note that the word methodology is preferred in this thesis instead of method.

[8] The maintenance policy is a description of the interrelationship between the maintenance echelons, the indenture levels and the level of maintenance to be applied for the maintenance of an item (IEV 191-07-03).

[9] Maintenance Plan is here defined as a structured set of tasks that includes the activities, procedures, resources and the time scale required to carry out maintenance (SS-EN 13306).

failures or faults, the design of the product or system can be changed in order to eliminate the need for maintenance during the life cycle (Kelly, 1999). The decision regarding the choice of maintenance strategy should be taken already at design phase of the technical system (Markeset & Kumar, 2003; Kumar, 2002).

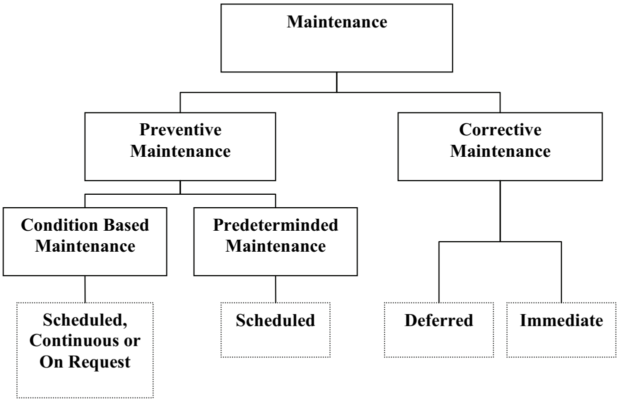

Figure 2.1. An illustration of different Maintenance Strategies. The top structure is broken down into the prevention of failures or the correction of faults that are recognised. (Source: SS-EN 13306)

Preventive Maintenance may be seen as the maintenance carried out at predetermined intervals or according to prescribed criteria, intended to reduce the probability of failure[10] or the degradation of the functioning of an item (IEV 191-07-07, 2002). This means that maintenance is performed before a failure is developed. Preventive Maintenance can be done at predetermined intervals, e.g. after a certain time or when the state of an item has reached predetermined limits. Corrective Maintenance is the maintenance carried out after fault[11] recognition, intended to bring back an item into a state in which it can perform a required function (IEV 191-07-07, 2002). This means that maintenance is performed after the fault of an item has been detected, in order to restore the item.

The complexity of maintenance has made it necessary for both maintenance personnel and management to have a maintenance model as a fundamental reference point in all decision-making regarding maintenance aspects (Kumar, 2002). Therefore, an attempt was made by Coetzee (1998) to illustrate

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[10] Failure is here defined as the termination of the ability of an item to perform a required function (SS-EN 13306).

[11] A fault is defined as the state of an item that is characterised by the inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to lack of external resources (IEV 191-05-01).

Maintenance Management, see Figure 2.2. Maintenance Management must meet different maintenance demands, which arise from the system design and are defined in the maintenance plan development. Maintenance Management must also control the different external resources supporting the maintenance work, such as maintenance consultants and different original equipment manufacturers (OEM). It is also important to control the internal resources, such as maintenance operators and the capacity of the system. Control of spare parts and rotables (e.g. items that are removed from the system and then replaced) are another important aspect of Maintenance Management. The results of Maintenance Management are evaluated and feedback should be given to the maintenance demands and the design phase of new similar systems as a part of the continuous quality improvement work (Coetzee, 1998).

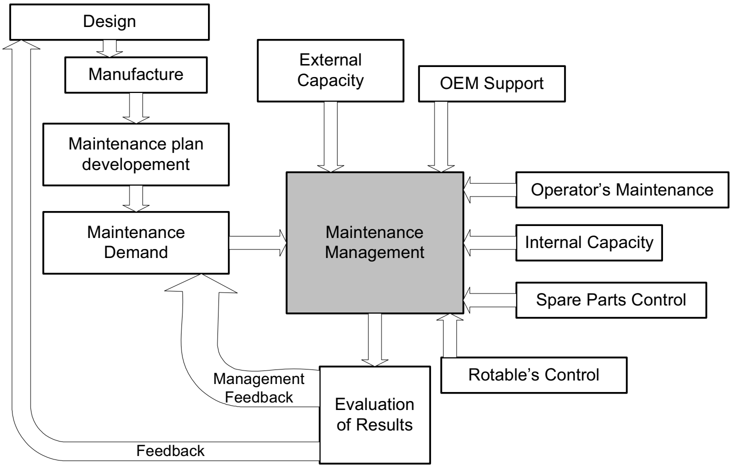

Figure 2.2. An illustration of Maintenance Management, which is supported by different external and internal resources. This illustration emphasises that the maintenance demands of the technical system, which originate from the system design, must be met with certain internal and external resources. (Source: Coetzee, 1998)

However, Cotzee's (1998) approach to Maintenance Management, illustrated in Figure 2.2, does not describe the activities conducted inside the maintenance organisation on a sufficiently detailed level. Therefore, it is necessary to find a way of illustrating these activities. The European Federation of National Maintenance Societies, EFNMS, has made an attempt to illustrate these activities and therefore developed two maintenance processes[12], for corrective maintenance, and preventive maintenance respectively, see Figure 2.3 and 2.4 for an illustration.

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[12] A process may be defined as a network of activities that, by the use of resources, repeatedly converts an input to an output for stakeholders (Isaksson, 2004).

2.1.1 Preventive Maintenance Process

One Preventive Maintenance Process, developed by EFNMS (2000) is illustrated in Figure 2.3. The Preventive Maintenance Process consists here of four process activities, supported by documents, data and resources. The process starts with a failure statistics report and the configuration of Preventive Maintenance starts. The configuration of Preventive Maintenance is supported by a maintenance policy for the equipment, and asset data, such as drawings, technical specifications and location of the equipment. The second process activity is preventive maintenance planning, which is supported by maintenance measurement of previously conducted maintenance work. The output of the second process activity is a work order used for the preventive maintenance performance. The third activity is the preventive maintenance performance. This activity is supported by maintenance manuals, staff or contractors and spare parts. The output is a functioning system, plus consumed materials, such as worn-out parts, which must be disposed of. Feedback is given when the preventive maintenance work has been done. The final process activity is control of the function. In this activity feedback is given regarding the different activities in the Preventive Maintenance Process and the account register is updated. (EFNMS, 2000)

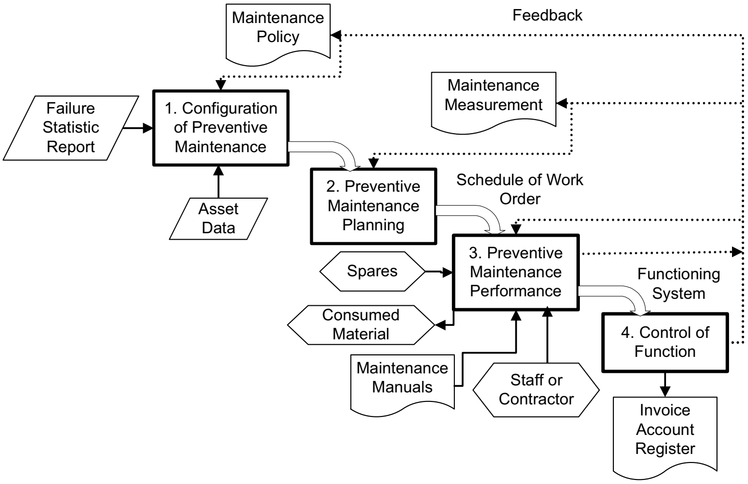

Figure 2.3. A Preventive Maintenance Process illustrating the workflow, consisting of four different activities, and the supported resources. (Source: EFNMS, 2000)

2.1.2 Corrective Maintenance Process

One Corrective Maintenance Process, developed by EFNMS (2000) is illustrated in Figure 2.4. The Corrective Maintenance Process consists here of four process activities, supported by documents, data, and resources. The Corrective Maintenance Process starts with a failure report at the first process activity, failure registration. The failure registration is supported by a service policy for the equipment and asset data, such as drawings, technical specifications and location of the equipment. The second process activity is corrective maintenance planning, which is supported by the maintenance policy. The output of the second process activity is a work order, used for the performance of the Corrective Maintenance. The third activity is the repair performance. This activity is supported by maintenance manuals, staff or contractors and spare parts. The output is a functioning system, but consumed materials, such as worn out parts, must be disposed of. Feedback is given when the corrective maintenance work has been done. The last process activity is control of the function. In this activity feedback is given back to different activities of the Corrective Maintenance Process and the account register is updated. (EFNMS, 2000)

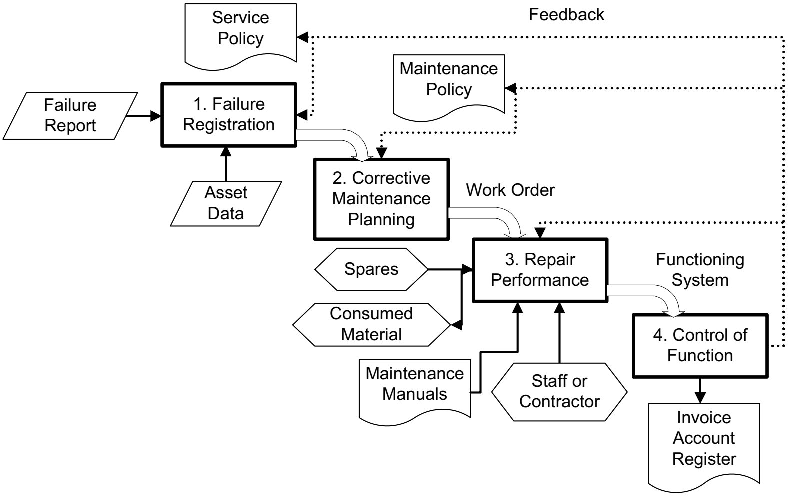

Figure 2.4. A Corrective Maintenance Process, illustrating the workflow, consisting of four different activities, and the supported resources. (Source: EFNMS, 2000)

2.2 Quality and Continuous Improvements

Crosby (1979) defines product quality as “conformance to requirements”, Deming (1986) says that “quality should be aimed at the needs of the customers, present and future”, and Taguchi & Wu (1979) state that “the lack of quality is the losses a product impacts to society from the time the product is shipped”, and provide thereby a definition, which is closely related to today’s concept of the ”sustainable society”. According to the international standard ISO 9000:2000 “quality is the degree to which a set of inherent characteristics fulfils the requirements i.e. the needs and expectations that are stated, generally implied or obligatory". In summary this means that today's view of quality is closely related to customer satisfaction, a view that is also expressed in the definition by Bergman & Klefsjö (2003) when they claim that "the quality of a product is its ability to satisfy, or preferably exceed, the needs and expectations of the customers".

The concept of product quality has many dimensions. For goods, some of them are (Bergman & Klefsjö, 2003):

- Reliability, which is a measure of how often problems occur and how serious these are.

- Maintainability, which summarizes how easy or difficult it is to detect, locate and take care of problems.

- Environmental impact, which is a measure of how the product affects the environment, e.g. in the form of emissions or recyclability, and how environmental aspects are treated in the production.

- Safety, meaning that the article does not cause damage to people or property, or, in some cases, provides adequate protection against damage.

Quality activities and continuous improvements are today often covered in the concept of Total Quality Management (TQM). This concept may be described in several ways, but during the last few years a couple of papers have been presented in which a perspective of management system has been used to define TQM. One of these papers is Hellsten & Klefsjö (2000), who define Total Quality Management as "a continuously evolving management system consisting of values, methodologies and tools, the aim of which is to create external and internal customer satisfaction with a reduced amount of resources".

The values, which should be the basis for the quality culture, are, according to Bergman & Klefsjö (2003):

- Focus on customers
- Focus on processes
- Base decisions on facts
- Let everybody be committed
- Improve continuously
- Committed leadership

In today's society we are becoming increasingly dependent on technological systems. The consequences of interruption or accidents caused by these systems are often serious, sometimes disastrous. Consequently, reliability and safety are extremely important quality dimensions and reliability engineering, comprising methodologies and tools for increased reliability and safety is a vital part of Total Quality Management. According to Bergman & Klefsjö (2003), the main aim of reliability engineering is to:

- Find causes of failures and try to eliminate these, i.e. increasing the failure resistance of the product.

- Find the consequences of failures and, if possible, reduce and eliminate their effects, i.e. increasing the tolerance of the product to failure. This is sometimes called increased fault tolerance.

In reliability engineering and reliability management the importance of progressive, systematic improvement work cannot be overemphasized. Here the decisions have to be based on facts. The causes of failure, or the possible events that might cause failure, have to be systematically analysed and it is, as in most other improvement work, important to look systematically at the relevant processes and improve their ability to produce and maintain a system's reliability and safety in an efficient way. The more complex the products are that we study, the more important it is to establish a system view taking the interaction between the elements into consideration in order to ensure that the system is something more than the sum of the individual elements. (Bergman & Klefsjö, 2003)

2.2.1 The Improvement Cycle

The Improvement Cycle is often used in order to establish a mental model of continuous improvement work. The different phases of the Improvement Cycle are illustrated in Figure 2.5.

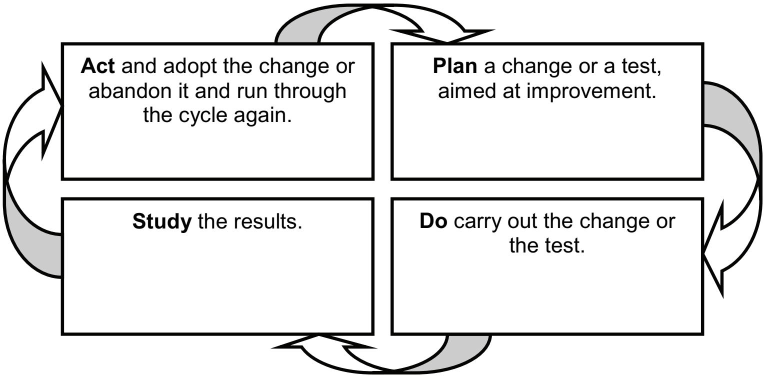

Figure 2.5. The Improvement Cycle illustrates different phases in the continuous improvement work. The first step starts with an identified problem and a suggestion for improvement is planned (plan). In the second phase (do) the change for improvement is applied. Then, the result of the change is studied (study). Finally, if the change was successful, the results are adopted and new routines and methodologies are established. (Source: Deming, 1994)

Plan: The first step starts with an idea of improvement of a product or a process. It leads to a plan for the test, comparison or experiment. It is very important to plan the improvement carefully; too quick start may be ineffective (Deming, 1994). The decisions taken must be based on facts (Bergman & Klefsjö, 2003).

Do: Carry out the change or test (Deming, 1994). It is at this point important to make everybody involved fully aware of the problem and the agreed improvement steps (Bergman & Klefsjö, 2003).

Study: When appropriate steps have been taken to solve the problem during the Do-phase, we need to study suitably chosen parameters and carefully analyse the data (Bergman & Klefsjö, 2003). This means that we study the results (Deming, 1994).

Act: Adopt the change or abandon it and run through the cycle again with different conditions (Deming, 1994). If we got an improvement we have to adopt the change and establish new routines and methodologies. If the actions taken did not give the expected results we need to abandon the change and run through the cycle once again. However, it is important also to learn from the way we perform improvements in order to improve our improvement work (Bergman & Klefsjö, 2003).

2.3 Risk Management

It is necessary for the management to understand the level of risks the organisation is facing, and how these risks change as a result of the operating conditions (Hunt & Wierman, 1990). Undesirable events may occur as a result of component and subsystem failures and might lead to loss of life, personal injury, damage to the environment or loss of economic values (Aven, 1992).

Risk Management aims at predicting where hazardous events[13] may happen and thereby making it possible to prevent the accidents that have not yet occurred (McKinnon, 2000). Shortcomings when analysing, evaluating and controlling risks are the key events that produce losses in the organisation (Bird & Loftus, 1976).

The aim of Risk Management is to consider the impact of certain risky events on the performance of the organisation. Alternative methodologies[14] for controlling these risks and their impact on the organisation must be devised. These methodologies must be related to the general decision framework used in the organisation. (Ridley & Channing, 1999)

Risk Management may, more exactly, be defined as a systematic application of management policies, procedures and practices to the tasks of analysing, evaluating and controlling risks[15] (IEC60300-3-9, 1995). Therefore, Risk Management is often structured in the three parts Risk Analysis, Risk Evaluation, and Risk Control, see Figure 2.6.

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[13] Hazardous event is here defined as an event which may cause harm. Harm is defined as a physical injury or damage to health, property, or the environment. (SS-EN 13306)

[14] Ridley & Channing (1999) use the term strategy when describing Risk Management. The present writer prefers to use the term methodology, which is defined as a way to work within an organisation to reach the values, and consists of a number of activities performed in a certain way (Hellsten & Klefsjö, 2000).

[15] A risk is here defined as a combination of the frequency, or probability, of occurrence and the consequence of a specified hazardous event (IEC60300-3-9, 1995).

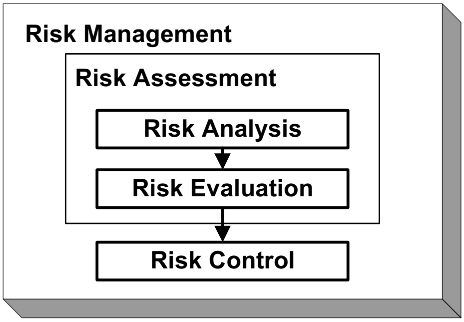

Figure 2.6. Risk Management consists of Risk Analysis, Risk Evaluation and Risk Control. Risk Analysis aims at identifying hazards, and at estimating the risk to individuals, populations, property, or environment. Risk Evaluation includes judgements of the tolerability of the risk on the basis of the Risk Analysis. Risk Control aims at managing and reducing the risk, and at implementing control activities in the organisation. (Source: IEC60300-3-9, 1995)

Risk Management requires an integrated approach, including both organisational and technical aspects. This is, for example, supported by the Presidential Commission that investigated the loss of the space shuttle Challenger in 1986 (Baron & Paté-Cornell, 1999). The Commission concluded that organisational factors were at the root of the technical failure that led to the disaster. Some organisational factors could be traced to weak communication, misguided incentives and resource constraints, which in turn could be linked to the rules, structures, and culture of the organisation (Paté-Cornell & Fischbeck, 1993).
Risk Assessment, as a part of Risk Management, may be defined as an overall process consisting of Risk Analysis and Risk Control (IEC60300-3-9, 1995). However, as in many other cases, the interpretation of the concept differs among authors. For some authors, Risk Assessment means the entire process from identifying hazards and risks, estimating the risks and eliminating or reducing them. See, for example, Schlechter (1995) and Kumar & Svanberg (1999), who describe such risk assessment processes.

Among the benefits of Risk Assessment are that it indicates where the greatest gains may be obtained with the least amount of resources, and which activities should be given priority (McKinnon, 2000).

2.3.1 Risk Analysis

Risk Analysis is a methodology with the aim of systematically measuring the degree of danger in an operation (McKinnon, 2000). Risk Analysis may be defined as a systematic use of information to identify hazards[16] and to estimate the risk of individuals or populations, property or the environment (IEC60300-3-9, 1995).

The purpose of Risk Analysis is to reduce the uncertainty of a potential accident situation and to provide a framework for systematically investigating all eventualities that may occur (IEC60300-3-9, 1995). Risk Analysis is a methodology that looks not only at what happened in the past, but also at what could happen in the future (McKinnon, 2000).

Simply stated, Risk Assessment is a methodology for identifying possible accidents that have not yet occurred (McKinnon, 2000). This methodology is useful for identifying different risks and approaches to their solution, but also for providing objective information, useful for fact-based decisions (IEC60300-3-9, 1995).

- Some of the benefits of Risk Analysis are (IEC60330-3-9, 1995):
- Systematic identification of potential hazards is established.
- Systematic identification of potential failure modes is established.
- Quantitative risk statements or ranking are obtained.
- Important contributors to risks and weak links in the system are identified.
- Better understanding of the system and its installation is obtained.
- A basis for preventive maintenance and inspection is obtained.

In summary, Risk Analysis aims at answering three fundamental questions, see Figure 2.7. In order to answer these questions, Hazard Identification, Frequency Analysis and Consequence Analysis are used as support.

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[16] A hazard is here defined as a source of potential harm or a situation with a potential for harm (IEC60300-3-9, 1995).

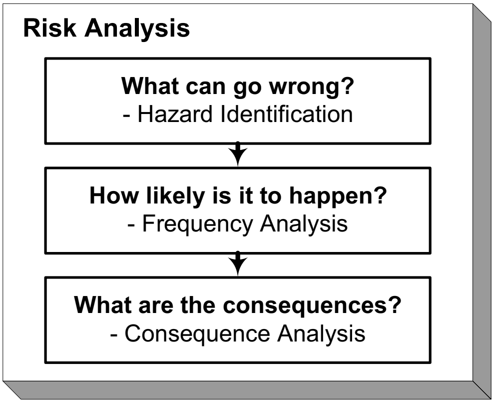

Figure 2.7. A Risk Analysis aims at answering three fundamental questions. To answer these questions different tools are used as a support. (Source: IEC60300-3-9, 1995)

Hazard Identification[17] of all possible hazards is the first step of the Risk Analysis. Correct Hazard Identification ensures effective and beneficial Risk Management. But, if risk managers do not succeed in identifying all possible risks that challenge the organisation, then these non-identified risks will become non-manageable (Tchankova, 2002).

There are numerous ways of performing hazard identification, such as Hazard and Operability Studies (HAZOP) (Harms-Ringdahl, 2001); Failure Mode and Effect Analysis (FMEA) (Stamatis, 1994) and other tools such as incident and accident investigations (Ferry, 1988).

Studying past accident reports is a way of predicting future hazards. By studying past loss-producing events, a pattern can be derived that would indicate certain recurring and inherent hazards in the organisation (Jones et al., 1999). Incidents are also vital for Hazard Identification (Jones et al., 1999). Incidents, or events, which under slightly different circumstances could have resulted in losses, are good indicators of the presence of hazards challenging the organisation (McKinnon, 2000).

Frequency Analysis is used for the estimation of the likelihood of each undesired event, which is identified in the hazard identification step (McKinnon, 2000). Here for example historical records and Failure Mode and Effects Analyses are useful (Stamatis, 1994).

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[17] Hazard Identification is a process of recognizing that a hazard exists and defining its characteristics (IEC60300-3-9, 1995).

Consequence Analysis is used for the estimation of the impact, if an undesired event should occur (IEC60300-3-9, 1995). Here, for instance, Fault-Tree Analysis (FTA), are useful (Harms-Ringdahl, 2001).

Neither Frequency Analysis nor Consequence Analysis is used in this thesis. Therefore these concepts will not be further discussed.

2.3.2 Risk Evaluation

The second step in the Risk Assessment is Risk Evaluation[18]. The main objective of Risk Evaluation is to ensure that the cost of risk reduction justifies the degree of risk reduction. The main aim of Risk Evaluation is to enable the management to make decisions on risk reduction priorities in the business. (McKinnon, 2000)

However, Risk Evaluation is not used in this thesis, and therefore it will not be further discussed.

2.3.3 Risk Control

The final step in the Risk Management is Risk Control[19]. The objective of Risk Control is to minimize, or when possible, transfer the risks that have been assessed (McKinnon, 2000). The goal of Risk Control is to reduce the severity and frequency of the likelihood of undesired events occurring to a level As Low As Reasonably Practicable (ALARP) (Melchers, 2001).

There are basically four ways of controlling the risks (McKinnon, 2000):

- Terminate the risk. This is the ideal way to terminate the risk entirely by stopping a hazardous procedure or processes.

- Tolerate the risk. If the risk is tolerated, the benefits deriving from the risk outweigh the consequences of the risk. The potential impact of the risk is also lower than the cost of eliminating it.

- Transfer the risk. The risk is transferred somewhere else, by ensuring the risk, or placing it somewhere outside the business. The risk is not eliminated, but just transferred to someone else outside the company's own organisation.

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[18] Risk Evaluation is here defined as a process in which judgements are made on the tolerability of the risk on the basis of Risk Analysis, and taking into account aspects such as socio-economic and environmental consequences (IEC60300-3-9, 1995).

[19] Risk Control is here defined as a process of decision-making for managing and/or reducing risk, its implementation, enforcement, and re-evaluation from time to time, using the results of risk assessment as one input (IEC60300-3-9, 1995).

- Treat the risk. Treating the risk involves setting up a control for reducing the risk and thereby reducing the probability of an undesired event.

Risk Control is not applied in this thesis. Therefore it will not be further discussed here.

2.4 Accident Causation Models

There are different models that describe accident causation sequences (Ridley & Channing, 1999). According to Groeneweg (1998), the simplest representation of an accident is the result of a single unsafe[20] or substandard act[21], see Figure 2.8. The substandard act is also referred to as an unsafe act. However, it is not always clear that the act really is unsafe (Groeneweg, 1998).

Whether an act is substandard or not is related to the standards and guidelines of the organisation. Therefore, the term substandard act is used in this thesis.

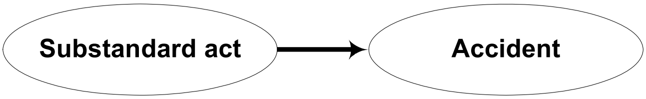

Figure 2.8. A simple model that describes an accident causation scheme, starting with one single substandard act, which results in an accident. (Source: Groeneweg, 1998)

2.4.1 Reason's Accident Causation Model

Reason (1990) illustrates accident causation with substandard acts and safety barriers[22]; see Figure 2.9.

Accident prevention may be accomplished by adding some safety barriers. Only when all safety barriers have been broken is accident causation a fact. If one safety barrier has been able to prevent the accident from occurring, an incident is caused. However, as defined earlier, an incident may also cause losses. The difference is that an accident causes injuries to a person.

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[20] The term unsafe act is here defined as an act that initiates the accident causation scheme. Note that an unsafe act is only "unsafe" in a certain context. (Groeneweg, 1998)

[21] Substandard act is here defined as an act that deviates from the established standard, regulations or guidelines of the organisation. (Groeneweg, 1998)

[22] A safety barrier here defined as defensive barrier that prevents the accident to occur. Some examples of safety barriers are "child-proof" lids, air-bags and safety belts. (Groeneweg, 1998)

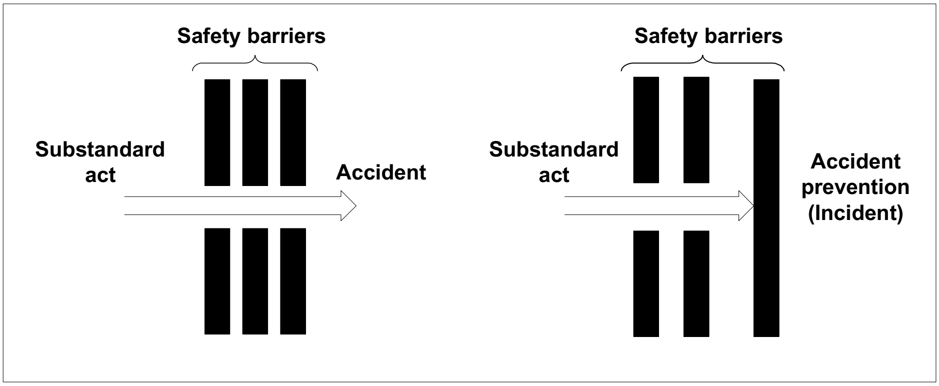

Figure 2.9. Reason's accident causation model. The accident causation starts with a substandard act, but safety barriers can prevent an accident from occurring. (Source: Groeneweg, 1998)

2.4.2 Heinrich's Loss Causation Model

In 1931, Heinrich formulated a foundation, based on ten axioms, which is the origin of many sequential accident causation models (Groeneweg, 1998). Heinrich developed the first approach to loss causation models, see Figure 2.10. Heinrich distinguished five steps one after the other, in which the third step stands for the single, critical unsafe act, instead of a possible combination of unsafe acts and specific situations (Groeneweg, 1998). Petersen (1988) states that Heinrich's approach is quite clear and practical as an approach to loss control. Simply stated: if you are to prevent losses from occurring, remove the unsafe acts.

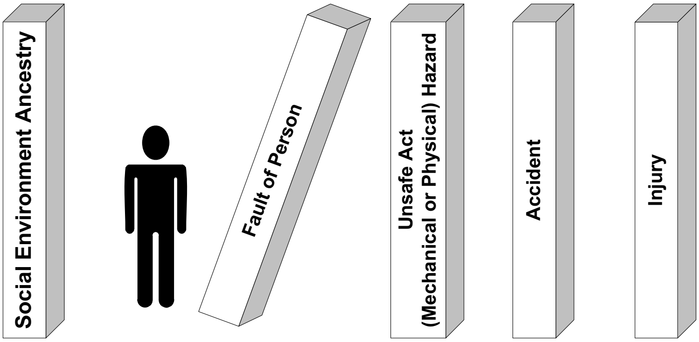

Figure 2.10. Heinrich's five-step domino model, first presented in 1931. The person is burdened by the social environment; an unsafe act initiates the domino effect causing accidents. (Source: Heinrich et al., 1980)

However, Petersen (1988) also states that the interpretation of Heinrich's theory has been too narrow. For instance, when a single act or a single condition that caused the accident is identified, it is possible that many other causes are left unmentioned. When the unsafe act or condition that is identified at the inspection is removed, it is possible that the root cause[23] of the potential accident is not found.

Today, we know that there may be many contributory factors, or causes, behind every accident (Petersen, 1988). There are other theories that consider multiple causes, factors combined together in random fashion causing accidents, but these are too complicated to use for the fulfilment of the purpose of this thesis. See, for instance, Ferry (1988) for a description of multiple accident causations and descriptions thereof.

2.4.3 Bird and Loftus Loss Causation Model

Another sequential Loss Causation Model, LCM, was developed by Bird & Loftus (1976). This model is an updated version of Heinrich's early domino model. The LCM model, see Figure 2.11, was updated to reflect the direct management relationship involved in the causes and effects of all incidents that could downgrade a business operation (Bird & Germain, 1976). Bird and Germain added a factor of influence to the domino chain by putting lack of control by management at the beginning of each accident causation scheme in their Loss Causation Model (Groeneweg, 1998). Since fundamentally uncontrollable factors were not considered, this model suggests that all accidents are avoidable if the management exerts enough control.

Lack of control is manifested in immediate causes, which are merely the symptoms of the problem. These immediate causes result in incidents at contact, with the possibility of loss of people or property (Groeneweg, 1998). The different steps in the model are briefly presented below.

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[23] Root cause is here defined as the underlying cause to the accident causation scheme.

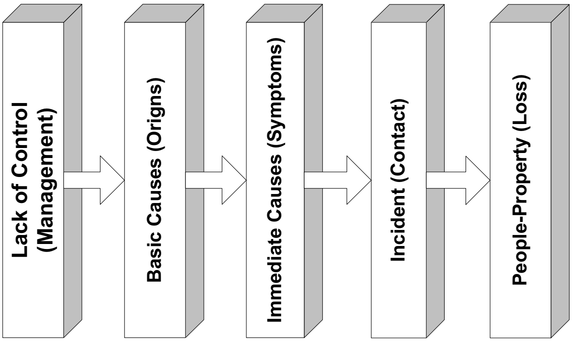

Figure 2.11. The Loss Causation Model, an updated Heinrich model, reflecting the direct management relationship involved in the causes and effects of all incidents. (Source: Bird & Loftus, 1976)

Lack of Control: By control, Bird & Loftus (1976) refer to aspects of management: planning and controlling. Some of the causes that make the first domino fall are (Bird & Loftus, 1976):

- An inadequate control program and inadequate program knowledge.
- Inadequate control program standards and knowledge of program standards.
- Failure to perform to standards, or to manage employee compliance to standard.

Basic Causes: Lack of management control leads to certain basic causes[24] of incidents that downgrade the business operation. There are other names for the basic causes, such as root causes, indirect causes, underlying causes or real causes (Groneweg, 1998). Basic causes contain both personal factors and job factors. Personal factors include: lack of knowledge or skill, improper motivation and physical or mental problems. Job factors include inadequate work standards, inadequate design or maintenance, inadequate purchasing standards, normal wear and tear and abnormal usage. (Bird & Germain, 1996)

The basic causes aim at explaining why people engage in substandard practices. Likewise, the basic causes, referred to as job factors, explain why substandard conditions are created or exist. Basic causes then are clearly the origin of substandard acts and conditions, and failure to identify these origins of loss in

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[24] Basic causes are also referred to as indirect causes in this thesis.

this step in the sequence permits this domino to fall, initiating the possibility of a further chain reaction. (Bird & Loftus, 1976)

Immediate Causes: The immediate causes[25], or substandard practices and substandard conditions, are associated with the incident that originates directly from the basic causes. The immediate cause is a substandard act, which is a violation of an accepted safe procedure. This violation could permit the occurrence of an accident.

Whether we refer to these deviations as substandard practices[26] or substandard conditions[27], there is one important thing common to all. Basically, these are only a symptom of the basic cause that permitted the practices or conditions to exist. If, and when, we fail to determine what the basic causes behind the symptoms really are, we fail to prevent this domino from falling, and the direct potential for loss still exists but is merely hidden. (Bird & Loftus, 1996)

Incident: The definition of incident is, according to Bird & Loftus (1976), an undesired event that may result in losses. Whenever substandard practices and substandard conditions are permitted to exist, the door is always open for the occurrence of an incident. The incident is undesired, since the final results of its occurrence are difficult to predict and are most frequently a matter of chance[28]. (Bird & Loftus, 1976)

Loss: Once the entire accident sequence has taken place and there is a loss, with people or property involved, the results are usually chance events. See McKinnon (2000) for further development of chance events. The element of chance is involved in quality and production losses as well as those involved in safety. Losses involved in all areas may be considered as minor, serious, major or catastrophic depending on the outcome. (Bird & Germain, 1996)

2.4.4 McKinnon's Loss Causation Model

McKinnon (2000) has further developed the Loss Causation Model, LCM, developed by Bird & Loftus (1976). The model is called Cause, Effect, and Control

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[25] Immediate causes are also referred to as primary causes in this thesis.

[26] The substandard practice could involve both acts of people and conditions related to physical things. (Bird & Loftus, 1976)

[27] A substandard condition is described as a condition that could directly permit the occurrence of an accident. (Bird & Loftus, 1976)

[28] Chance is here defined as the result, or manifestation of circumstances that could not be predicted or controlled.

of Accidental Loss Domino Sequence (CECAL), see Figure 2.12. This model describes the chain of events from poor control due to the failure to the assessment of all risks (McKinnon, 2000). The causation scheme still follows the basic and immediate causes, as presented by Bird & Loftus (1976), but different forms of chance, called "Luck Factors", are introduced. Depending on chance, the magnitude of the losses varies. These losses are manifested in incidents and accidents, while some losses still remain hidden. (McKinnon, 2000)

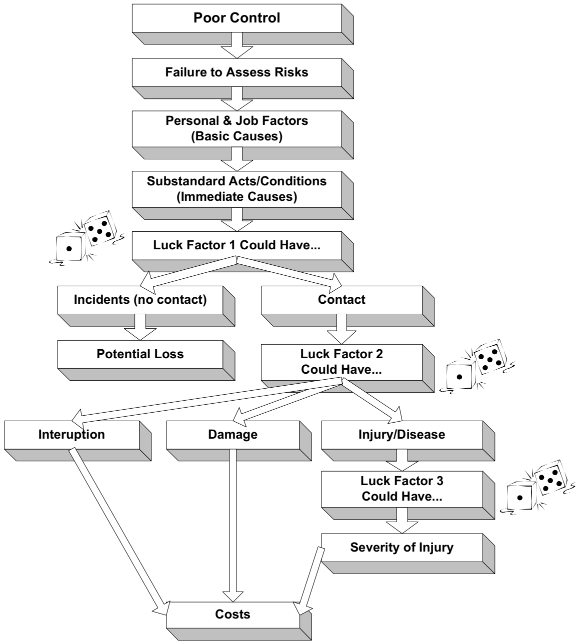

Figure 2.12. The Cause, Effect, and Control of Accidental Loss domino sequence, CECAL. The model shows how the failure to assess the risk triggers poor control and leads to losses and subsequent costs. Chance is introduced in some different steps, impacting the outcome and introducing the impact of randomised events. (Source: McKinnon, 2000)

2.4.5 Reason & Hobbs Organisational Accident Model

Reason & Hobbs (2003) describe a model for organisational accidents. The model has been applied by Reason & Hobbs (2003) within maintenance errors. However, the causes of these accidents were related to latent conditions within the organisation as a whole. The model is therefore presented as a generic model describing organisational accidents. The model can be used to guide accident investigations. (Reason & Hobbs, 2003)

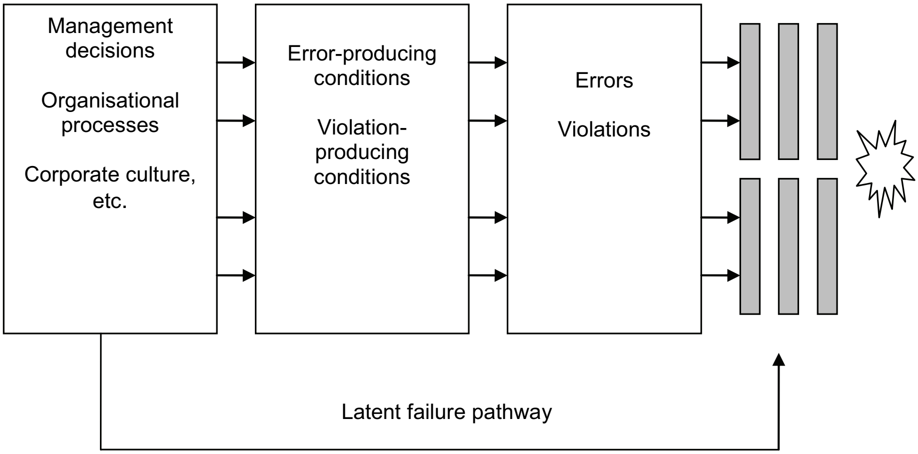

Figure 2.13. A model describing contributory factors and stages involved in organisational accidents. (Source: Reason & Hobbs, 2003)

The model describes causality from left to right. An accident sequence starts with the negative consequence of organisational processes, depending on different management decisions. Corporate culture is also an influencing factor. Latent conditions are created and transmitted along departments to the workplaces. These conditions, for instance, time pressure, high workload and poor equipment which promote errors and violations. At the individual level, these local latent conditions combined with psychological (human) errors and violations, create unsafe acts. Not all unsafe acts will cause bad outcomes due to different safety barriers. Some unsafe acts will penetrate all barriers and cause losses.

2.4.6 Hollnagel's Systemic Accident Model

Hollnagel (2004) presents a systemic accident model, see Figure 2.14. This model describes the complex linkage between different events contributing to an accident. Every event may be preceded by several other events as well as followed by other events, ordered temporally or in casual relations. The model proposes that failure in the events is due to sharp end and blunt end impact of the different events. The sharp end is factors present here and now, while the blunt end factors are removed in space and time. The direction of reasoning in this model is backwards, when tracing the reasons for development of the accident. There is no direction of causality, such as in the sequential models, in the systemic model. (Hollnagel, 2004)

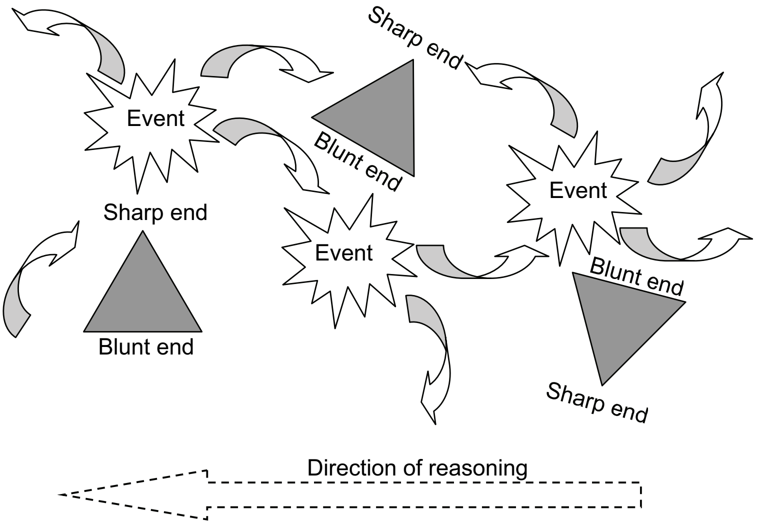

Figure 2.14. A systemic accident model describing the complex linkage between different events in relation to Sharp and Blunt ends, contributing to an accident. (Source: Hollnagel, 2004)

2.5 Accident Investigation

The main reasons for performing accident investigations[29] are to find correct causes and contributing factors, and to prevent the recurrence of a similar accident (McKinnon, 2000; Ferry, 1988; Groeneweg, 1998). These investigations aim at "explaining a part of the past" (Dekker, 2002). Of particular interest is the investigation of incidents, since they give excellent learning opportunities to prevent recurrence and future accidents. The hazards, or contributory causes of the problem, should be eliminated, as a part of the continuous improvement work, in order to strive for higher quality of the system (Bergman & Klefsjö, 2003).

Accident investigation is, according to Kletz (1994) "like peeling an onion. Beneath one layer of causes and recommendations, there are other, less superficial, layers. The outer layers deal with the immediate technical causes while the inner layers are concerned with ways of avoiding the hazards and finding underlying causes, such as weaknesses in the management system. "Very often only the outer layer, the immediate technical causes or immediate human interventions are investigated (Kletz, 1994). Although it is possible to prevent the most recent accident from happening again by removing the immediate causes,

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[29] An accident investigation is the collection and examination of facts related to an occurred specific event (Harms-Ringdahl, 2004).

considering the indirect causes (such as blunt end factors) and immediate causes (such as sharp end factors) together may prevent similar accidents from happening again in the future (Kletz, 1994).

The accident investigation process may be described according to the steps presented below (Kletz, 1994):

- Describe what happened. It is important to document and describe the accident as clearly as possible.

- Determine real causes. If real causes are not identified, there is little or no return of the investment of the time spent looking for them.

- Describe the risks. Good investigations provide the basis for deciding the likelihood of recurrence and the potential for major losses. These two factors are critical for determining the time and money to be spent on corrective actions.

- Develop control. Adequate control aimed at minimizing, or eliminating a problem can only come from an investigation that has truly solved the problem. If not, the problem will appear again and again but with different symptoms.

- Define trends. Few incidents and accidents are isolated events. However, when a significant number of good reports are analyzed, emerging trends can be identified, and dealt with.

- Demonstrate concern. Accidents give people pictures of threats to their well-being. Sometimes it is reassuring to see an objective investigation in process.

2.5.1 Biases in Accident Investigations

Accident investigations are retrospective, and therefore dependant on our ability to link pieces together in a sequence of events, starting from a known outcome (Dekker, 2002). There are therefore some possible biases in accident investigations (Hollnagel, 2004):

"The explanations of accidents, or the search for explanations, are often based on the assumption – incorrect as it turns out – that explanations can be deduced from the facts. Thus accident explanations and the search for causes are very often just trying to fit all the facts together, in the belief that there is some kind of objective truth to be found." (Hollnagel, 2004)

- We do not have all the facts

It is therefore important to emphasize that accident investigations should not be concerned with finding scapegoats, i.e. someone to blame, instead of the contributory causes. If the focus is to blame someone, then people will not report all known facts and we will never find out what really happened (Kletz, 1994). Dekker (2002) states that accident investigations tend to focus on individuals (Sharp end) rather than on the organisational context (Blunt end). That is due to organisations' resistance to attributing distal problems to an accident, because it challenges the beliefs of the system as safe and well designed. For this reason it easier to attribute direct causes to an accident.

The Sharp end may be described by individuals that are in the direct contact with hazardous events, i.e. close to the accident initiation. At the Blunt end, factors are removed in space and time, i.e. distal factors (Reason, 1990). In summary, what seems to be the root cause at the sharp end, may only be one contributory factor, where the rest of the explanations are to be found at more abstract or distal levels. Therefore, all facts may not be identified or present at the accident investigations.

- All data may not be facts, just unrelated observations

When trying to understand an accident, the problem is addressed from an outside perspective. Hence, the investigator studies the accident sequence in a retrospective way. However, the accident propagation is due to system behaviour and human actions as perceived from inside of the system. Dekker (2002) describes an inside and outside view of understanding accidents, see Figure 2.15.

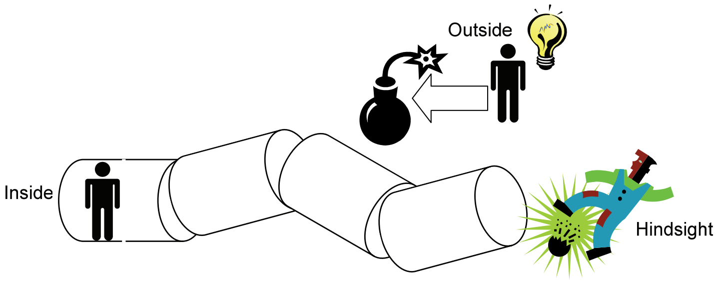

Figure 2.15. Two different perspectives on the sequent of events involved in an accident development. When an accident is investigated (view from the outside) the bad outcome and its linked hazards are known (as derived from hindsight). The situation is different when looking from the inside of the system (during accident propagation), the outcome and hazards are not known to those involved. It is therefore important to study accidents from the inside perspective, to understand different actions and why they then made sense to those involved in the accident sequence. (Source: Similar to Dekker, 2002)

- Data are dependent on accident analysis model

"Facts are not found, but sought after…" (Hollnagel, 2004)

The accident analysis model guides the investigator to focus on aspects important for the accident propagation (Groneweg, 1998; Hollnagel, 2004). The search for causes may therefore be biased. Some authors state that there is no single root cause to a problem. Instead, what is cited as a root cause is completely dependent on where the investigation starts and ends. The root cause is then where the investigation stops (Hollnagel, 2004; Dekker, 2002). Attributing root causes may be due to oversimplification. Oversimplification may be described as pointing out a few hot-spots on a complex causal pathway trying to explain its shape and behaviour (Dekker, 2002). This is a problem when using sequential models, such as The Loss Causation Model (LCM). Hence, the model represents thinking in clear and well defined cause-effect links (Hollnagel, 2004). In reality, accidents are the effect of complex organisational and system interactions. It is therefore better to search for likely explanations as to why accidents occur, rather to look for the root causes (Hollnagel, 2004). For this reason, it is important how the accident models are used in practice.

2.6 Human Failures

Human failures are in this thesis defined as consisting of both human errors[30] and rule violations[31]. The difference is the intent of the actions.

2.6.1 Human Error

Reason (1990) describes three elements of the definition of human error:

- A plan or intention that incorporates the goal and means to achieve it
- A sequence of actions that are initiated by the plan
- The extent of which these actions are successful in achieving their purpose

A distinction can therefore be made between errors having their origin in problem solving (what?) and the development of a plan to solve a certain problem (how?), storage of the plan to be used (remember), and the execution of the plan (do). (Reason, 1990)

Reason (1997) makes a distinction between different three different levels of human performance:

- Skill Based (SB) level
- Knowledge Based (KB) level
- Rule Based (RB) level

At the Skill based level slips and lapses may occur due to failures in the execution of an action or failures in the storage of a plan for the execution of an action. On the Knowledge based level mistakes may occur when the plan behind an action is incorrect. On the Rule Based level mistakes may be due to incorrect rules to solve a problem.

2.6.2 Rule Violations

Violations[32] to a rule may be either deliberate or not deliberate, without awareness, such as driving too fast but being unaware of that (Reason, 1997).

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[30] Human error is here defined as: "… occasions in which a planned sequence of mental or physical activities fails to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some chance agency" (Reason, 1990).

[31] Rule violation is here defined as: "deviations from safe and established procedures, standards or rules to control a system" (Reason, 1997).

[32] In this thesis, rule violations are seen as deliberate actions. However, these actions are not intended to do harm.

Rule violations may be divided into (Reason, 1990):

- Routine violations
- Optimizing violations
- Necessary or situational violations

Routine violations involve corner-cutting or taking short cuts, i.e. choosing the path of least effort between tasks. Such short cuts may be habitual, especially when work is performed in environments that sanctions such behaviour or guided by rigid procedures (Reason, 1990). Such procedures may be seen as promoting unnecessarily long pathways for solving the tasks.

Optimizing violations are motivated by more or less rational motives, such as thrill. Such motives are guided by non-functional aspects (Reason, 1990). Driving a car too fast, such as overspending without a functional motive, may be such a violation.

Necessary or situational violations may be due to organizational failures in providing sufficient resources such as optimal tools, equipment and time necessary to get the job done. Such violations may also be conducted when they make the work easier to perform. (Reason, 1990)

2.6.3 An approach for Human Failure Identification

An approach for Human failure identification is presented in Table 2.1. (HSE, 2006).

Table 2.1. A classification of human failures similar to Hazard and Operability studies (HAZOP) guidewords. (Source: HSE, 2006)

Action Errors	A1 Operation too long/short A2 Operation mistimed A3 Operation in wrong direction A4 Operation too little/much A Operation too fast/slow A6 Misalign A7 Right operation on wrong object A8 Wrong operation on right object A9 Operation omitted A10 Operation incomplete A11 Operation too early/late
Checking Errors	C1 Check omitted C2 Check incomplete C3 Right check on wrong object C4 Wrong check on right object C5 Check too early/late
Information Retrieval Errors	R1 Information not obtained R2 Wrong information obtained R3 Information retrieval incomplete R4 Information incorrectly interpreted
Information Communication Errors	I1 Information not communicated I2 Wrong information communicated I3 Information communication incomplete I4 Information communication unclear
Selection Errors	S1 Selection omitted S2 Wrong selection made
Planning Errors	P1 Plan omitted P2 Plan incorrect
Violations	V1 Deliberate actions

3 RESEARCH METHODOLOGY

There are many different ways of performing scientific research. In this chapter a brief introduction to research methodology is presented and the chosen research methodology is discussed.

3.1 Introduction

In general the reason for doing research is to find out why things happen as they do (Carey, 1994). To carry out research a suitable research methodology must be chosen. Denzin & Lincon (1994) state that the term research methodology focuses on "best means for gaining knowledge about the world". The term research methodology refers to the way in which the problem is approached in order to find an answer to it (Taylor & Bogdan, 1984).

3.2 Research Purpose

There are basically three different ways of classifying a research study: exploratory, descriptive and explanatory. The exploratory study aims at generating basic knowledge and demonstrating the character of a problem by collecting information through exploration. Exploratory studies are conducted in order to create an understanding of different conditions and events. An explorative study may be used for unstructured research problems, which are difficult to delimit. (Yin, 2003)

A descriptive study is appropriate when the research problem is structured for identifying relations between certain causes. The aim of a descriptive investigation is to perform empirical generalizations. (Marshall & Rossman, 1999)

The explanatory research approach aims at establishing causal connections between different phenomena (Dane, 1990). The explanatory study may therefore be used for analyzing causes and relationships, which together explains a certain phenomenon (Eriksson & Wiedersheim-Paul, 1997).

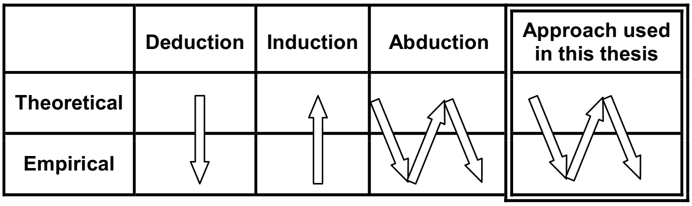
3.2.1 Purpose of this thesis

The purpose of this thesis is to "explore and describe hazards contributory to maintenance-related incidents and accidents, in order to support continuous risk reduction." To fulfil this purpose an exploratory and descriptive approach has been chosen. A motive for approaching the research as exploratory is to generate knowledge and understanding about maintenance-related incidents and accidents. The knowledge gained from the explorative approach is intended to be used for continuous improvement of the maintenance activities through hazard reduction. The reason for also choosing a descriptive approach is the need to describe how maintenance-related incidents and accidents can be illustrated and analysed in order to structure the search for a network of contributory hazards, which may result in improper maintenance. Improper maintenance is in turn manifested in different incidents and accidents. The reason for excluding the explanatory research approach is the complexity involved in establishing causal relations between hazards and their connected incidents and accidents through retrospective studies. Hence, the contributory hazards may be identified, but causal connections are difficult to establish through this approach (Hollnagel, 2004).

3.3 Research Approach

According to Alvesson & Sköldberg (1994), the research approach may be based on deduction, induction or abduction, see Table 3.1. Another type of classification is where the approach is divided into qualitative or quantitative approach (Eriksson & Widersheim-Paul, 1997).

Table 3.1. Illustration of the different research approaches: Deduction, Induction and Abduction (Source: Alvesson & Sköldberg, 1994). To the right the approach chosen in this thesis is illustrated.



3.3.1 Deduction, Induction or Abduction

The deductive approach strives to generate hypotheses, which are testable statements, based on existing theory. The results are derived by logical conclusions. (Eriksson & Widersheim-Paul, 1997)

The inductive approach is based on empirical data and conclusions are drawn from the experience gained from the study (Patel & Davidson, 1994).

Abduction may be considered as a combination of deduction and induction. The researcher can start with a deductive approach and make an empirical collection based on a theoretical framework, and then continue with the inductive approach to develop theories based on the previously collected empirical data. During the research process an understanding of the phenomenon is developed and the theory is adjusted with respect to the new empirical findings. (Alvesson & Sköldberg, 1994)

3.3.2 Qualitative or Quantitative

Research may also be divided into a qualitative or a quantitative approach. Quantitative information is conveyed by numbers and qualitative information is generally conveyed by words (Eriksson & Widersheim-Paul, 1997). The quantitative approach emphasises the measurement and analysis of causal relationships between different variables (Denzin & Lincoln, 1994). The qualitative approach aims at giving an explanation of causal relationships between different events and consequences (Miles & Huberman, 1994).

3.3.3 Applied Research Approach

The research process in this thesis started with a deductive approach, initiated by a literature study aimed at identifying the need for further investigation of maintenance-related incidents and accidents. Thereafter, identified data analysis models were adapted, which can be used for the analysis of maintenance-related incidents and accidents. Hence, these models are based on identified theoretical foundations. The analysis models were then applied, in an inductive approach, when analysing empirical data, i.e. archival records, from the database containing incidents and accidents on the Swedish railways (see Section 3.5.2.1) and empirical data from the paper mill case study. Conclusions could be drawn due to experience gained from those empirical studies, which guided the search for new theoretical foundations. The inductive approach was then used once more for the study of incident and accident investigations, i.e. documentation (see Section 3.5.2.3) and in the paper mill case study (see Section 3.5.3). Conclusions could be drawn with support of the data collected from these studies and comparisons could be made with theory. The applied research approach is therefore similar to the abductive approach, see Table 3.1.

The research approach in this thesis is mainly qualitative, but also supported by a quantitative approach. The qualitative approach aims at exploring maintenance-related hazards at maintenance execution. Furthermore, the approach also aims at describing different deviations in the maintenance process, manifested in different incidents and accidents. A quantitative approach is chosen to explore the magnitude of the losses and hazards related to accidents on the railways. However, the quantitative approach is not chosen to draw any statistical generalisations of the different incidents and accidents, but to illustrate some of the connected losses, in terms of fatalities and injuries. In Table 3.2 the chosen research strategies are presented in relation to the different research questions and the papers in which the studies are presented.

Table 3.2. Illustration of the strategies used for the research questions. Furthermore, the number of each different study and the paper in which the study is presented are also outlined.

Research Question	**1**	**2**
Type of Research Question	How	What
Research Strategy	Literature Study	Case Studies
Paper	I, II, III, IV, V	II, III, IV, V

The initial literature study resulted in four basic research propositions:

- Maintenance contributes to incidents and accidents.
- Human error is not the root cause to maintenance-related accidents.
- Maintenance is a generic approach independent of industrial application.
- It is possible to learn from incidents and accidents to reduce future occurrences.

3.4 Research Strategy

The choice of research strategy depends on what kind of information the researcher is looking for due to the purpose of the study and the research questions (Merriam, 1998; Yin, 2003). Each research strategy has strengths and weaknesses depending on three conditions: the type of research question, the extent of control the researcher has of behavioural events and the degree of focus on contemporary events, as opposed to historical events (Yin, 2003). The selection of an appropriate research strategy is illustrated in Table 3.3.

Table 3.3. The selection of appropriate research strategies for different research situations (Source: Yin, 2003).

Strategy	**Form of research question**	**Requires control of behavioral events?**	**Focuses on contemporary events?**
Experiment	How, why	Yes	Yes
Survey	Who, what, where, how many, how much	No	Yes
Archival analysis	Who, what, where, how many, how much	No	Yes/No
History	How, why	No	No
Case Study	How, why	No	Yes

3.4.1 Applied Research strategy

The stated purpose of the research presented in this thesis is to concentrate on the following two research questions:

1. How can methodologies and tools be used for identification of maintenance-related hazards contributing to incidents and accidents?

2. What kind of hazards contribute to maintenance-related incidents and accidents?

The two research questions focus mainly on “how” and “what”. According to Yin (2003) several research strategies are appropriate for “how” and “what” related research questions, see Table 3.3. These research strategies are: experiment, survey, archival analysis, history and case studies. Yin (2003) also makes a division between the research strategies depending on the control over behavioural events and whether they focus on contemporary events. In this research it is not possible to control behavioural events, which excludes experiment. According to Yin (2003) “how many” is a form of “what” related research questions. This gives the quantitative approach to losses and hazards.

Therefore, case studies have been chosen as the main research strategy. However, the railway case study encompassed an archival analysis as well. The main motive for the archival analysis was the focus on non-contemporary events, since retrospective analysis of past incidents and accidents was of interest. Another motive for performing archival analysis was to identify the magnitude of fatalities and injuries as well as hazards on the Swedish railways due to accidents linked to track maintenance. The data was also available in a database and in different incident and accident investigations, which makes archival analysis suitable, according to Yin (2003).

The motive for choosing a supporting case study related to the paper mills is the focus on contemporary events and the author’s knowledge about current maintenance practices within the area. This fact enhances the understanding of the maintenance process and the different needs of maintenance operators in relation to critical systems. Another reason is that the paper-mill case study, together with appropriate theories, is believed to support an analytical generalisation of the findings from the railway case study.

The case studies were supported by a literature study, in order to gain knowledge about the research area. The literature study was also conducted in order to identify and to adapt suitable data analysis tools, which can be used in the case studies. The literature study supports both research questions.

3.5 Data Collection

Yin (2003) presents different ways of collecting data; see Table 3.4. In qualitative research, six sources of evidence for gathering information are typically used: participant observations, direct observations, interviews, documents or archival records (Marshall & Rossman, 1999; Yin, 2003).

Table 3.4. The selection of appropriate data collection methodologies for different research situations (Source: Yin,2003).

Source of Evidence	Strengths	Weaknesses
Documentation	- Stable, can be reviewed repeatedly - Unobtrusive, not created as a result of the case study - Exact, contains exact names, references, and details of an event - Broad coverage, long span of time, many events, and many settings	-Retrievability, can be low -Biased selectivity, if collection is incomplete -Reporting bias, reflects (unknown) bias of author -Access, may be deliberately blocked
Archival Records	-Same as above for documentation -Precise and quantitative	- Same as above for documentation - Accessibility due to privacy reasons
Interviews	- Targeted , focus directly on case study topic - Insightful, provides perceived causal inference	- Bias due to poorly constructed questions - Response bias - Inaccuracies due to poor recall - Reflexivity – interviews gives what interviewer wants to hear
Direct Observations	- Reality, covers events in real time - Contextual, covers context of event	- Time consuming - Selectivity, unless broad coverage - Reflexivity, events may proceed differently because it is being observed - Cost, hours needed by human observers
Participant Observations	- Same as above for direct observations - Insightful into interpersonal behaviour and motives	- Same as above for direct observations - Bias due to investigator's manipulation of events
Physical Artefacts	- Insightful into cultural features - Insightful into technical operations	- Selectivity - Availability

Data may also be divided into primary or secondary. Data collected by the researcher for the purpose of the study is called primary data. Data already collected by other people and used by the researcher is called secondary data. (Dahmström, 1996)

Some advantages of secondary data are that it may be an easy, cheap way of receiving information. Some disadvantages are that it may be difficult to find relevant material and to assess the quality and usefulness of secondary data. As a related consequence the reliability may also be difficult to evaluate, when using secondary data. (Eriksson & Wiedersheim-Paul, 1997)

3.5.1 Applied Data Collection in Literature Study

In the literature study data was collected from different databases and scientific journals. First of all appropriate books were identified through LIBRIS (the National Swedish Library Data System). The database contains more than four million titles representing the holdings of about 300 Swedish libraries, mainly research libraries, including foreign literature.

Different databases have also been used to search for documents and research papers, e.g. Compendex, Scirus, Science Citation Index, Emerald, and Elsevier Science Direct.

Different keywords were formulated, such as: maintenance, hazard, risk, accident, incident, human error, accident model, cause and disaster. These keywords were used in different combinations to search in the different databases, resulting in a large number of hits.

In order to find relevant data, all headline titles were read and compared to the purpose of the study. This reduced the data of the material collected from the databases. Secondly, the abstracts of the remaining material were read carefully, which further reduced the material. Finally, the remaining full articles were read. The data collection approach used for databases is illustrated in Figure 3.1.

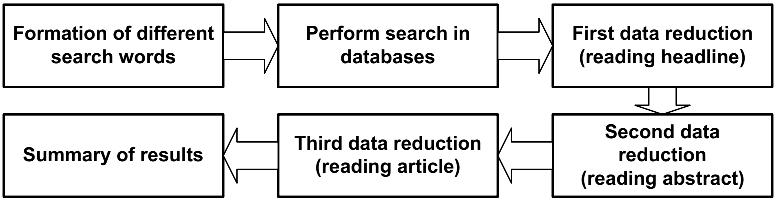


Figure 3.1. The data collection approach used for search in different databases. The arrows represent the steps taken to reduce the amount of information, and to find relevant information.

To strengthen the data collection through search engines, data was also collected directly from different scientific journals; see Figure 3.2. The reason for this extension was to include data that may be missed through the formulation of the different search words. This collection is limited to 1995-2006 due to on-line availability of relevant journals, e.g. *Safety Science; Reliability Engineering and System Safety; Journal of Loss Prevention in the Process Industries; Journal of Quality in*

Maintenance Engineering; Accident Analysis and Prevention; and *International Journal of Industrial Ergonomics*. The journals were chosen, based on the contents, in different areas such as Risk and Maintenance Management.

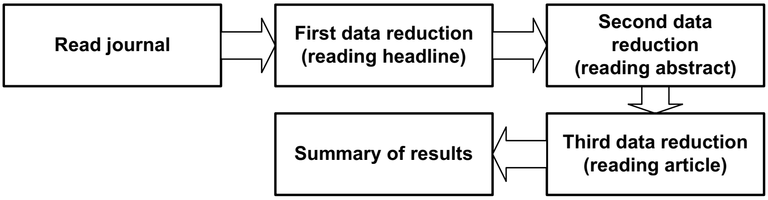


Figure 3.2. The data collection approach used for data collection in journals. The arrows represent the steps taken to reduce the amount of information, and to find relevant information.

3.5.2 Applied Data Collection in Railway Case Study

Data needed to investigate contributory causes of the maintenance-related incidents and accidents on the railways was collected through the three different approaches: archival records, interviews and documents. The archival records consist of a database containing descriptions of railway-related incidents and accidents. The interviews were performed with accident investigators at the railways. The documentation consists of different descriptions generated at incident and accident investigations at the Swedish railway.

Archival Records

The BOR database contains all train derailments and collisions on the Swedish State Railways. The database was created in Microsoft Access; see Bäckman (2002) for a detailed description of this database. BOR contains passenger train derailments for the period 1988-2000 and passenger train accidents with passengers or train crew fatalities for the period 1960-2000. All in all, 973 incidents and accidents are reported in the database (Bäckman, 2002). The database contains five different data sources: BIS, JAS, INCIDENT, HÄR and Sparre.

BIS: The Swedish National Rail Administration has a computerised system called BIS, containing different modules for track information and for accident reporting from 1988 onwards.

JAS: The Swedish Railway Inspectorate has a database called JAS, which contains information from 1989 onwards. The criteria for the accidents to be reported in the database are either fatalities, injuries or material costs of approximately 100 000 USD.

INCIDENT: Swedish State Railways (SJ) has a database called INCIDENT. SJ began reporting accidents in this computerised database in February 1995, but the database was closed in December 1997.

HÄR: The Swedish Railway Inspectorate administrated a database called HÄR between 1994 and 1998. It contains accidents as well as incidents.

Sparre: A study conducted by Sparre on accident investigations from the Swedish State Railways containing collisions, derailments and fires on the Swedish network between 1985 and 1994 generated data that has been included in BOR.

Due to the fact that the Swedish State Railways went through a major organisational change in 1988, earlier data is excluded from the study in this thesis, based on BOR. The database contains 666 incidents and accidents between 1988 and 2000.

Interviews

Interviews were conducted to validate empirical data that was collected through the archival records. The interviews were held with experienced accident investigators about different hazards and probable causes for their occurrences. The different topics of discussions were related to a set of pre-defined questions. The interviews were held over the telephone and recorded on tape. Short notes were also made by the author during the interviews.

Documentation

Data needed to further investigate contributory causes of the maintenance-related losses on the railways was achieved through a study of different documentations generated at incidents and accidents investigations.

These investigations were selected based on the findings of the archival records, presented in Paper IV. The result consists of 58 identified incidents and accidents that correspond to the purpose of this thesis. These 58 infrastructure-related incidents and accidents were classified as related to the execution of track maintenance. However, only 27 investigations were accessible through the Swedish Rail Agency (Järnvägsstyrelsen). The probable reason for this is the division of incidents and accidents into two different severity groups, of which only the more severe events are reported to the Swedish Rail Agency. The less severe events are investigated locally at different regional offices, and the investigations are stored locally, which makes them more difficult to access. Another obstacle to access for these investigations is that the division of track regions has changed over the studied time frame (1988-2000). This is the main reason for excluding the less severe events in the study.

The average number of pages for the analysed investigations is 30. However, the extents of the investigations vary between 11 and 154 pages. The studied investigations cover the years 1989-1999. The investigations consist of descriptions of: date and time, place of occurrence, incidents and outcome of the accidents, cause descriptions and surrounding environmental factors. Furthermore, recommendations for countermeasures are also suggested. The investigations are written in Swedish by professional railway accident investigators.

3.5.3 Applied Data Collection in Paper Mill Case Study

Empirical data was collected through three approaches, namely: direct observations, participant observations and interviews.

Direct and participant observations

Data was collected through both direct and participant observations of the maintenance execution at different paper mills. The observations focused on the working environment and the related conditional hazards.

Interviews

Data was collected through informal interviews with experienced maintenance technicians about the requirements and risks that emerge during maintenance execution in paper mills. The theory and the author's pre-understanding of problems regarding maintenance execution guided the different areas of discussion. During the informal interviews only short notes were taken. The reason for this was that the interviews took place in the plants between maintenance tasks. The answers were kept anonymous. The reason for this was to allow the respondents to answer freely, without possible fear for repercussions. Shortly after the interviews were conducted some concluding notes were made by the author of this thesis. The interviews that were considered vital for this thesis were verified with the interviewed personnel.

3.6 Data Analysis

It is important that every investigation should have a general analytic strategy to guide the decisions regarding what will be analyzed and for what reason (Yin, 2003). Data analysis includes aspects of: examining, categorizing, tabulating, or recombining the evidence to address the propositions of a study (Yin, 2003).

3.6.1 Applied Data Analysis in Railway Case Study

Data have been analysed through different approaches. The archival records analysis has been performed through a Loss Causation Model, supported by a Five-why methodology, see Paper III and IV. The incident and accident investigations have been analysed by using a generic maintenance process combined with an application of different guidewords, similar to those used in Hazard and Operability (HAZOP) studies, see Paper V.

Archival Records

In order to identify maintenance-related incidents and accidents in the BOR database, the data must be classified. Most of the incidents or accidents, which have been transferred from the different data sources described in Section 3.5.2, into the BOR database, contain a description of background and course of events leading to losses.

The BOR database has been studied without consideration of previous classification. The reason for this is to avoid being biased, though the classification in the database is not made with track maintenance-related causes in mind. Therefore, the incidents and accidents have been classified due to possible causes, in three iterative steps, based on the incident and accident descriptions.

The first classification is made with respect to all railway accidents and incidents reported to the database 1988-2000; see Figure 3.3.

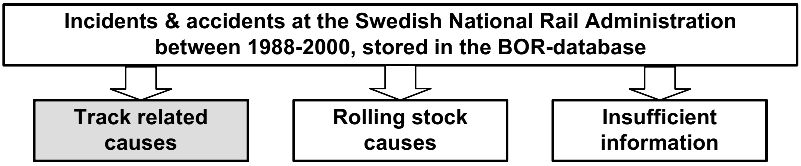


Figure 3.3. The first classification of the data aims at dividing the railway related accidents and incidents between 1988 and 2000 into track related causes, rolling stock causes and insufficient information. (Source: Holmgren, 2005)

The group classified as track related causes consists of contributory causes related to the infrastructure including the ballast, points, sleepers and rails or objects placed on or near the track. The rolling stock causes are a collection of track bound vehicles, such as trains and trolleys that are driven on the track. The group classified as insufficient information has a serious lack of information in the descriptions of the incidents and accidents. Therefore, it is not possible to determine probable causes to these incidents and accidents.

This study aims at investigating contributory causes related to the infrastructure, with a focus on track related causes. Further classification is based on the track related causes; and therefore the rolling stock causes and insufficient information were excluded from the second classification step. The reason for this limitation is that infrastructure maintenance is outsourced, and therefore may increase the need for better administrative control by identification and reduction of important hazards.

In the second classification step, track related causes were divided into maintenance-related causes, railway operation causes, sabotage and uncertain, see Figure 3.4. However, this was done in order to identify maintenance-related causes. The other groups, e.g. railway operation and sabotage, were made to gain comprehension of their occurrences.

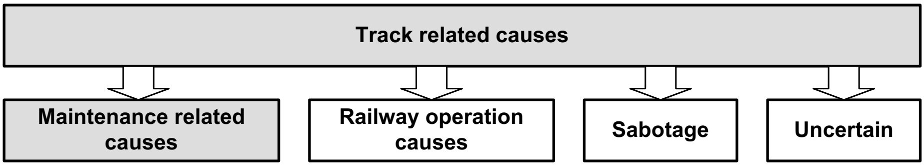


Figure 3.4. The second classification of the data is a further breakdown of the track related causes into maintenance related causes, railway operation, sabotage and uncertain. (Source: Holmgren, 2005)

The group of maintenance-related causes consists of events that are classified as being caused indirectly or directly by track maintenance. The group railway operation causes is a collection of various other events, e.g. train operation and operation of points, leading to incidents and accidents. The group sabotage consists of incidents and accidents occurring when objects are placed intentionally on or nearby the track, presumably by vandals. The group uncertain contains causes where there is insufficient information in the description of the primary causes or the consequences. All the other groups except maintenance related causes have been excluded in the third classification step, due to the main purpose of identifying maintenance-related causes.

In the third classification step, maintenance-related causes were divided into maintenance execution and lack of maintenance execution; see Figure 3.5. The reason for this classification is that it is of interest to see whether the contributory causes are due to incorrectly performed maintenance tasks or as a consequence of overseen necessary maintenance tasks.

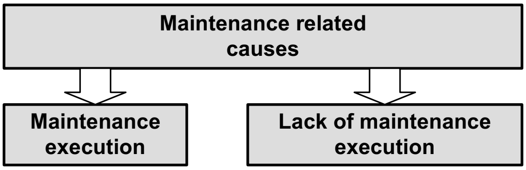


Figure 3.5. The third classification aims at dividing the maintenance related causes into maintenance execution and lack of maintenance execution in order to determine if the impact of maintenance is direct or indirect. (Source: Holmgren, 2005)

The group maintenance execution is a collection of direct maintenance-related causes occurring during the execution. The group lack of maintenance execution is a collection of various indirect events caused by lack of maintenance.

The two groups obtained in the third classification step, maintenance execution and lack of maintenance, have been thoroughly analysed in order to identify all possible contributory causes, limited by the resolution of the available data. Here the Loss Causation Model, illustrated in Figure 3.6, is applied to structure the contributory causes into the two different groups: basic causes (which may also be seen as blunt end causes) and immediate causes (which may also be seen as sharp end causes), which all precede the occurrence of the incident or accident with its connected losses. See Section 2.4.6 for Hollnagel’s sharp end and blunt end factors.

The analysis of the maintenance-related accidents and incidents, classified as maintenance execution and lack of maintenance execution, was then structured according to the Loss Causation Model in order to identify events, which are deviations from the ideal situation in the maintenance process. The most abstract level in this model is lack of control, which may here be related to the maintenance management; see also Figure 3.7 for a view of the LCM in relation to a systemic accident analysis model. It would be desirable to identify contributory causes in the range from losses to lack of control in all maintenance-related accidents and incidents, but due to the variety of the quality of the data presented in BOR, this is not possible. However, the contributory causes could be identified in the range of immediate causes and in some cases also the basic causes.

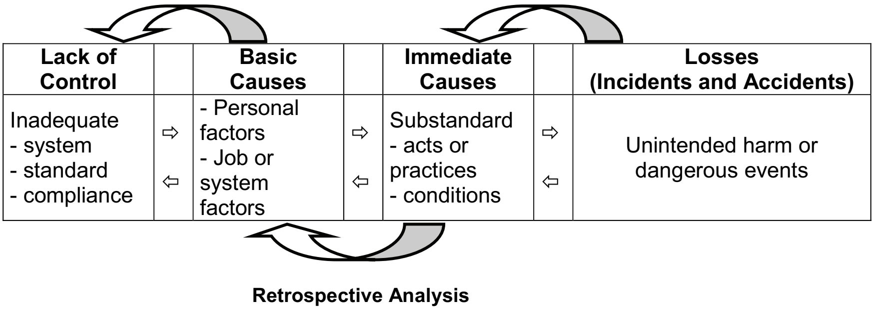


Figure 3.6. The data analysis model used for identification of contributory causes of maintenance related losses is a modified Loss Causation Model, originally developed by Bird & Loftus (1976). The retrospective analysis starts at the losses, manifested in incidents and accidents in order to identify contributory events caused by lack of control.

In Figure 3.7 the LCM model is described in relation to a systemic accident analysis model to clarify the mindset used for data analysis. The LCM is a sequential accident model that aims to identify causal connections in its original application. However, when used for analysis of railway incidents and accidents, the application has been different from its intended use, i.e. identify cause and effect (causal) relations. In the combined view there are four ovals representing different stages of the accident causation, i.e. abstraction levels. These four levels relate different human actions and system conditions contributing to the incidents and accidents.

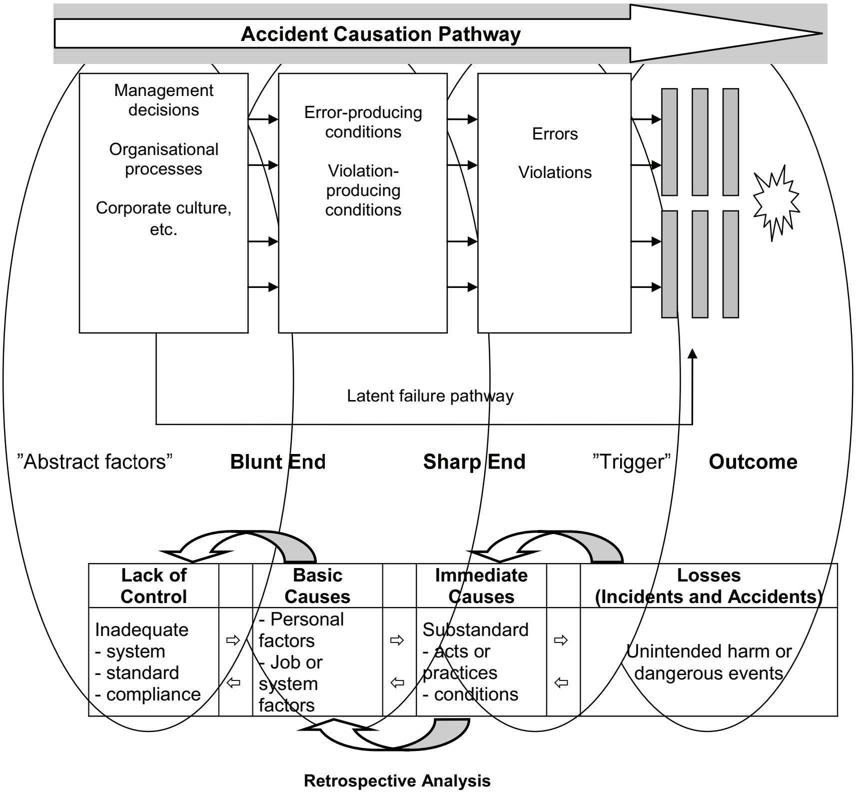


Figure 3.7. One combined view of the LCM data analysis model in relation to a systemic accident analysis model, presented by Reason & Hobbs (2003). In this model four ovals represent different abstraction levels of accident causation pathway. The immediate causes may be seen as sharp end factors close to events that trigger the accident. To the left in the model the basic causes, or blunt end factors are present, which represent causes distal from the trigger events to the accidents.

Four stages of analysis

Stage One: The retrospective analysis starts on the right side in the first oval where the magnitude of the outcome is determined. In Reason & Hobbs’s (2003) model this is determined by penetrated safety barriers. Seen in this perspective the contributory causes towards incidents and accidents are similar, only the outcome is different, i.e. accidents cause harm. This is the reason for treating incidents and accidents in the same way.

Stage Two: Some actions, such as substandard acts (e.g. human error and violations) do directly ”trigger” the incidents and accidents. Such actions are identified as sharp end factors. However, these factors are symptoms of hazards impacting on human performance through environmental impact. One must remember not to just label such factors as "the cause", there are probably more contributory factors to be found.

Stage Three: The reasons for errors and violations are determined by basic causes. These causes are personal factors and system factors (Bird & Loftus, 1976) and error and violation producing conditions (Reason & Hobbs, 2003). Such factors are seen as blunt end factors, e.g. contributory to the immediate causes in a more abstract way. These causes are determined by asking questions, e.g. using the Five-why methodology, see Kazuo & Tetsuichi (1990).

Stage Four: Discuss probable reasons for the occurrences of hazardous conditions with a focus on the surrounding environment and personal factors, thereafter suggest control measures.

One related example:

One -> Loss:
Accident, collision leading to derailment, four people injured.

Two-> Immediate causes:
Rail maintenance, digger machine was placed on the track directly causing the derailment, someone had made an error or violation.

Three -> Basic causes:
Supporting question 1: Why was the digger placed on the track?
… Due to the need for digging operations during rail change.

Supporting question 2: Why was the digger placed there when train arrived?
…Due to a misunderstanding regarding the time table.

Supporting question 3: Why was there a misunderstanding regarding time tables?
…Maintenance operator was not informed of changes in time table?

Supporting question 4: Why was he not informed?
…Train dispatcher was not aware about this track work.

And so on…

Four-> What can be done to prevent such hazards?
Suggestions of control measures.

The identification of basic causes requires logical reasoning. Such reasoning is guided by the LCM model, seen in a systemic view in Figure 3.7. These basic causes are in turn created by more abstract factors such as different management decisions, organisational processes (here with a focus on the maintenance process) leading to insufficient control.

Documents

The incident and accident investigations have been analysed using two complementary approaches. The first approach is by using a generic maintenance process, see Figure 4.3. The maintenance process is based on the four phases of the Improvement Cycle (Plan-Do-Study-Act). The second approach was the application of guidewords, similar to those used in Hazard and Operability studies (HAZOP), as described by the Health and Safety Executive (HSE, 2006), see Table 2.1. See Figure 3.8 for a description of the combined approach, when applying different guidewords on the maintenance process.

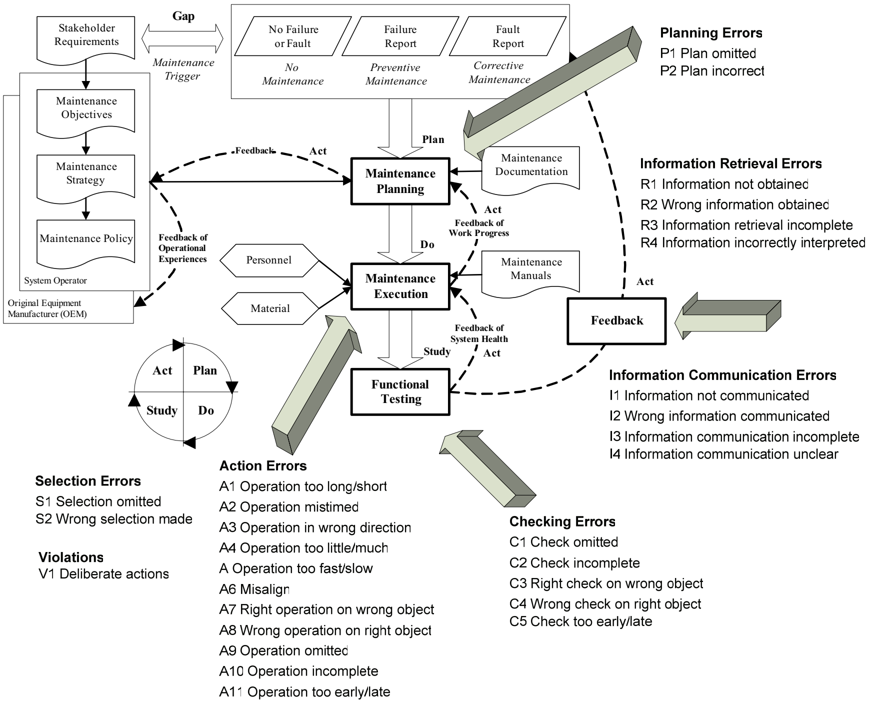


Figure 3.8. A combined approach, using different guidewords to identify human failures in relation to different activities of a generic maintenance process.

The process model was applied to illustrate contributory factors in the accidents' loss in relation to different activities in the maintenance process, i.e. Maintenance Planning (Plan), Maintenance Execution (Do), Functional Testing (Study), and Feedback (Act). The reason for using a generic maintenance process influenced by the improvement cycle in the analysis is to promote continuous improvement and hence continuous risk reduction by hazard reduction and elimination.

In order to pinpoint the contributory causes in relation to the steps of the maintenance process, the classification according to Table 2.1 was applied as a support. This classification was selected as a support in the analysis since it was developed with the purpose of identifying possible human failures. It is also important to note that the analysis was performed from a maintenance execution perspective, see Figure 3.8. The reason for this is that the studied material consists of investigations of accidents and incidents, which primarily are manifested during maintenance execution. However, the underlying causes, i.e. distal factors of the incident and accident may often be found in other process activities within the maintenance process.

3.6.2 Applied Data Analysis in Paper Mill Case Study

Data was analysed through the application of a generic maintenance process model, see Figure 3.8. The process model was supported by the two quality improvement tools: the Ishikawa diagram, see Ishikawa (1982), and Affinity diagram, see Kazuo & Tetsuichi (1990).

Observations and Interviews

The data collected through observations and interviews were structured through the maintenance process. The process model was used to relate observations to the steps described in the process model. The data analysis was performed using a maintenance process model that acted as a theoretical framework, see Figure 3.8. The initial analysis of unstructured empirical data resulted in an affinity diagram that consisted of four clusters based on the activities within the maintenance process. These clusters were then displayed in an activity-based Ishikawa diagram, pointing out maintenance-related hazards, as experienced by maintenance personnel and which affected the outcome of the maintenance process. The results of the analysis were verified with some of the maintenance technicians that initially had been interviewed.

3.7 Validity

Validity is here divided into construct validity, internal validity and external validity. Construct validity involves actions to determine the extent to which a measure represents the intended proposition of the study (Dane, 1990). One approach to strengthen the construct validity is called triangulation. This approach aims at using combined methods to collect data (Yin, 2003).

Internal validity aims at establishing causal relationships between different variables. Internal validity is only of concern for explanatory studies (Yin, 2003).

This thesis's aim is to describe and explore. The explanatory approach is not chosen. Internal validity is therefore not further discussed.

External validity refers to the generality of the findings that were made during the research (Hertzog, 1996). External validity of case studies refers to the ability to generalize findings beyond the immediate case study (Yin, 2003). Yin (2003) states that analytical validation requires that theory be tested in another case study.

3.7.1 Construct validity

Regarding the analysis of archival records within the railway case study

The group classified as insufficient information, see Figure 3.3, has a serious lack of information about the causes and consequences in the incident and accident descriptions. This fact created some uncertainty in the data material, which might affect the construct validity of the results negatively. The insufficient information may contain track-related accidents with maintenance-related connections, which in turn should be included in further studies.

There was also some uncertainty involved in the description of the causes and the consequences in the BOR database. Although it has been possible to identify that the causes are track-related, see Figure 3.4, it is hard to draw further conclusions from the data in that group with respect to the purpose of this study. The main problem was that the causes were in some cases briefly described. This uncertainty may affect the construct validity of this study.

To strengthen the construct validity of the railway case study both archival records, documents and interviews have been performed, which gives a triangulation of three different sources.

Triangulation was also applied in the paper mill case study (see Paper II). Furthermore, the outcomes of the analysis presented in Paper II were verified with the maintenance technicians that initially had been interviewed to eliminate misinterpretation.

In both case studies, colleagues of the author gave comments on the research design and worked with the different papers at seminars to strengthen the construct validity.

3.7.2 External validity

Some of the findings from the railway case study were subjected to analytical validation. For this reason the findings derived from the railway case study were tested through comparison to theories and the paper-mill case study. These comparisons are believed to strengthen the external validity outside the railway context.

3.8 Reliability

Reliability demonstrates that the operations of a study, such as the data collection procedures, can be repeated by somebody else with the same results. High reliability may be seen as the absence of errors and biases in the study. With high reliability, it is possible for another researcher to arrive at the same results on condition that the same methodology is used. One condition for high reliability is that the methodology used for data collection is clearly described. (Yin, 2003)

In order to affect the reliability positively the data collection and classification methodology has been described in Section 3.6. The incident and accident investigations, transferred into BOR, are further described in Holmgren (2006) to strengthen the reliability of the railway case study in this thesis, the BOR database is accessible through its creator Dr. Bäckman.

In Holmgren (2006) information regarding date and place of the studied incident and accident investigations are described. With support of this information, the investigations should be accessible through the Swedish Rail Agency, which strengthens the reliability.

Furthermore, the theoretical concepts used as support in the different studies are explained in Chapter 2. These concepts serve as a basis for pre-understanding of the different areas to guide another researcher. The analysis approach is described in each paper and the thesis in order to guide other researchers.

3.9 The Research Process

The main activities of the research process are illustrated in Figure 3.9.

<u>Plan Phase</u>: First of all, a preliminary literature study was performed to identify the need for further investigation of maintenance-related incidents and accidents, but also to formulate appropriate research propositions. Thereafter, the research design was constructed.

<u>Do Phase</u>: The need for further investigation of maintenance-related incidents and accidents was identified in the plan phase. This fact leads to some questions regarding the definition of maintenance activities. And furthermore, how can maintenance work be illustrated? A further literature study was performed. A generic maintenance processes was developed during this phase. Finally, data analysis models were adapted, based on identified accident causation models, see Figures 2.9-2.14.

Study Phase: The study phase focuses mainly on the identification of the contributory causes of the maintenance-related incidents and accidents. Therefore, two case studies were conducted. The data analysis models that were adapted in the do phase were applied to analyse railway related incidents and accidents in order to find the contributory causes of their occurrence. The maintenance process was used in order to illustrate important actions where losses frequently occur within both case studies.

Act Phase: Continuous improvement work is always a matter of learning and gaining experience in order to avoid the same problem again. The research process conducted for this thesis has resulted in the identification of important causes that possibly affect rail safety, economy, and delays due to improper maintenance work. The next question is: What can be done in order to improve the maintenance work? Future research work is planned, to act and take advantage of the knowledge of maintenance-related causes, see Chapter 5. Finally, reliability and validity issues regarding the case studies were discussed; see Section 3.7 and 3.8.

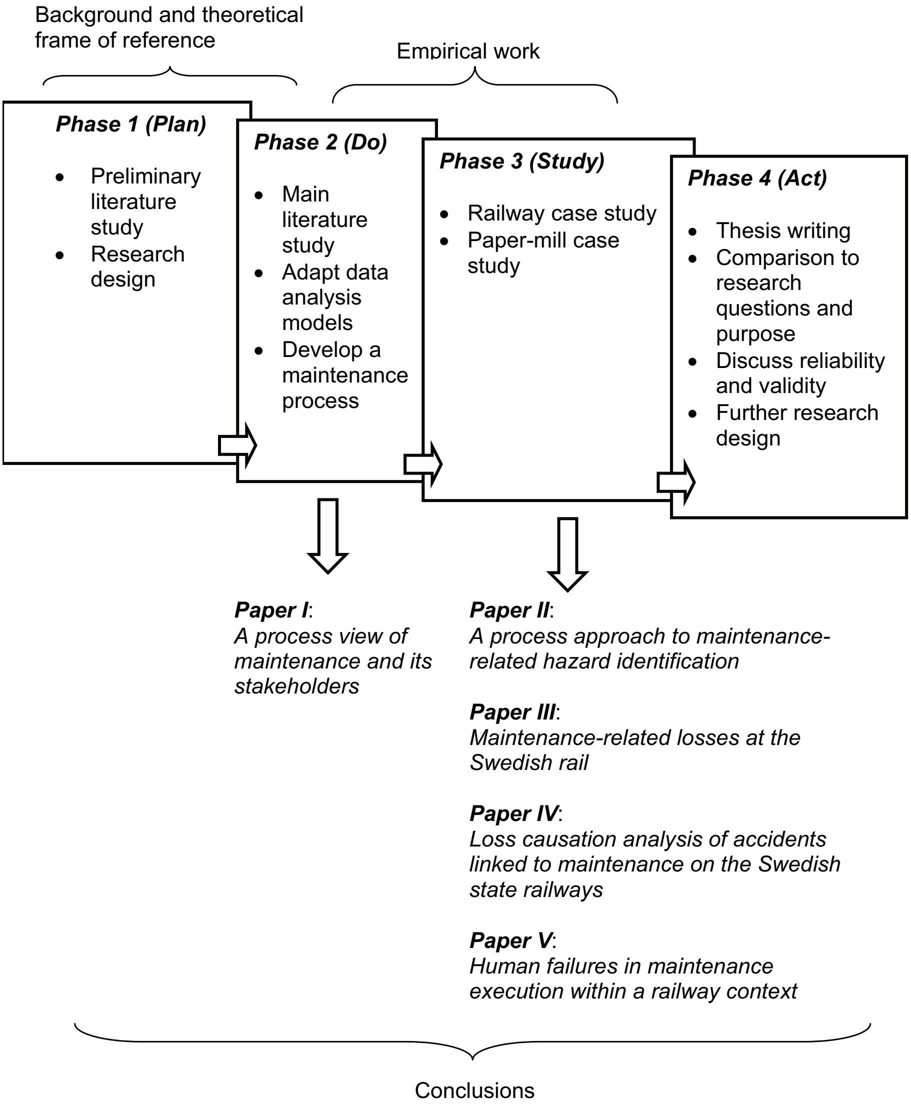


Figure 3.9. The main activities of the research process in this thesis. The different phases follow the continuous improvement cycle, presented in Section 2.1.1.

4 SUMMARY OF APPENDED PAPERS

This chapter summarises the five appended papers and describes the relations between them. The results are related to the data analysis approach described in Section 3.6. For more information the reader is referred to the appended papers.

4.1 Paper I

Söderholm, P., Holmgren, M. & Klefsjö, B. (2006). A process view of maintenance and its stakeholders. Accepted for publication in Journal of Quality in Maintenance Engineering.

4.1.1 Purpose

The purpose of this paper is to describe maintenance in a generic process model, in order to support an alignment of maintenance with other company internal processes aimed at fulfilling external stakeholder requirements.

4.1.2 Study Approach

The proposed maintenance process model is based on existing theories and is illustrated by experiences from a paper-mill case study related to the maintenance of direct current motors.

4.1.3 Findings

The paper outlines a system model of maintenance that aims at increased stakeholder satisfaction due to increased effectiveness with a reduced amount of resources which in turn increase efficiency, see Figure 4.1. The system model consists of three elements, namely core values, methodologies and tools. This system model is intended to support classification and understanding of the maintenance area.

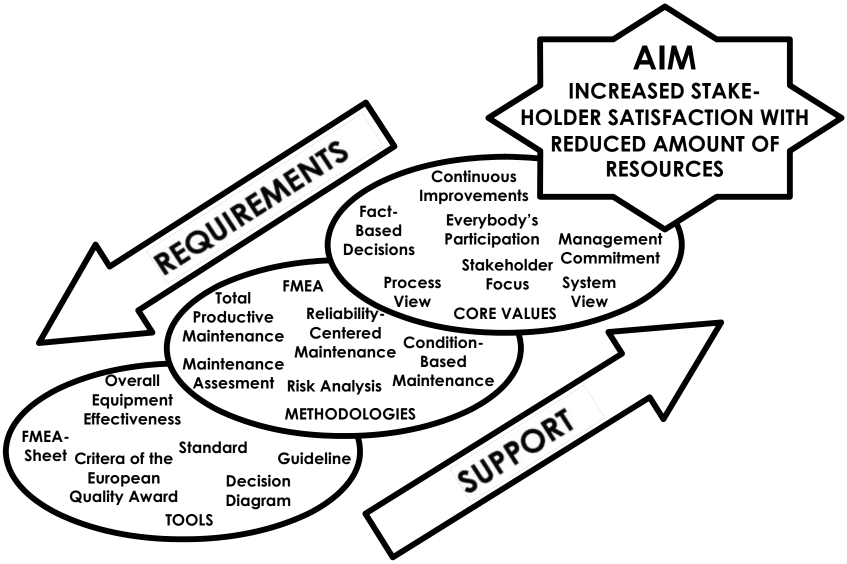


Figure 4.1. A holistic management system model of Maintenance Management. The model includes proposals for methodologies and tools that support the core values, in order to reach the aim of increased stakeholder satisfaction (increased effectiveness) with a reduced amount of resources (increased efficiency) (Source: Söderholm et al., 2006)

In this paper a generic maintenance process is also described, in two degrees of resolution. In Figure 4.2 the maintenance process is described in low resolution in relation to other processes in the operational organisation. The process measures the gap between the system service and stakeholder requirements. The gap illustrates the degree of stakeholder satisfaction with the delivered service. Here the interrelationship between the Operational Process, Modification Process, and Maintenance Process is emphasised.

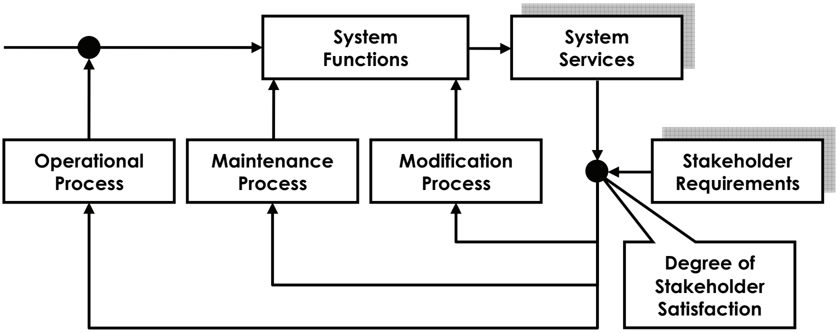


Figure 4.2. A view of maintenance as a process in relation to the operational and the modification processes. The gap between delivered system services and stakeholder requirements is a measure of the degree of stakeholder satisfaction. (Source: Söderholm et al., 2006)

The maintenance process is also outlined in a higher resolution, see Figure 4.3. This process emphasises the relationship between different phases within the maintenance process. It consists of the four activities Maintenance Planning, Maintenance Execution, Functional Testing, and Feedback. These activities and their relations are associated to the Improvement Cycle (Plan-Do-Study-Act). This process model is intended to support continuous risk reduction through continuous improvements of the maintenance activities.

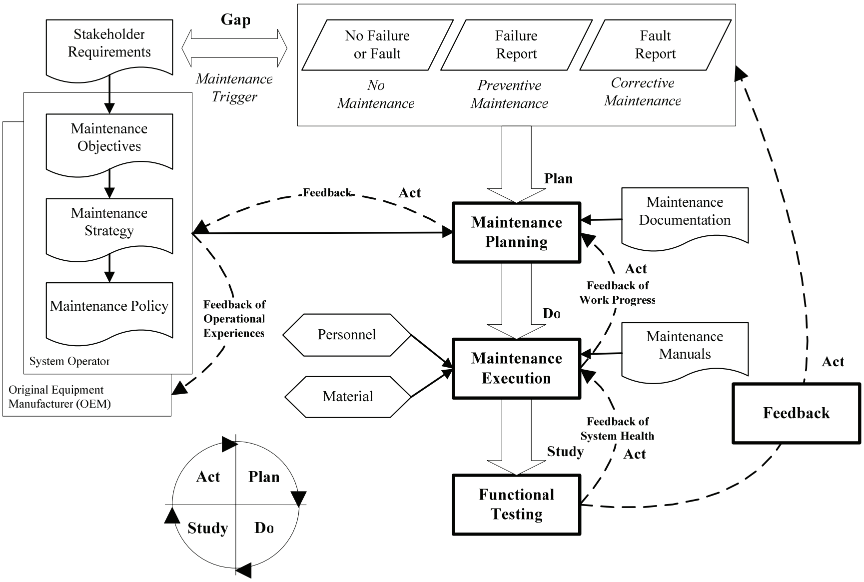


Figure 4.3. Maintenance as a process that consists of the four activities: Maintenance Planning, Maintenance Execution, Functional Testing, and Feedback. These activities and their relations are associated to the Improvement Cycle (Plan-Do-Study-Act). The activities are supported by information and different resources, such as personnel, time, and material. (Source: Söderholm et al., 2006)

4.1.4 Main Conclusions

The proposed model supports a holistic view of maintenance and the alignment of the maintenance process with other company internal processes, in order to fulfil external stakeholder requirements.

4.1.5 Relation to other Papers

The paper presents a generic process model of maintenance as a support for continuous risk reduction. The model is applied for hazard identification within a paper mill case study, presented in Paper II. The model is also applied in hazard identification within a rail context, presented in Paper V. The system view of Maintenance and its value-contributing role is something that permeates all papers.

4.2 Paper II

Holmgren, M. & Söderholm, P. (2006a). A process approach to maintenance-related hazard identification. Accepted for publication in International Journal of Comadem.

4.2.1 Purpose

The purpose of this paper is to describe a process approach for maintenance-related hazard identification, in order to support continuous risk reduction in maintenance activities.

4.2.2 Study Approach

A qualitative research approach was selected, and a case study, supported by a literature study, was chosen as research strategy. The case study was related to the maintenance of direct current motors within paper-mills. Empirical data was collected through interviews with experienced maintenance technicians about requirements and risks that emerge during maintenance execution in a critical and complex environment. The data analysis was performed using a process model that acted as a theoretical framework together with some of the seven Quality Control (7-QC) tools.

4.2.3 Findings

In this paper a process model of maintenance is applied, in order to identify maintenance-related hazards. This paper also outlines some maintenance executors' perceived risks, or hazards, in relation to the four activities of the maintenance process, see Figure 4.4. A recurring hazard is insufficient feedback. Hence, proper feedback may help to reduce risk. Further findings indicate that incidents manifested during execution may be due to hazards in other process phases. The maintenance of complex and critical systems is also affected by the work environment and knowledge of technicians, whose requirements should be fulfilled through appropriate organisational and technical support.

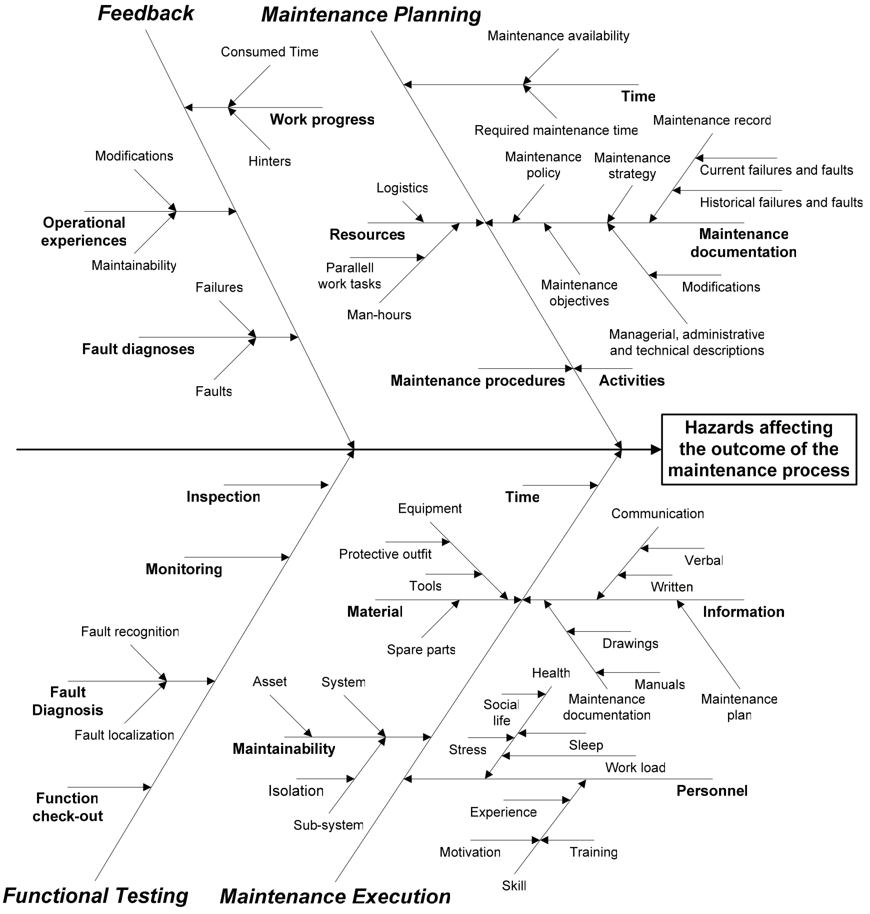


Figure 4.4. Some examples of maintenance-related hazards that may result in unwanted consequences for maintenance process stakeholders. The hazards are clustered into the four phases of the proposed maintenance process in Figure 4.3, i.e. Maintenance Planning, Maintenance Execution, Functional Testing, and Feedback. (Source: Holmgren & Söderholm, 2006a)

4.2.4 Main Conclusions

Maintenance may be a solution to the problem of increasing systems' dependability, but it may also introduce hazards that must be assessed and managed properly. One approach, to identify maintenance-related hazards in relation to the maintenance process, has been demonstrated in this paper. The proposed process model supports a systematic identification of maintenance hazards, which provides valuable input for continuous risk reduction.

4.2.5 Relation to other Papers

This paper applies a process model that structures different activities involved in maintenance, which was presented in Paper I. In paper V the process model is applied within a railway context, where it supports the analysis of incident and accident descriptions with a focus on maintenance execution. Findings of Paper II and V support each other.

4.3 Paper III

Holmgren, M. (2005). Maintenance–related losses at the Swedish Rail. Journal of Quality in Maintenance Engineering, 11(1), 5-18.

4.3.1 Purpose

The purpose of this study is to identify maintenance-related losses, and their causes, in order to describe different deviations in the maintenance process that contribute to incidents and accidents at the Swedish Railway.

4.3.2 Study Approach

The approach used in this study was an archival analysis of a database containing railway related incidents and accidents. The analysis was supported by a Loss Causation Model (LCM) and the Five-why methodology.

4.3.3 Findings

The paper presents the results of the classification of 666 derailments and collisions at the Swedish railways between 1988-2000. Incident and accident data is classified in three steps. The first classification step presents the distribution of the primary cause of all 666 incidents and accidents, namely: rail and track (263); rolling stock (311) and incomplete information (92). Thereafter, the rail and track related causes are classified into a more detailed resolution of contributory causes, namely: railway operation (78); maintenance (77); sabotage (69) and uncertain (39). In the third classification all 77 maintenance related causes are classified into maintenance execution (61) and lack of maintenance (16).

4.3.4 Main Conclusions

This paper outlines a classification of the causes to collisions and derailments in Swedish rail traffic. The paper presents the distribution of infrastructure and track bound vehicles impact on derailments and collisions.

4.3.5 Relation to other Papers

The classification presented in this paper consists of all collisions and derailments reported to the database. In Paper IV this classification is used as a basis for further classification and analysis with a focus on the infrastructure maintenance related incidents and accidents. This analysis is further enhanced in Paper V.

4.4 Paper IV

Holmgren, M. & Alm, H. (2006). Loss Causation Analysis of Accidents Linked to Maintenance on the Swedish State Railways. Submitted for publication.

4.4.1 Purpose

The aim of this paper is to study maintenance-related incidents and accidents in order to identify and quantify causes contributing to losses due to collisions and derailments on the Swedish railways.

4.4.2 Study Approach

A qualitative research approach was selected, and a single-case study, supported by an archival analysis, was chosen as research strategy. A database, containing a collection of different data sources was studied. This database contains reported railway-related accidents and some incidents on the Swedish State Railways. The Loss Causation Model (LCM) was used to structure the analysis of the maintenance related losses.

4.4.3 Findings

In this paper all identified causes of 81 maintenance-related incidents and accidents, see paper III, are presented. The classification is based on the descriptions of events contributing to the incidents and accidents. Hence the Loss Causation Model provided logic for classification of the different causes to which different events were related, in order to describe the combination of causes leading to an accident.

The causes are illustrated as contributory events, or dominos, starting from the right side in the model at lack of control and leading to different losses or consequences at the left side of the model, see Figure 4.5.

Of these 81 maintenance-related incidents and accidents, 58 were classified as due to improper maintenance execution and 23 were classified as due to lack of maintenance. The 58 maintenance execution incidents and accidents resulted in 43 collisions, five derailments and five cases with both collisions and derailments. These events resulted in four fatalities and 58 injuries. These events were classified as being caused by human error in 44 cases and by rule violation in 14 cases. The 23 incidents and accidents classified as lack of maintenance, resulted in 23 derailments. These derailments resulted in losses consisting of four injuries and economical harm. However, the magnitude of these economical losses was not established within this study.

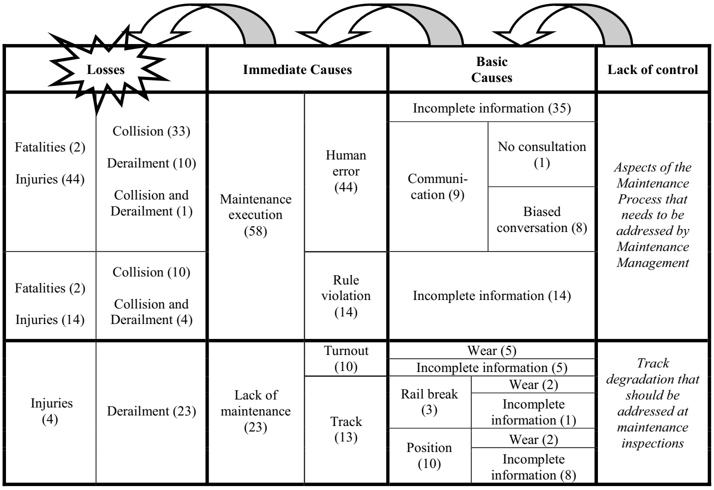


Figure 4.5. Identified causes illustrated as contributory events, or dominos, starting from the right side in the model at lack of control and leading to different losses at the left side of the model. (Source: Holmgren & Alm, 2006)

4.5 Paper V

Holmgren, M. & Söderholm, P. (2006b). Human Failures in Maintenance Execution within a Railway Context. Submitted for publication.

4.5.1 Purpose

The purpose of this study is to identify contributory causes to human failures at maintenance execution, in order to support prevention of maintenance-related losses.

4.5.2 Study Approach

The accident and incident investigations have been analysed through two complementary approaches. The first approach is a generic maintenance process. The second approach was the application of guidewords, similar to those used in Hazard and Operability studies (HAZOP).

The process model was applied to illustrate contributory causes to the accidents' ultimate loss in relation to different maintenance activities. The application of guidewords was used to identify and classify possible human failures.

4.5.3 Findings

The result of the analysis of 26 incident and accident investigations is presented in this paper. The paper outlines contributory factors in human failures during maintenance execution leading to severe incidents and accidents within the

Swedish railways between 1988 and 2000, see Table 4.1 and Figures 4.6-4.10. The majority of human failures in maintenance were related to information deficiencies, i.e. communication errors or retrieval errors, see figure 4.7. These information deficiencies were located in Feedback between different steps of the maintenance process, or within the Maintenance Execution phase, see Table 4.1.

Table 4.1. The table presents the result of the classification of human failures according to the applied maintenance process and the Health and Safety Executive (HSE) classification. (Source: Holmgren & Söderholm, 2006b)

Accident or Incident*	**Losses**	**Process Phase**	**Failure Classification**
1	F=0, I=0, M=Yes	D/ADP	A3/I1
2	F=1, I=0, M=Yes	P/D	A2
3	F=0, I=0, M=Yes	P/D/ADP	A5/A9/R3/I4/P2
4	F=0, I=2, M=Yes	D/ADP	C1/R3/I3/I4
5	F=0, I=3, M=Yes	P/D/ADP	A9/R4/I3/I4/P2
6	F=0, I=8, M=Yes	D/ADP	R4/I2/I3
7	F=0, I=0, M=Yes	P/D/ADP	A10/I1/P2
8	F=1, I=0, M=Yes	D/ADP	A2/R3/R4/I1/I3/I4
9	F=0, I=0, M=Yes	D/ADP	A9/R4/I1/V1
10	F=0, I=5, M=Yes	P/D/ADP	A5/R4/I2
11	F=0, I=0, M=Yes	D/ADP	A3/A9/R4/I1
12	F=0, I=0, M=Yes	P/D	A9/P2
13*	F=0, I=0, M=No	P/D/ADP	I3/I4
14	F=0, I=1, M=Yes	P/D	A9/I4/P2
15	F=0, I=1, M=Yes	D/ADP	A9/I1
16	F=0, I=0, M=Yes	P/D/APD	A2/C1/I4
17*	F=0, I=0, M=No	D/S/ASP	C2
18	F=0, I=0, M=Yes	D/S/ASP	C2
19	F=0, I=1, M=Yes	D/ADP	A2/I3/P1
20	F=0, I=0, M=Yes	D/S/ASD	A8/C2
22	F=0, I=5, M=Yes	D/ADP	A2/R4/I4
23	F=1, I=0, M=Yes	D/ADP	A2/V1
24*	F=0, I=0, M=No	P/D/APD	A8/A9/R4/I3
25*	F=0, I=0, M=No	P/D/ADP	R4/I4
26	F=0, I=2, M=Yes	P/D/APD	I1
27	F=0, I=1, M=Yes	D	A5
Summary of incidents and accidents Country: Sweden Years: 1988-2000 Selection of investigations: collisions and derailments related to maintenance of railway infrastructure. Number of investigations: 26 Number of incidents: 4 Number of accidents: 22 Full investigations are accessible through the Swedish Rail Agency (Järnvägsstyrelsen).	I=29 F=3 M= In 22 cases out of 26 **Abbreviations** I: Injury F: Fatality M: Material loss	D=25 P=12 APD=11 ADP=9 S=3 ASP=2 ASD=1 **Abbreviations** P: Maintenance Planning (Plan) D: Maintenance Execution (Do) S. Functional Testing (Study) ADP: Feedback from Do to Plan APD: Feed forward from Plan to Do ASP: Feedback from Study to Plan ASD: Feedback from Study to Do See Figure 1 for the relationships between different process phases.	R4=9 I4=9 A9=8 I1=7 I3=7 A2=6 P2=5 A5=3 C2=3 R3=3 A3=2 A8=2 C1=2 I2=2 V1=2 A10=1 P1=1 **Abbreviations** See Table 1.

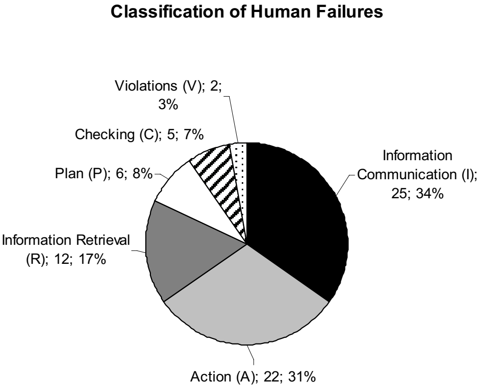


Figure 4.6. Classification of human failures causing maintenance-related incidents and accidents on the Swedish railways between 1988 and 2000. (Source: Holmgren & Söderholm, 2006b)

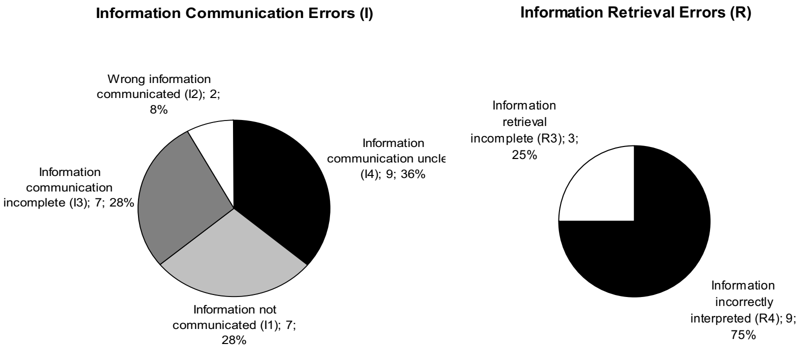


Figure 4.7. Classification of human failures during railway maintenance execution related to information communication errors (I), on the left, and information retrieval errors (R), on the right. (Source: Holmgren & Söderholm, 2006b)

The next largest group of human failures consisted of action errors, see Figure 4.8. These action errors are located in the Maintenance Execution phase of the maintenance process. Thereafter, the groups are in descending order: planning errors, which are located in the process phase of Maintenance Planning, checking errors located in the Maintenance Execution phase, or violations, see Figures 4.9 and 4.10.

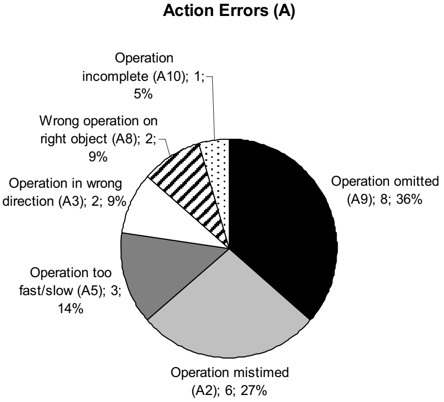


Figure 4.8. Classification of human failures during railway maintenance execution related to action errors (A). (Source: Holmgren & Söderholm, 2006b)

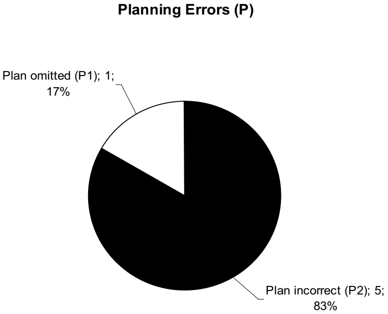


Figure 4.9. Classification of human failures during railway maintenance execution related to planning errors (P). (Source: Holmgren & Söderholm, 2006b)

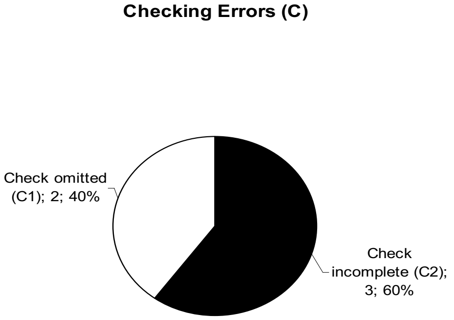


Figure 4.10. Classification of human failures during railway maintenance execution related to checking errors (C). (Source: Holmgren & Söderholm, 2006b)

The checking errors are, in addition to Maintenance Execution, also connected to the process phases of Maintenance Planning or Functional Testing through Feedback. The violations are all located in the Maintenance Execution, but are also related to both the Feedback and Maintenance Planning phases.

4.5.4 Main Conclusions

This paper gives insights into contributory factors of human failures in the maintenance process within railway infrastructure maintenance. Such information may be valuable for those involved in maintenance of other technical systems. Furthermore, the study indicates that human failures may occur at different phases of the maintenance process. The further away in space and time a failure occurs, the more intangible it becomes. However, the impact during the maintenance execution phase may be significant.

4.5.5 Relation to other Papers

Paper V consists of an in depth analysis of incident and accident investigations with a focus on infrastructure maintenance execution. Those investigations were selected with support from the enhanced classification presented in paper IV, which was based on the one presented in Paper III. The process model described in Paper I is applied for hazard identification, in the same manner as in Paper II. The findings of Paper II and V support each other.

5 CONCLUSIONS AND DISCUSSION

This chapter summarises the findings of the present thesis. The findings are related to the stated research questions. Furthermore, some aspects of the findings will be discussed. Finally, some suggestions for further research will be presented.

5.1 Conclusions

The purpose of this thesis is "to explore and describe hazards contributory to maintenance-related incidents and accidents, in order to support continuous risk reduction."

The thesis focuses on the following two research questions:

1. How can methodologies and tools be used for identification of maintenance-related hazards contributing to incidents and accidents?

2. What kind of hazards contribute to maintenance-related incidents and accidents?

5.1.1 Findings Regarding Research Question 1

Some methodologies useful for the investigation of maintenance-related incidents and accidents have been identified in the literature study and adapted in order to fulfil the purpose of this thesis, see Chapters 2.2, 3.5, 3.6 and Papers I, II and V. Some of these methodologies have also been applied in order to fulfil the second research question, i.e. for hazard analysis, see Papers II, III, IV and V. The application of adapted methodologies for hazard identification has been influenced by both a system perspective and a process perspective. The system view is supported by the holistic management system model, presented in Paper I. The process view is supported by the Process Mapping methodology. This methodology is in turn supported by the Process Chart tool, which is utilised to illustrate a generic maintenance process, see Papers I and II. In addition, these methodologies are applied within the case studies in the data collection stage, i.e. interviews, observation and archival records, but also in the analysis of empirical evidence.

Some of these methodologies are supported by the different tools that are presented in Section 2.4; see Figures 2.11-2.14. The aim of these tools, which are illustrated by different models, is to enable an understanding of contributory causes related to incident and accident propagation. These tools also provide a basis for hazard identification at different organisational levels, i.e. in relation to Research Question Two. Various tools have also supported the data collection, data analysis and data display in this thesis in order to identify maintenance-related hazards, see Chapter 3. One example of a tool used for data collection in the paper-mill case study was the maintenance process model, which guided the interviews and observations. Examples of tools used for data display are the Ishikawa diagram, see Paper II; circle diagram; see Paper IV and LCM model; see Paper V.

One combination of two tools to identify maintenance-related hazards is the constructed maintenance process model together with the HAZOP-influenced guidewords. This combination is further described in Paper IV. Another combination of tools used for identification of maintenance-related hazards within the railways case study is the guidewords akin to HAZOP combined with circle diagrams, see Paper V. A further example of combination is to apply the LCM model as a tool in order to support the Five why methodology, which is used in the railway case study, see Paper III.

By applying a process view of maintenance, it is possible to facilitate the identification of stakeholders, requirements and risks. Furthermore, the holistic management system model supports an understanding of how to identify hazards by selecting, adapting and combining appropriate methodologies and tools. The application of the methodologies should be influenced by core values as described in the holistic management system model, see Paper I. The core values that have influenced the methodologies used in this thesis are: continuous improvement, fact-based decisions, system view and process view. One example of this is to look at the maintenance process from two different perspectives. The first perspective is deductive, where the maintenance process is viewed from a perspective based on stakeholder requirements. The other perspective is inductive, where the maintenance process is based on the status of the system's functions. The deductive and inductive perspective of the maintenance process can be adapted from case to case. In Papers I and II, the inductive perspective has been applied in order to identify maintenance-related hazards. The deductive approach has not been thoroughly applied and tested in this thesis, even though its application has been demonstrated in Paper I.

In this thesis the LCM methodology is applied for retrospective analysis of incidents and accidents at the railways, see Papers III, IV and V. In Papers I and II the process model is applied in prospective manner focusing on perceived hazards and incidents in order to be pro-active. However, it should be noted that both the retrospective and prospective applications are intended to support continuous improvement, or continuous risk reduction, of maintenance activities.

The value of combining different tools may be illustrated by the use of both guidewords and the maintenance process model. One example is to identify the hazards contributing to incidents and accidents in relation to the different activities of the constructed maintenance process by applying and adopting a data analysis tool. This tool consists of a classification of guidewords. This tool supports the identification of possible human failures in relation to different activities in the maintenance process. Hence, the approach of combining the guidewords and the process model provides information about both ”what” and ”where” aspects of hazards contributing to human failures. These guidewords are presented in Table 3.1, Section 3.6.2.

5.1.2 Findings Regarding Research Question 2

Different maintenance-related hazards within railways and paper mills have been presented in this thesis. The main findings related to the railways are presented in Papers II, IV and V. In Papers I and II perceived hazards during maintenance execution at paper mills are outlined.

Improper maintenance contributes to approximately 1/3 of all infrastructure-related incidents and accidents linked to collisions and derailments on the Swedish railways, see Paper III. These maintenance-related incidents and accidents were in turn related mainly to improper maintenance execution, see Paper IV. In the railway maintenance context different forms of individual errors, such as human error and rule violation affecting the maintenance execution have been identified, see Paper V. The most common hazards identified within railway maintenance are related to information deficiencies, i.e. communication errors or information retrieval errors. These findings were corroborated by the paper-mill case study. In addition, the paper-mill case study highlighted the importance of proper horizontal communication when maintenance consultants are used, i.e. outsourcing of maintenance.

These identified information deficiencies are located in the feedback loops between different actions in the maintenance process, or within the maintenance execution itself. The reason that information deficiencies have been identified within maintenance execution is that the focus of the performed analysis was on this process step. This shows that incidents and accidents might occur in the maintenance execution (sharp end factors), even though the contributory hazards may be located in other distal process activities (blunt end factors). These findings are also corroborated by the paper-mill case study.

The second most common hazard contributing to incidents and accidents on the Swedish railways consists of different action errors within the maintenance process. These action errors are located in the maintenance execution step of the maintenance process. The largest class of action errors is omitted operations, e.g. the omission of safety devices. The second largest class of action errors is mistimed operations. One example is omitting to ask for permission to start maintenance work on the railway infrastructure or initiating work before permission is given. One consequence of these mistimed operations is that maintenance personnel and maintenance vehicles were on the track at the wrong time and therefore got hit by a train.

Within paper-mills, maintenance staff's conflicting requirements on the systems are identified as crucial hazards, see Paper II. Conflicting requirements on the systems consist of hazards related to sub-system isolation. One example of isolation is the release of mechanical and electrical energy from the system. Poor maintainability of the systems was also identified as a critical hazard. One example of hazards related to poor maintainability consists of the latent failures of the maintained system that may be introduced during maintenance execution. These latent failures represent system hazards that may result in extensive losses, see Papers I and II.

5.2 Discussion

In this thesis it is shown that maintenance-related incidents and accidents are the result of improper maintenance execution or lack of adequate maintenance. The results in this thesis indicate that most of the maintenance-related incidents and accidents on the Swedish railways happen during maintenance execution[33], rather than as a consequence of lack of maintenance, see Papers III and IV.

The studied archival records consist of accident descriptions stored in a database. Some obstacles were experienced when studying these archival records. First of all, it was not always easy to identify the possible contributory hazards of the incidents and accidents based on the descriptions. It is hard, for instance, to determine if a track fracture is caused by overseen track maintenance or by a train with some defective wheels, e.g. wheel flats due to heavy breaking with locked wheels. One reason for this might be that the performed analysis deals with secondary data, i.e. data not originally compiled for the purpose of this thesis. However, both analyses should share the same purpose: to identify causes contributing to incidents and accidents. Hence, the quality of the original investigation should be improved.

All in all, it has been quite challenging to determine if the contributory causes to the incidents and accidents were maintenance-related or not, when data was first classified, as presented in Paper III. When looking at the results of the third classification step, presented in Paper III, one must be aware that some data in the

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[33] Maintenance on the rolling stock is not included in this thesis. However, improper maintenance activities and lack of adequate maintenance on the rolling stock, e.g. track bound vehicles, may also result in derailments and collisions.

archival records was excluded when the data was classified due to incomplete information in the archival records. As a consequence of this, the number of incidents and accidents classified as maintenance-related losses in Paper IV may also be too small.

Due to the lack of information in some incident and accident investigation descriptions, it was not easy to identify the underlying causes that triggered the immediate causes in the accident initiation sequence, as presented in Paper IV. If the contributory causes of the losses were clearly described in the archival records, it would be easier to make fact-based decisions in order to pro-actively prevent further similar occurrences, and thereby continuously improve the safety of the railway. The contributory causes of the incidents and accidents can, due to the limitations in the cause descriptions in the archival records, only be traced back to the immediate, or trigger, causes in the Loss Causation Model, as presented in Paper IV. In a few cases some basic, or underlying, causes, have been identified. It is important to remember that the immediate causes are just the direct triggers of the accidents, but these are in turn created by deficiencies manifested in distal factors such as the basic causes and lack of control of the operations.

The classification that was presented in Section 4.3.4, see Figure 4.4, see also Paper III and IV, illustrates the primary causes of the maintenance-related losses and the basic causes that precede the primary causes, when they have been identified. However, the resolution of the available data does not allow any deeper analysis of the contributory causes. This results in a quite generic classification of the immediate and basic causes for maintenance execution as well as lack of maintenance, see Figure 4.4. Hence, the research presented in this thesis shows the importance of thorough investigations in order to support continuous improvement. Without addressing the underlying causes only ”quick fixes” can be achieved.

Human error is identified as triggers of the incident and accident initiation scheme, illustrated in the Loss Causation Model. However, it is difficult to explain why human error occurs with support of the archival records. Rule violations are also identified as a contributory cause of maintenance related incidents and accidents. However, explanations that could be given with support of the archival records, see Papers III and IV, were not satisfactory, e.g. the fact that someone had done something wrong was obvious. However, the reasons for their actions could not be identified. Therefore, the study of the archival record was complemented by a documentation study, consisting of full accident investigations. The main problem was that these accident investigations were not easily accessible. These investigations are stored in separate registers at the different regional offices of the Swedish National Rail Administration. However, severe incidents and accidents should also be reported to the Swedish Rail Agency (Swedish: Järnvägsstyrelsen). This thesis covers those investigations that are related to severe incidents and accidents, which were reported to the Swedish Rail Agency.

One thing that could be noticed when analysing the investigations was that the focus seems to have changed over time. Earlier investigations (1989-1997) seem to have focused on finding someone responsible for the accident, i.e. a blame focus on individuals, while later investigations (1998-1999) seem to have a somewhat more MTO-influenced (Man, Technology, and Organization) perspective, see Rollenhagen (2003). However, it is still difficult to identify hazards that contribute to human error and rule violation. It should be noticed that human error is a label that should be seen as unsatisfactory when trying to prevent future accidents. Human error should instead be seen as symptom and not as the ”root cause” of incidents and accidents. This view is in line with Reason & Hobbs (2003), Whittingham (2004) and Dekker (2005). It is also worth noticing that the Swedish National Rail Administration has initiated a special group, the task of which is to analyse incident and accident investigations to obtain a holistic view of the railway context and accordingly act more proactively in the future.

Furthermore, the author considers that an incident or accident is caused by a complex interlinked network of contributory hazards. In this thesis some accident models have been applied to understand the events and conditions leading to incidents and accidents. Although the models are quite simple, it has been difficult to apply them. When using the LCM model for data analysis some obstacles occurred. First of all, the model assumes that an accident is caused by insufficient managerial control, basic cause and an immediate cause, which in turn leads to different losses. Hence, the LCM model was not applied as a causal model. Instead, the model was used to identify a series of contributory causes all together leading to different incidents and accidents. It was difficult to determine the difference between immediate (proximal) causes or basic (distal) causes. It turned out that this is due to the focus of the investigation. This is somewhat reflected in the different result between Papers III and Paper IV. In Figure 9, presented in Paper III, a schematic description of causes is presented in relation to the LCM model. However, in this description the contributory causes of losses are not logically derived, due to difficulties in establishing cause and effect relations. This description was the author’s first attempt to apply an accident model for data analysis. Kletz (2001) is critical to the use of accident models. The reason is that the accident investigator must struggle to fit different pieces of data, e.g. evidence, into the framework of the used accident model. Such work is an obstacle that reduces free-ranging thinking, which may be needed to identify less obvious causes of an incident or accident (Kletz, 2001). This was realised during the work and therefore a combination of methodologies and tools were applied in later analyses. The opinion of the author of this thesis is that some accident models are useful, but they should be complemented by different methodologies and tools to support the analysis of incidents and accidents. The author’s second application of the LCM model is presented in Paper IV. The results here differ somewhat from Paper III.

The relations between the identified causes, i.e. hazards, are not easily understood, nor determined. It is too easy to address human error as ”the root cause” of the incidents and accidents, although it is much more difficult to really understand and explain why human error occurs. To understand how maintenance-related errors comes about and limit their occurrences, one must go beyond the psychology of the individuals and consider latent conditions, existing within the system (Reason & Hobbs, 2003). This fact underlines the importance of making accurate and detailed investigations of all the incidents and accidents occurring on the railways. Due to the regulations controlling Swedish rail traffic, severe incidents and accidents on the Swedish railways must be investigated and reported.

A recommendation would therefore be to transfer more comprehensive descriptions of the causes and consequences stated in these incident and accident investigations to the current database. It is also important to adapt databases that are compatible with the railway operators’ databases, so that current incident and accident information can be easily exchanged. However, current work at the Swedish National Rail Administration is focusing on the possibility of adapting such standardisation, regarding which type of database should be used, see Bäckman (2002) and Högberg & Mattiasson (2005).

However, the methodologies and tools presented in this thesis are not only valuable as theoretical and analytical support. For example, during maintenance execution the constructed maintenance process model is valuable as a mental model that supports the performed maintenance activities, which in turn may reduce the introduction of latent faults into the maintained system.

One of the major differences between the railway case study and the paper-mill case study is the depth of the performed hazard identifications. In the railway case study the evidence presented in the archival records and accident investigations ends with attributing human error as the root, or underlying, cause to the incidents and accidents. However, the situation is different in the paper-mill case study, where it was possible to identify hazards contributing to human error. Here, the chosen methodologies, i.e. participant observations and interviews, focused on human error at maintenance execution. The perceived hazards contributing to human error are identified and presented in Figure 2 in Paper II.

The findings of both the paper mill and the railway case studies presented in this thesis corroborate each other. However, it might also be interesting to see what other studies indicate regarding maintenance-related hazards, in similarity to an analytical validation against other cases. The paper mill case study can be compared to other applications of DC-motors, but also to other process industries. Regarding other application areas of DC-motors, even though the system and process view of maintenance have been illustrated by examples derived from the maintenance of DC-motors in paper-mills, see Papers I and II, it is believed that they are mostly transferable to maintenance of other critical technical systems. One reason is that DC-motors have a wide diversity of applications and can be found whenever there is a need of transferring power into rotating movement, e.g. within steel mills, mining industry, marine applications, and trains. The same basic principles as for the DC-motor are also applicable when generating electricity from rotating movement, e.g. hydro power, wind mills, and steam generators.

However, the findings of the paper mill case study can also be compared to other process industries, where there are several examples of when maintenance has contributed to accidents with extensive losses. Two major hazards identified within the performed paper mill case study are insufficient horizontal communication, aggravated by the use of outsourcing, and difficulties to properly isolate different parts of the system when multiple actors worked in parallel, see Paper II. These two hazards can also be seen to be contributing to severe accidents within the process industry. One of the worst accidents that has occurred in the chemical industry so far is the accident at the Union Carbide plant at Bhopal, India on 3 December 1984. One explanation of this accident is improper maintenance actions, where maintenance personnel forgot to isolate a pipe-section before carrying out the repair work (Kletz, 1994). The Piper Alpha disaster in 1988 is another example with similar contributory hazards. Some of these were the problem of properly isolating the work area together with communication and information exchange deficiencies between two maintenance shifts (Kletz, 2001). In the Piper Alpha case, maintenance was performed by contractors. These are just two examples of accidents where maintenance-related hazards similar to those identified in the work presented in this thesis contributed to severe accidents within the process industry. However, there are several other examples. In Korea, 93 major chemical industrial accidents between 1988 and 1997 were investigated by Kang (1999). Kang (1999) also classified the accidents due to the circumstances, the result was that the maintenance is the most accident-contributing phase with 34% followed by the normal operating phase which contributed to 28% of all the accidents. It should also be noticed that the start-up (15%) and shut down phase contributes (23%) the rest of the accidents, these are related to incorrectly performed maintenance. Several further examples where maintenance has contributed to severe accidents within the process industry can be found in Kletz (1994, 2001). Hence the hazards identified in the paper-mill case study are in line with findings from other process industries.

The identified hazards in the railway case study are corroborated by the paper-mill case study. However, the railway case study findings may also be corroborated by experiences from railway systems in other countries, but also from other modes of transportation, e.g. aviation, automotive and maritime. Two examples from the railway are the derailment and collision at Ladbroke Grove in 1999 and the derailment near Hatfield in 2000 (Health and Safety Executive, 2001; 2002). Several examples from the aviation can be found in Reason & Hobbs (2003). Hence the hazards identified in the railway case study are in line with findings from other transportation systems.

Based on the discussion above, it is reasonable to state that independent of what kind of philosophies, theories, and technologies are applied within an organisation, maintenance sooner or later comes down to maintenance execution, which still requires human intervention. Furthermore, the author thinks that maintenance is an approach that has generic characteristics independent of industrial application, and is more dictated by the complexity and criticality of the systems and the relationship between different stakeholders. Hence, considering the knowledge achieved when performing the research presented in this thesis the author believes that the propositions stated in Chapter 1 have been reinforced, i.e.:

- Improper maintenance contributes to incidents and accidents.
- Human error is not the root cause of maintenance-related accidents.
- Maintenance is a generic approach independent of industrial application.
- It is possible to learn from incidents and accidents to reduce future occurrences.

5.3 Further Research

Based on the findings presented in this thesis there are several opportunities for interesting further research, in order to support continuous improvement and risk reduction. Many of these opportunities are related to communication and information aspects in relation to the maintenance process. Three examples, which are briefly indicated below, are:

- Horizontal alignment of maintenance, operation and modification processes.

- Vertical alignment of the maintenance process, including external stakeholder requirements.

- Feedback from maintenance experiences, in order to achieve continuous improvement and risk reduction.

One example of the importance of horizontal alignment of the maintenance process is the situation where maintenance is contracted out. As indicated in this thesis, the maintenance contractor situation may further increase the need for transferring adequate information and requirements between different stakeholders active within the maintenance process. Hence, further research could focus on how to secure the exchange of required information between contractors and system owners. The information exchange can be performed during different cooperation phases, e.g. when writing maintenance contracts and during maintenance execution. Another crucial phase is follow-up and evaluation, during which the performance of the combined maintenance process shared between the two stakeholders should be in focus. One available case for this further research is the Swedish National Rail Administration, which already has begun to purchase maintenance from contractors.

Another example of the importance of horizontal alignment of the maintenance process is the modification and production processes. As described in the thesis, modifications are common when adapting the technical system to fit the present current operational requirements. However, information regarding the changes must be transferred to the maintenance documentation, which may be partly found in a Computerised Maintenance Management System (CMMS). Hence, it is very important to monitor the result of the modification and feed this information back to the person that performed the change, so that any necessary countermeasures can be taken before the performance of the whole system is impaired. However, if the modification is actually an improvement, the updated documentation enables it to be maintained properly the next time. A related hazard is that maintenance decisions are based on old information regarding the configuration of the technical system. Hence, the aspect of reconfiguration management and lateral process alignment is of most importance, especially when dealing with critical systems. Hence, one possibility of further research is to study how to avoid information island within the maintenance area, e.g. through the application of e-Maintenance, where Information & Communication Technologies (ICT) is applied in order to support the maintenance process, see Candell & Söderholm (2006).

Regarding vertical alignment of the maintenance process, this thesis touches upon maintenance effectiveness, but it has not been thoroughly investigated. Hence, further research could focus on establishing a link between maintenance execution and resulting value to stakeholders external to the organisation, e.g. customers, regulators and society. This linkage could be performed within a Maintenance Performance Measurement (MPM) framework including maintenance measures such as Return on Maintenance Investment (ROMI) and Overall Equipment Effectiveness (OEE). Other researchers have shown that maintenance of existing equipment can contribute to enhanced effectiveness without any investment in new equipment, see Ahlmann (2002), Liyanage & Kumar (2003) and Parida & Kumar (2006). Another related aspect of vertical alignment is the two ways in which system faults or failures are manifested, see Söderholm (2005a) and Söderholm et al. (2006). One possibility is that the function has degraded due to such things as wear and tear. An other possibility is that some stakeholders' requirements of the function have changed. In the degradation case, maintenance is a possible solution in order to correct the failure or fault. If the stakeholder requirements have changed within the capabilities of the item, maintenance may also be a possible solution in order to prevent a fault. However, the latter situation requires that the requirements do not exceed the system's inherent capability. This example highlights the importance of linking maintenance to external stakeholder requirements in order to determine its effectiveness, which is an important scope for further research.

Regarding the third area for further research, this thesis stresses that it is important to learn from both incidents and accident in order to achieve continuous improvement and risk reduction. The comparison between the two different case studies indicates that when having maintenance execution as the starting point for investigations it is easier to identify hazards contributing to human error. However, when starting at the losses caused by an accident it seems as there is a risk that human error is identified as the root cause. A study of literature indicates that this observation also is valid outside this thesis, see, for example, Whittingham (2004). Hence, further research could focus on what kind of methodologies and tools that is valuable in order to learn from normal and abnormal operation, at the same time as from both incidents and accidents. This information should be feedback to all phases of the system life cycle, for example from the operational and support phases to the design and development phases. One example is the need for proper information during maintenance execution. In order to enable this, the requirements of the maintenance technician must be understood and considered already in the design of the technical system, e.g. through testability and maintainability, see Söderholm (2005b, 2006). The maintenance technicians' situation must also be properly understood in order to plan the maintenance satisfactorily. By adapting the resources and technical system to maintenance requirements, the true hazards (or root causes) of maintenance are eliminated, and symptoms (or immediate causes) such as human error during maintenance execution do not become the focal point of the improvement efforts.

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PAPER I

A process view of maintenance and its stakeholders

Söderholm, P., Holmgren, M. & Klefsjö, B. (2006). A process view of maintenance and its stakeholders. Accepted for publication in: *Journal of Quality in Maintenance Engineering.*

A process view of maintenance and its stakeholders

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Abstract

Purpose
The purpose of this paper is to describe maintenance in a generic process model, in order to support an alignment of maintenance with other company internal processes aimed at fulfilling external stakeholder requirements.

Approach
The proposed maintenance process model is based on existing theories and is illustrated by examples from a paper-mill case study related to the maintenance of DC-motors.

Findings
The proposed model supports a holistic view of maintenance and the alignment of the maintenance process with other company internal processes, in order to fulfil external stakeholder requirements.

Research implications
Further research could include an application of the proposed maintenance model to test its usefulness to identify stakeholders and also hazard diagnosis.

Originality/value
The proposed process view highlights that maintenance can contribute to the fulfilment of external stakeholders' requirements, which strengthens the proposition that maintenance should be seen as a business-process that creates value and not as something that is a 'necessary evil'.

Keywords
System view, maintenance process, maintenance stakeholders, maintenance requirements, process industry, DC-motors.

Paper type
Research paper/Case study

Practical implications
The importance of vertical and horizontal alignment between the maintenance process and other processes in order to achieve effectiveness and efficiency is illustrated. The model can be used to increase the understanding of the role of maintenance within a company. Thereby, the proposed process model provides valuable support for effective, efficient, and continuous risk reduction.

Introduction

In today’s society we are strongly dependent on correct functions of technical systems, which have made us vulnerable to disturbances. With time, the stakeholders’ requirements on these systems’ functions will change due to the technical development, varying operational environment, changing laws and regulations, etcetera. The stakeholders are individuals and groups that have both the means of bringing their requirements to attention and for taking action if their requirements are not fulfilled (e.g. customers, shareholders, and authorities). Hence, in order to maintain a high level of stakeholder satisfaction throughout the system’s whole life cycle, organisations responsible for the systems have to react to changes in requirements through improved maintenance and system evolution. Many complex technical systems are also critical ones with stringent requirements on safety, dependability, and costs throughout the system’s life cycle (Juran, 1992; Moubray, 1997; Sommerville and Sawyer, 1997; Kotonya and Sommerville, 1998; Herzwurm and Schockert, 2003; Liyange and Kumar, 2003; Foley, 2005).

Maintenance and continuous improvement are two complementary approaches that can be applied in order to ensure the safety and dependability of technical systems, and also to decrease the cost of operation throughout the system’s life (Mobley, 1990; Deming, 1993; Campbell and Jardine, 2001). Hence, different maintenance methodologies have been developed in order to manage the complexity and criticality of technical systems and their functions. Two examples of established maintenance methodologies are Reliability-Centred Maintenance (RCM) (Nowlan and Heap, 1978) and Total Productive Maintenance (TPM) (Nakajima, 1988). Both these methodologies emphasise continuous improvement founded on fact-based decisions, and the close cooperation between different stakeholders such as production, maintenance, and system design. Physical asset management may be seen as the highest level of maintenance management, by a combination of RCM and TPM that together with continuous improvement aims at maintenance excellence (Champbell and Jardine, 2001). There is also an emerging view that maintenance not only reduces business risks, but also should be seen as a value-adding process in today’s dynamic and competitive business environment (Liyange and Kumar, 2003; Markeset, 2003).

The purpose of this paper is to describe maintenance in a generic process model, in order to support an alignment of maintenance with other company internal processes aimed at fulfilling external stakeholder requirements. The process is described from both a deductive and an inductive perspective. The deductive perspective is founded on a management system view of maintenance management and its components of values, methodologies, and tools, with a focus on stakeholders and their requirements. The inductive perspective is founded on experiences from maintenance execution within the process industry and focuses on system functions and their conditions.

Maintenance in a management system view

There are many management approaches that have evolved over time in response to increased stakeholder requirements. Two examples are Quality Management and Maintenance Management. However, the view and naming of these approaches differ between different descriptions. This can probably be explained by different stages or schools (see, for example, Garvin, 1988; Dale, 1999; Kroslid, 1999). An examination of Maintenance Management reveals that it is a multi-disciplinary area, consisting of many related or included approaches such as Logistics, Terotechnology, Asset Management, Total Productive Maintenance (TPM), Reliability-Centred Maintenance (RCM), and Condition-Based Maintenance (CBM).

This diverse situation is the same for Quality Management, where some authors have suggested a system approach in order to structure the area (see e.g. Shiba et al., 1993; Dean and Bowen, 1994; Hellsten and Klefsjö, 2000). A system may be seen as a composite entity, at any level of complexity, which consists of personnel, procedures, materials, tools, equipment, facilities, and software (IEC 60300-3-9). The elements of this composite entity are used together in the intended operational or support environment to perform a given task or achieve a specific objective (IEC 60300-3-9). According to Hellsten and Klefsjö (2000), Quality Management may be seen as a management system that aims at increased external and internal customer satisfaction using fewer resources. This management system consists of the three interdependent elements: values, methodologies, and tools. A similar management system view has been applied to Maintenance Management (Akersten, 2002), Dependability Management (Akersten and Klefsjö, 2003), and a combination of Requirements Management and Health Management (Söderholm, 2003, 2005). In this paper the management system view is applied to Maintenance Management, see Figure 1.

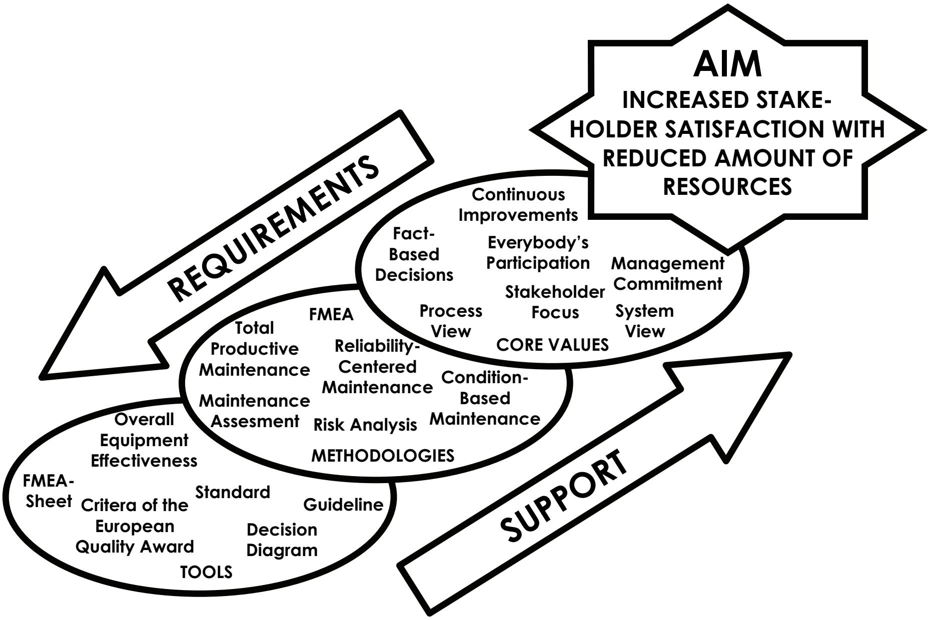

Figure 1. A holistic management system model of Maintenance Management. The model includes proposals for methodologies and tools that support the core values, in order to reach the aim of increased stakeholder satisfaction (increased effectiveness) with a reduced amount of resources (increased efficiency). Adapted from Söderholm (2003, 2005).

The fact that the core values are fundamental to Quality Management is commonly stressed (see e.g. Kanji and Asher, 1993; Oakland, 1993; Lewis, 1996; Boaden, 1997). According to Hellsten and Klefsjö (2000), the core values constitute a very important element as they are the basis of the culture of the organisation and also the basis of goals set by the organisation. Three examples of core values are Stakeholder Focus, Continuous Improvement, and Fact-Based Decisions. In this paper it is assumed that the core values have the same importance for Maintenance Management as for Quality Management, since the goal of both management approaches should be increased stakeholder satisfaction (increased effectiveness) using fewer resources (increased efficiency). The second element of the management system is the set of methodologies, i.e. the methods an organisation applies to reach its goals. A few examples of methodologies closely related to maintenance are Reliability-Centred Maintenance (RCM), Total Productive Maintenance (TPM), Failure Mode & Effects Analysis (FMEA), and Maintenance Assessment. The third element in the management system consists of tools that are rather concrete and well-defined. These tools can have a statistical basis, in order to support decision-making or facilitate the analysis of data. Some tools that support the methodologies mentioned above are decision diagrams, the Overall Equipment Effectiveness (OEE) model, FMEA-sheets, and the booklet of criteria for the European Quality Award. Some additional tools that support the methodologies above are standards and guidelines, such as IEC 60300-3-11 (RCM) and IEC 60812 (FMEA). For further discussion about the management system view, see Hellsten and Klefsjö (2000), Akersten and Klefsjö (2003), and Söderholm (2004).

One application of the management system perspective to maintenance can be illustrated by the approach of this paper. One fundamental proposition is that changing stakeholder requirements drives continuous improvement of both the technical system and its support system, and that this work should be fact-based when dealing with complex and critical systems (Söderholm 2004, 2006). This proposition reflects the core values of Stakeholder Focus, Continuous Improvement, and Fact-Based Decisions. Furthermore, it is believed that the Process View should be an additional core value in this context, see Figure 1. The mentioned core values are supported by the Process Mapping methodology. This methodology is in turn supported by the Process Chart tool, which is utilised in this paper to illustrate a generic maintenance process (Figure 3). The process view of maintenance will be further discussed in the remaining part of this paper.

Maintenance in a process view

Maintenance is defined as the combination of all technical and administrative actions, including supervisory actions, intended to retain an item in, or restore it to, a state where it can perform a required function (IEV 191-01-07). A process may be defined as an activity or set of orderly linked activities transforming input to output for customers in a repetitive flow (Rentzhog, 1996). Another definition is that a process is a network of activities that by the use of resources, repeatedly converts an input to an output for stakeholders (Isaksson, 2004). The repetitiveness is an important characteristic of the process, since it distinguishes the process from a project or a linear description of cause and effect without any feedback (Bergman and Klefsjö, 2003; Isaksson, 2004). The combination of generic maintenance activities or actions that are repeated and transforms input into output may be seen as a maintenance process (Champbell and Jardine, 2001; Holmgren, 2003; ISO/IEC 15288). The purpose of the maintenance process is to sustain the capability of the system to provide a service (ISO/IEC 15288). The maintenance process monitors the system’s capability to deliver services, records problems for analysis, takes corrective, adaptive, perfective, and preventive actions and confirms restored capability (ISO/IEC 15288).

The maintenance process can be seen with different degrees of resolution. In Figure 2, the maintenance process is seen in a rather low resolution, where its relation to some other processes within the operational organisation is emphasised. In Figure 3, the maintenance process is viewed in a higher resolution, where the relationship between the phases within the process is highlighted.

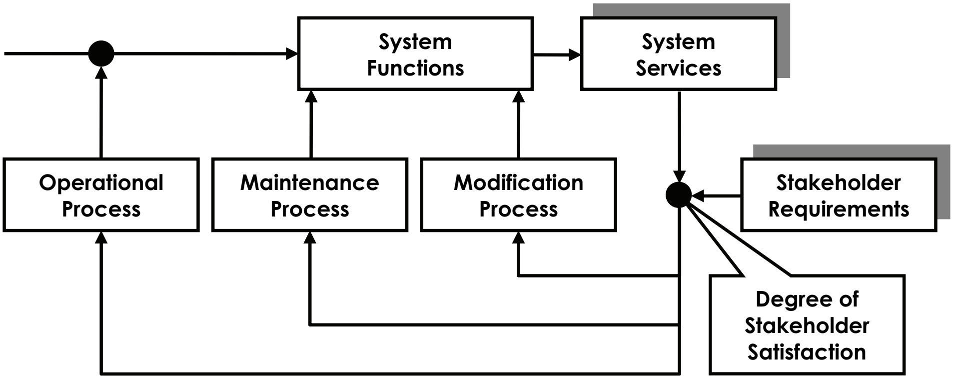

Figure 2. A view of maintenance as a process in relation to the operational and the modification processes. The gap between delivered system services and stakeholder requirements is a measure of the degree of stakeholder satisfaction. Adapted from SS 441 05 05 (2000).

The maintenance process presented in Figure 3 is based on the four phases of the Improvement Cycle (Plan-Do-Study-Act), as described by Deming (1993). The purpose of relating a generic maintenance process to the Improvement Cycle is to highlight the fact that the approach supports the work with continuous improvement, and thereby also continuous risk reduction by hazard elimination. The four phases of the proposed maintenance process are Maintenance Planning (Plan), Maintenance Execution (Do), Functional Testing (Study), and Feedback (Act). See Figure 3.

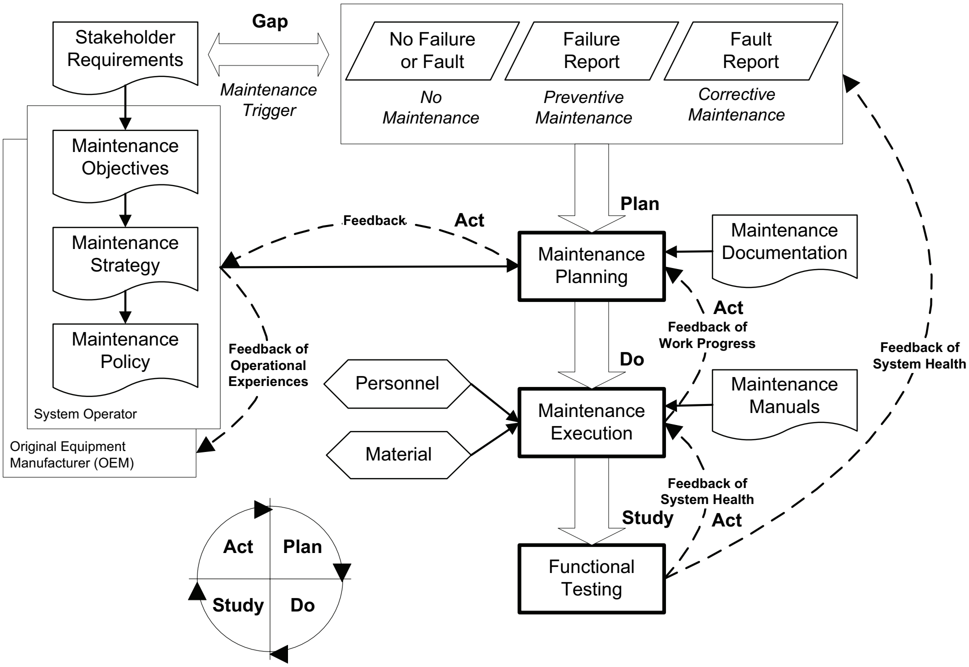

Figure 3. Maintenance as a process that consists of the four activities Maintenance Planning, Maintenance Execution, Functional Testing, and Feedback. These activities and their relations are associated to the Improvement Cycle (Plan-Do-Study-Act), as described by Deming (1993). The activities are supported by information and different resources, such as personnel, time, and material.

In the first phase of the maintenance process, Maintenance Planning, Maintenance Execution is planned, see Figure 3. One input to this phase is information about the current system health derived from the Functional Testing phase. Other inputs are maintenance documentation, such as maintenance objectives, strategies, and policies, which all should be based on stakeholder requirements. The maintenance objectives are targets assigned and accepted for the maintenance activities, which may include availability, cost reduction, product quality, environment preservation, and safety (SS-EN 13306). The maintenance strategy is in turn the management method used in order to achieve the maintenance objectives (SS-EN 13306). The maintenance policy is a description of the interrelationship between the maintenance echelons, the indenture levels and the level of maintenance to be applied for the maintenance of an item (IEV 191-07-03). Other important inputs to the maintenance process are information about available resources and the physical asset. Examples of resources are manpower (in-house and outsourced), stock levels, and logistics. Depending on whether the gap between the stakeholders' requirements and the system health is manifested as a failure or a fault, the planned maintenance may be preventive or corrective. One major output of maintenance planning is a maintenance plan. The maintenance plan is a structured set of tasks that includes the activities, procedures, resources and the time scale required to carry out maintenance (SS-EN 13306).

The second phase within the maintenance process is Maintenance Execution, see Figure 3. Inputs to this phase are not only the maintenance plan generated during Maintenance Planning, but also the maintenance environment, the maintainability of technical systems, maintenance documentation, and the actual availability of time, personnel, and resources. There may also be an input from the Functional Testing phase, which will be further discussed in relation to the Functional Testing and Feedback process phases.

The third maintenance process phase is Functional Testing, see Figure 3. The purpose of Functional Testing is to test the function of an item, in relation to some requirements. Functional Testing may be performed continuously, or periodically during scheduled checks, in order to establish the current health of the system and the actual need for maintenance. Functional Testing is also performed after Maintenance Execution, in order to verify that the system has been maintained in, or restored to, a state where it can deliver a required function. Functional Testing can also be applied iteratively with Maintenance Execution, in order to recognise and localise failures and faults by troubleshooting. The above description of Functional Testing is in line with different maintenance-related standards (i.e. IEC 60050(191), SS-EN 13306, and SS 441 05 05) and includes activities such as inspection, monitoring, fault diagnosis, and function check-out. It should be noted that Functional Testing is a crucial maintenance phase since it is here that data and information about the actual health of the system is gathered. This data and information is feedback to all other process activities and should also be distributed to stakeholders outside the operating company, such as the Original Equipment Manufacturer (OEM). Hence, it should be noted that even though Functional Testing is illustrated as the third process phase in Figure 3, it is in reality often the first phase, which generates input to the other phases. The different data and information transferred between different process phases is further discussed in the next paragraph, which covers the Feedback phase.

The fourth phase within the maintenance process is Feedback of information, see Figure 3. This Feedback goes mainly from Functional Testing to Maintenance Planning and Maintenance Execution. The information in these feedback loops represents the current health of the system. However, there is also other important feedback from Maintenance Execution to Maintenance Planning, which establishes the progress of the Maintenance Execution. The actual progress should result in a follow-up and update of the original maintenance plan. There should also be a feedback loop from the operative maintenance process to stated maintenance objectives, strategies, and policies. This feedback loop should be applied in order to validate maintenance documentation, such as maintenance manuals, and when necessary perform changes. These changes should be recognised by both the operative organisation and the Original Equipment Manufacturer (OEM). All the feedback loops mentioned are critical in order to achieve continuous improvement and continuous risks reduction in relation to the maintenance process.

In addition to different degrees of resolution, the maintenance process can be viewed from different perspectives. In this paper the maintenance process is seen from two different perspectives, in addition to the two different resolutions. The first perspective is deductive, where the maintenance process is viewed from a perspective based on stakeholder requirements. The other perspective is inductive, where the maintenance process is founded on the status of the system’s functions. The deductive and inductive perspective on the maintenance process can be adapted from case to case and independent of the selected resolution.

If one looks at the maintenance process from a deductive perspective, the input to the maintenance process is the gap between the offered system services and the requirements of the stakeholders. Hence, the trigger of the maintenance process, as well as the operational process and the modification process, is the quality of the offered services, see Figure 2. The quality of a service is the collective effect of service performance, which determines the degree of satisfaction of a user of the service (IEV 191-19-01). However, the term 'user' should perhaps be replaced with 'stakeholder', as discussed in the next section of this paper. So, based on stakeholder satisfaction, it is possible to decide if maintenance or modification is necessary, or if the operational practice should be adapted or changed. In this deductive perspective the intended output from the maintenance process, as well as the two other processes, is stakeholder satisfaction. The deductive perspective is considered necessary in order to achieve organisational effectiveness, i.e. to do the right things (Garvin, 1988).

In an inductive perspective, the maintenance process is managed by the state, or health, of system functions, i.e. the presence or lack of failures and faults. A required function is a function or a combination of functions of an item, which is considered necessary to provide a given service (IEV 191-01-05). Therefore, it is beneficial if one initiates the maintenance process when a required function encounters a fault or a failure, thereby avoiding dissatisfaction among service stakeholders. A fault is defined as the state of an item that is characterised by the inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to lack of external resources (IEV 191-05-01). Hence, faults are mostly connected to corrective maintenance, at least on a functional level, but not necessarily on a service level. A failure is the termination of the ability of an item to perform a required function (IEV 191-05-01). Hence, a fault is often the result of a failure of the item itself, but may exist without a prior failure (IEV 191-05-01). However, after failure the item has a fault (IEV 191-05-01). Another important distinction between failures and faults is that a failure is an event, as distinguished from a fault, which is a state (IEV 191-05-01). Hence, failures are often connected to preventive maintenance, where one tries to discover an impending fault and prevent it. The inductive perspective contributes mainly to the efficiency of an organisation, i.e. that things are done right (Garvin, 1988).

A process view comparable to the one presented in Figure 3 has been applied to Maintenance Management by Holmgren (2003). A similar process view has also been applied to Health Management and Requirements Management by Söderholm (2004).

Stakeholders and requirements of the maintenance process

Closely related to the process view is the customer concept. The 'customer' receives the outcome from the process, which has been processed by a 'processor', after that it has been delivered as input from a 'supplier' (Juran, 1992; Bergman and Klefsjö, 2003). However, the customer concept may vary from a narrow, more traditional, view to a rather wide interpretation. One example of a narrow sense definition can be found in the standard ISO9000:2000, where the customer is an "organisation or person that receives a product". A wider customer definition is given by Juran and Blanton (1999), who state that a customer is "anyone who is affected by the product or by the process used to produce the product". In this paper we chose to apply the word 'stakeholder' instead of 'customer'. The reason for this is to apply a more traditional (and narrow) interpretation of the word 'customer', at the same time as recognising that an organisation is part of a system of interdependencies, of which the customers are one stakeholder, see Schilling (2000). Examples of additional stakeholders are employees, suppliers, shareholders, and the community, see Okland (1993). A wide definition of 'stakeholders' can be found in the standard ISO/IEC 15288, which states that "a stakeholder is an interested party having a right, share or claim in the system or in its possession of characteristics that meet that party's needs and/or expectations". In this definition stakeholders include, but are not limited to, users, supporters, developers, producers, trainers, maintainers, disposers, purchaser and supplier organisations, regulatory bodies and members of society (ISO/IEC 15288). However, in this paper we promote a more pragmatic definition, where a stakeholder is seen as an interested party that has both the means of bringing requirements to attention and for taking actions if their requirements are not met, see Foley (2005).

The maintenance process has a number of stakeholders who may be active within the process or external to the process itself. Some examples of stakeholders that are active within the maintenance process are people who perform technical and administrative actions, such as planning and execution. Then there are a number of stakeholders who are external to the maintenance process, and who are interested in the required function of the item, the state of which the maintenance is supposed to retain or restore. The internal stakeholders may be identified by applying the inductive perspective to the maintenance process. On a more aggregated level, i.e. when applying the deductive perspective to the maintenance process, there are also stakeholders who are mainly interested in the services that the required functions is intended to ensure. The approach of identifying stakeholders through process-mapping is also described by Juran (1992) and Sharp (1999).

Stakeholder requirements are expressed in terms of the needs, wants, desires, expectations and perceived constraints of identified stakeholders. Stakeholder requirements include, but are not limited to, the needs and requirements imposed by society, the constraints imposed by a purchasing organisation and the capabilities and limiting characteristics of operator staff. (ISO/IEC 15288)

In the performed case study, there are a number of processes within the paper-mill that interact with the maintenance process. Two examples are the production process and the modification process, see Figure 2. The three processes mentioned above must be laterally aligned with each other in order to improve organisational efficiency and avoid sub optimisation. However, these internal processes must also be vertically aligned in order to improve organisational effectiveness. The vertical alignment is mainly connected to stakeholders external to the paper-mill. The external stakeholders who first come to mind may be the paper-mill's customers. The main product may be seen as the produced goods, i.e. paper that should have some physical characteristics such as porosity, weight, smoothness, colour, and so on. However, the product also includes some services, such as delivery of the right amount of paper at the right time and to the right place. There are also other external stakeholders, such as regulatory bodies that have requirements related to safety and environmental issues. These laws and regulations are, together with other stakeholder requirements, often transferred to internal stakeholders and stated in documents such as maintenance objectives, strategies, and policies.

The requirements of the system's stakeholders are continuously changing (Juran, 1992; Kotonya and Sommerville, 1998; Herzwurm and Schockert, 2003). For example, the use of paper is increasing rapidly, not only in western, so-called 'paperless' societies, but also in developing countries where the standard of living is rising. Members of society may be concerned about environmental issues and work opportunities. One example of greater stakeholder requirements is the emerging concept of sustainable development. This concept has increased the requirements on environmentally sound production, waste management, and the use of renewable energy. Maintenance may be applied in order to reduce energy consumption, in response to increased stakeholder requirements. In addition, paper-mills can contribute an energy source that earlier has been seen as a waste product of the paper production process, and therefore has not been exploited. This energy source is black liquor (also called black lye or spent liquor), which today is seen as a promising energy source that might complement hydropower or replace fossil fuels and nuclear energy. Hence, some changing stakeholder requirements drive the development of a new product, and also add new stakeholders. These additional stakeholders may be connected to the energy aspect since the use of renewable energy, such as wood and recycled paper, has become more attractive. This in turn drives the prices of wood and recycle paper, the two main sources of raw materials when making paper. The addition of black liquor as a new paper-mill by-product creates a situation where maintenance is insufficient in order to fulfil stakeholders' requirements and where modification of the equipment within the paper mill is necessary.

The customers' increased demand for paper will also affect the existing paper production process, which in turn requires lateral process alignment. In response to the increased demand for paper, one internal paper-mill requirement will be to increase the capacity of the paper machine. This can be achieved by increasing the operational speed. One way to achieve this is to increase the voltage delivered to the DC-motors, by exploiting the motor's designed safety factor. This means that the motor is operated at too high a voltage, i.e. more than the intended design. However, operation at too high a voltage will influence the reliability and the lifetime of the motor, and hence the maintenance practices. Another aspect to consider is that the insulation, or the motor's ability to resist short cuts, will slowly decrease due to age and environmental factors, such as dirt and moisture. So, in order to ensure the dependability of the paper machine, it is not recommended to operate old DC-motors at too high a voltage. Another, more preferable solution for the fulfilment of the requirements on increased production is to modify the gearbox. This modification allows an increased speed of the paper machine, without increasing the voltage that is fed to the DC-motor. The reason for this is that the voltage controls the rotational speed of the motor, while the current impacts the motor's torque. Hence, the motors may be loaded up to the rated current, which is determined by the design. However, motors in the paper machine are seldom operated near the rated current, since it is the rated voltage that limits the maximum operating speed. Therefore, it is possible to achieve an increased production speed by increasing the transmission ratio of the gearbox that is linked to the motor. This will create a higher load on the motor, which in turn will consume more current. So, by an appropriate gear ratio selection, the motors can, in combination with the modified gearbox, deliver the required operational speed of the paper machine. This will lead to a higher current consumption by the motor, but it will still operate below the rated voltage, which is limiting. However, this modification will impact some other functions inside the motor. For example, the current is transferred to the motor by the interface between the commutator and the electrical brush. This interface is a critical function that needs to be maintained. Therefore, there are some maintenance requirements to consider due to the motor's increased consumption of current as a result of the gearbox modification. An increased current consumption changes the operational condition inside the motor. So, by modifying the gearbox, further modifications within the motor are required. Since there is more current for the brushes to transfer, the existing brushes may be insufficient and an exchanged quality of the brush may be required. Since the motors rotational speed will decrease, the mechanical wear of the brush will also decrease and thereby prolong the intervals between replacements. Hence, the maintenance documentation related to the motors must be changed.

The example described above highlights the necessity and complexity of lateral process alignment when performing vertical alignment against increased customer requirements. In summary, the gap between the delivered and required function of the technical system is intended to be filled by changed operating practices. However, in order to achieve this, adapting the maintenance practices is not sufficient. It is also necessary to perform some system modifications, which in turn will affect the maintenance. The example also illustrates the importance of knowledgeable personnel who understand the interactions between different subsystems.

If one looks at the term ‘required function’, there are two possible causes of a fault or failure. One possibility is that the function has degraded due to such things as wear and tear. The other possibility is that some stakeholders’ requirements of the function have changed. In the degradation case, maintenance is a possible solution in order to correct the failure or fault. If the stakeholder requirements have changed within the capabilities of the item, maintenance may also be a possible solution in order to prevent a fault. However, if the stakeholder requirements have changed beyond the item’s capabilities, maintenance is insufficient and modification is necessary. As distinguished from maintenance, the modification of an item is the combination of all technical and administrative actions intended to change an item (IEV 191-01-13). Hence, maintenance can be used in order to compensate for failures and faults that are related to the degradation of a function or a service, or if the stakeholders’ requirements have increased within the capabilities of the existing system design. So, improvements in operation and support may contribute to greater stakeholder satisfaction as long as there is scope for improvement due to existing ineffectiveness. However, if the failure or fault is due to increased stakeholder requirements that exceed the capabilities that contribute to the delivered service, maintenance and operational efforts are insufficient and modifications are necessary. This situation highlights with the necessity for the lateral alignment of processes that contribute to the service offered to the stakeholders, e.g. the situation described in Figure 2.

Conclusions and discussion

In this paper we have presented two models of maintenance. The first model is based on a management system perspective of maintenance management and its components of values, methodologies and tools (see Figure 1). This system model is intended to support a classification and understanding of the maintenance area. The second model is based on a generic process view of maintenance and consists of four interrelated activities of Maintenance Planning, Maintenance Execution, Functional Testing, and Feedback (see Figure 3). The process model is intended to support continuous improvement of and continuous risk reduction in maintenance activities.

In order to achieve organisational effectiveness and efficiency, we argue that the maintenance process must be seen from both a deductive perspective and an inductive perspective. Furthermore, the two perspectives must be linked to each other in order to fulfil both external and internal stakeholder requirements. By applying a process view of maintenance, it is possible to facilitate the identification of its stakeholders, requirements and risks. This identification supports the management of both requirements and risks, which should contribute to business prosperity through continuous improvement and risk reduction. By the combination of both a deductive and inductive approach to the maintenance of critical systems, synergetic benefits may be achieved that are more difficult to reach if only one single perspective is applied. This is achieved through identification and measurement of the gap between the required and offered services, which is deployed to functions and items within the technical system that must be maintained in order to ensure system dependability. The system dependability is one quality dimension that is necessary in order for the system to be fit for use. The gap represents the degree of stakeholder dissatisfaction, e.g. the fulfilment of the customers' need, expectations, and desires.

It is also emphasised that, even though maintenance may have a value-creating role within an organisation, there are also some situations when maintenance by itself is insufficient and other approaches, such as modification, are necessary. The basic reason for this is that maintenance has no effect outside the boundaries created by the intended design of the technical system. However, maintenance can compensate for system degradation caused by operational environment and usage. Hence, maintenance is necessary and valuable, but it can only compensate for deficiencies (compared to the intended design) and not create any additional value. The necessary continuous improvement of maintenance is governed by the increased requirements of stakeholders. However, even perfect maintenance cannot exceed the intended design of the technical system.

Even though the system and process view of maintenance have been illustrated by examples derived from the maintenance of DC-motors in paper-mills, it is believed that they are mostly transferable to maintenance of other critical technical systems. For example, the authors have experience from projects related to maintenance within both the railway industry and the aerospace industry, where the ideas presented in this paper are considered to be applicable.

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PAPER II

A process approach to maintenance-related hazard identification

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A process approach to maintenance-related hazard identification

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Abstract

History has shown that maintenance contributes to incidents and accidents with extensive losses. The purpose of this paper is to describe a process approach for maintenance-related hazard identification, in order to support continuous risk reduction in maintenance activities. The proposed maintenance process model has been applied within a study of maintenance execution of DC-motors in paper-mills. However, both the model and the findings from its application are believed to be transferable to the maintenance of other critical technical systems. A recurring hazard is insufficient feedback. Hence, proper feedback may help to reduce risk. Further findings indicate that incidents manifested during execution may be due to hazards in other process phases. The maintenance of complex and critical systems is also affected by the work environment and knowledge of technicians, whose requirements should be fulfilled through appropriate organisational and technical support.

Keywords

Maintenance process, hazard identification, risk reduction, paper-mill, DC-motors.

1 Introduction

The industrial risk problem and the diversification of risk types have increased concurrently with industrial development, at the same time as the acceptable risk threshold of the population has decreased [1]. Maintenance and continuous improvement are two complementary approaches that can be applied in order to ensure safety and dependability of technical systems, and also to decrease its life cycle cost [2, 3, 4]. However, it should be noted that even though maintenance is intended to ensure system safety and dependability, there are numerous examples when maintenance of complex and critical systems has resulted in accidents with extensive losses. Some examples of maintenance-related accidents within the process industry are the leak from a chemical plant at Bhopal (India, 1984), the Piper Alpha oil platform fire (North Sea, 1988), the disaster at Philips petrochemical plant in Texas (USA, 1989), the explosion and fires at the Texaco refinery at Milford Haven (UK, 1994), and the chemical release and fire at the Associated Octel Company Limited in Cheshire (UK, 1994).

The purpose of this paper is to describe a process approach for maintenance-related hazard identification, in order to support continuous risk reduction in maintenance activities. The process is applied in an inductive perspective, which is based on experiences from maintenance execution within paper-mills. The focus is on system functions and related maintenance hazards.

2 Study approach

In order to fulfil the study's purpose, a qualitative research approach was selected, and a single-case study, supported by a literature study, was chosen as research strategy. The case study was related to the maintenance of Direct Current motors (DC-motors) within paper-mills. The reason for choosing paper-mills as an application area is that its continuous operation results in rigorous maintenance requirements. The selection of the maintenance of DC-motors is due to the fact that these motors are critical components, the failure of which might result in consequences that are manifested in extensive economical losses. Empirical data was collected through interviews with experienced maintenance technicians about requirements and risks that emerge during maintenance execution in a critical and complex environment. The data analysis was performed using a process model that acted as a theoretical framework. The initial analysis of empirical data resulted in an affinity diagram that consisted of four clusters based on the activities within the constructed maintenance process. These clusters were then displayed in an activity-based Ishikawa diagram, pointing out maintenance-related hazards, as experienced by maintenance personnel and which affected the outcome of the maintenance process. Finally, the outcomes of the analysis were verified with the knowledgeable maintenance technicians that initially had been interviewed.

3 Maintenance in a process view

Maintenance is defined as the combination of all technical and administrative actions, including supervisory actions, intended to retain an item in, or restore it to, a state where it can perform a required function [5; IEV 191-01-07]. A process may be defined a network of activities that by the use of resources, repeatedly converts an input to an output for stakeholders [6]. The repetitiveness is an important characteristic of the process, since it distinguishes the process from a linear description or a project of cause and effect with no feedback [7, 6]. The combination of generic maintenance activities that are repeated and transforms input into output may be seen as a maintenance process [4, 8, 9, 10, 11]. The maintenance process monitors the system's capability to deliver services, records problems for analysis, takes corrective, adaptive, perfective, and preventive actions, and confirms restored capability [10].

The maintenance process applied in this paper is presented in Figure 1. The process is based on the four phases of the Improvement Cycle (Plan-Do-Study-Act), as described by Deming [3]. The purpose of relating a generic maintenance process to the Improvement Cycle is to highlight the fact that the approach supports the work with continuous improvement, and thereby also continuous risk reduction by hazard elimination [11]. The aspect of risks and hazards linked to the maintenance process will be discussed further in relation to Figure 2. The four phases of the proposed maintenance process are Maintenance Planning (Plan), Maintenance Execution (Do), Functional Testing (Study), and Feedback (Act), as illustrated by Söderholm et al. [11]. See Figure 1.

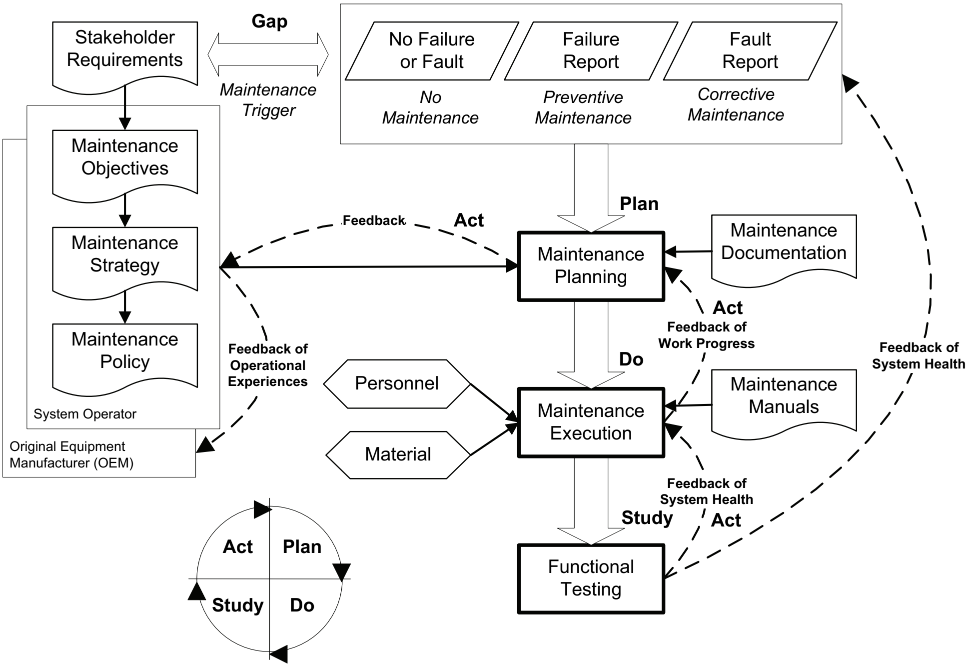

Figure 1. Maintenance as a process that consists of the four activities Maintenance Planning, Maintenance Execution, Functional Testing, and Feedback. These activities and their relations are associated to the Improvement Cycle (Plan-Do-Study-Act), as described by Deming (1993). The activities are supported by information and different resources, such as personnel, time, and material.

In this paper the maintenance process is seen from an inductive perspective, where the maintenance process is based on the status of the system's functions. In an inductive perspective, the maintenance process is managed by the state, or health, of system functions, i.e. the presence or lack of failures and faults. A required function is defined as a function or a combination of functions of an item, which is considered necessary to provide a given service [5; IEV 191-01-05]. Therefore, it is beneficial if one initiates the maintenance process when a required function experiences a fault or a failure, thereby avoiding dissatisfaction among service stakeholders. A fault is defined as the state of an item that is characterised by the inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to lack of external resources [5; IEV 191-05-01]. Hence, faults are mostly connected to corrective maintenance, at least on a functional level, but not necessarily on a service level. A failure is the termination of the ability of an item to perform a required function [5; IEV 191-05-01]. Hence, a fault is often the result of a failure of the item itself, but may exist without a prior failure [5; IEV 191-05-01]. However, after failure the item has a fault [5; IEV 191-05-01]. Another important distinction between failures and faults is that a failure is an event, as distinguished from a fault, which is a state [5; IEV 191-05-01]. Hence, failures are often connected to preventive maintenance, where one tries to discover an impending fault and prevent it. The inductive perspective contributes mainly to the efficiency of an organisation, i.e. that things are done right [12]. Some further details of the maintenance process and its four phases are discussed in relation to Figure 2.

4 Hazards related to the maintenance process

A risk may be seen as the combination of the frequency, or probability, of occurrence and the consequence of a specified hazardous event [13]. A hazardous event can cause harm, i.e. physical injury or damage to health, property or, the environment [13]. However, in addition to the frequency and consequence of a loss, the risk also involves the perception of the loss to the ultimate interested party [4]. Hence, a risk may be seen as the stakeholders' perception of the combination of the probability that his or her requirements have not been fulfilled and the consequences of this situation.

In Figure 2, some hazards that are related to the four activities within the proposed maintenance process (illustrated in Figure 1) and that may result in negative consequences for the process stakeholders are outlined. The presented hazards are derived from the perception of maintenance personnel, but have fortunately not resulted in any accident within the studied case. However, it is important to consider both incidents and near misses, and not only accidents, when deciding upon risk reduction activities in order to be truly proactive and avoid unwanted consequences [14, 15, 16].

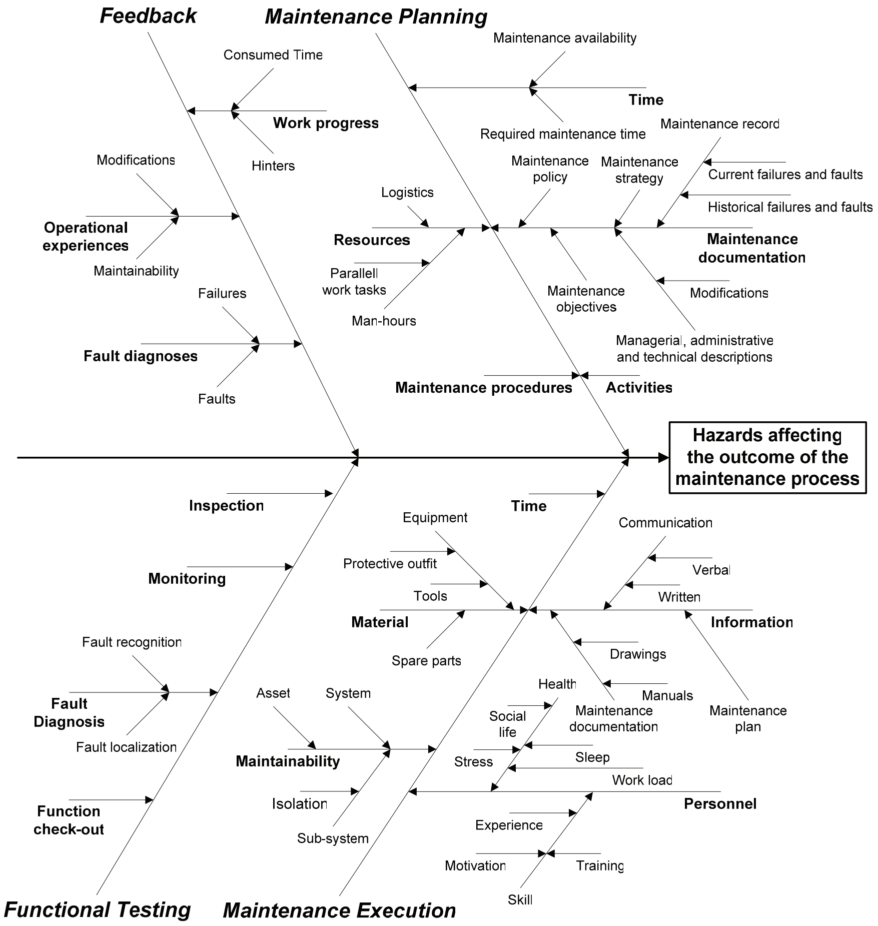

Figure 2. Some examples of maintenance-related hazards that may result in unwanted consequences for maintenance process stakeholders. The hazards are clustered into the four phases of the proposed maintenance process in Figure 1, i.e. Maintenance Planning, Maintenance Execution, Functional Testing, and Feedback

4.1 Maintenance Planning

In the first phase of the maintenance process, Maintenance Planning, Maintenance Execution is planned, see Figure 1. One input to this phase is information about the current system health derived from the Functional Testing phase. Other inputs are maintenance documentation, such as maintenance objectives, strategies, and policies, which all should be based on stakeholder requirements. The maintenance objectives are targets assigned and accepted for the maintenance activities, which may include availability, cost reduction, product quality, environment preservation, and safety [17]. The maintenance strategy is in turn the management method used in order to achieve the maintenance objectives [17]. The maintenance policy is a description of the interrelationship between the maintenance echelons, the indenture levels and the level of maintenance to be applied for the maintenance of an item [5; IEV 191-07-03]. Other important inputs to the maintenance process are information about available resources and the physical asset. Examples of resources are manpower (in-house and outsourced), stock levels, and logistics. Depending on whether the gap between the stakeholders' requirements and the system health is manifested as a failure or a fault, the planned maintenance may be preventive or corrective. One major output of maintenance planning is a maintenance plan. The maintenance plan is a structured set of tasks that includes the activities, procedures, resources and the time scale required to carry out maintenance [17]. Different hazards related to Maintenance Planning are discussed in the remaining part of this section and are depicted in Figure 2.

If the maintenance strategy is preventive and time-based, the planning is initiated by operating time. However, the maintenance strategy can also be condition-based and initiated by the actual health of the system. The actual system health is an input from the Functional Testing process phase and can roughly be based on the presence or lack of failures and faults. If the system is fulfilling the stakeholders' requirements, no maintenance is needed. However, if there is any failure or fault present, there might be a need for maintenance. The planning of preventive maintenance of the system can be initiated if there is a system failure, which can be due to a component failure or fault. If there is a faulty component within the system that experiences a failure, the planned maintenance will be corrective on a component level, but preventive on a system level. If the system experiences a fault, the maintenance will normally be unplanned and corrective, which may require an unplanned shutdown. A hazard emerges if the in-house maintenance is executed at the unplanned shutdown instead of at the next planned shutdown, which is then cancelled. If the external entrepreneur is not informed about the cancelled shutdown, some electrical brushes might wear out since the time to the next actual shutdown is so long that a system failure can develop into a system fault. This situation might require grinding of the commutator during operation, to remove ditches caused by too short brushes. This grinding requires proper equipment, such as flame-proof clothing and insulated tools. The above examples show that it is important during Maintenance Planning to inform all concerned stakeholders about performed changes.

In the paper industry, entrepreneurs are specialised in different unique areas of the technical system. This situation requires proper Maintenance Planning for mainly two reasons. Firstly, there is the limited capacity of each specialist. Secondly, the production stop is quite costly and is therefore kept to a minimum length of time. Often the availability of systems refers to the operational availability, but availability is also a most important factor from the maintenance perspective. Availability is one example of where the operational and maintenance processes must be laterally aligned in order to avoid sub-optimisation [11]. A time frame, where the system is shut down and isolated, is allotted for different maintenance tasks in the execution phase. One important example is the yearly maintenance stop, which is intended to enable major overhauls and maintenance of large subsystems, such as boilers and wire gauze, which is both extensive and time-consuming. The maintainers often also have conflicting requirements, which make planning a crucial activity. For example, during the yearly maintenance stop there are many parallel jobs that take place close to each other. In this situation it is common that different entrepreneurs have different requirements, which may cause hazardous situations at the interfaces between them. An example is mechanical and electrical replacement or overhaul, where one maintainer may wish the power to be shut off completely, while the other wishes to operate the system at a reduced speed.

Wear of the electrical brushes is one topic that is often discussed. The reasons for this are that their replacement may be quite difficult and time-consuming. The cost of the brush may also be a factor here; although seen in a larger system perspective this cost is negligible. Actually, assuming that the brushes have been selected properly, one hour of unplanned stoppage may very well cost more than a whole year's consumption of brushes in all motors throughout the entire paper-mill. More important is the effect of extensive wear, which causes two significant problems. The first is that the dust generated from the brush causes insulation problems and the second is that the brush will have to be changed more often than planned stoppages allow for. Both these problems might cause severe difficulties on a higher system level, e.g. a breakdown of the whole paper machine.

4.2 Maintenance Execution

The second phase within the maintenance process is Maintenance Execution, see Figure 1. Inputs to this phase are not only the maintenance plan generated during Maintenance Planning, but also the maintenance environment, the maintainability of technical systems, maintenance documentation, and the actual availability of time, personnel, and resources. There may also be an input from the Functional Testing phase, which will be further discussed in relation to the Functional Testing and Feedback process phases. Some hazards related to Maintenance Execution are illustrated in Figure 2, and will be further discussed in the remaining part of this section.

The planned maintenance time may turn out to be insufficient for a variety of reasons. These are often minor problems in accessing the equipment, due to requirements placed on the subsystems by other maintenance executors at the interfaces. The reason for this is that it is difficult during the planning phase to predict which obstacles will emerge during maintenance execution. Such obstacles may include a surprisingly amount of dirt, corroded bolts, or the need for unexpected tools. This lack of time is a crucial hazard, since it causes high stress for the maintenance personnel [18]. The increased stress levels in turn contribute to an increased amount of human error, i.e. maintenance tasks that are performed incorrectly [19]. In the process industry, which is characterised by its continuous operation, both a heavy work load and a high stress level may arise when the technical system is shut down for maintenance during a limited time period.

Another important input to Maintenance Execution is the availability of maintenance personnel. The skill and competence of personnel depends on both experience, training and, motivation. Given that the maintainer is motivated, insufficient training is an important hazard related to Maintenance Execution. It is important to ensure that the proper training has been undertaken, that the personnel are certified for the job, and so on. In the context of outsourcing, the requirements should be clearly stated, so that the need for the right maintenance skills can be met in a systematic way. A lack of knowledge among maintenance personnel about the working environment in which the maintenance is being carried out is also a crucial hazard. For example, the available maintenance time may become shorter than originally planned. In this situation it is important for the maintainer to be able to focus on the most critical items to be overhauled, if time pressure should become too intense. A heavy workload may not only impact motivation, but also the maintainer's ability to perform the maintenance task. It should also be noted that even though the workload can be managed by proper Maintenance Planning, there are other hazards related to personal health that are difficult to manage, such as social life, drug abuse, and sleep.

Maintenance Execution is also influenced by the maintainability of technical systems on different levels such as the entire paper-mill, single paper machines, and single DC-motors. The maintainability of a paper-mill, which is a widespread system, is affected by how well the localisation of equipment is communicated. The outcome of Maintenance Execution is affected negatively if maintenance is carried out on the wrong item, or on the right kind of item but in the wrong place. To avoid these problems, it is important to mark the equipment with unique identification tags that are easily accessible and easily understood. This is even more important when external entrepreneurs are brought into the plant. Besides the fact that it may be difficult to find the right motors, it is equally important to know in which motors the recognised faults are situated, so that proper decisions can be made by the system owner. If the wrong motor is reported as defect, the system risk still remains subsequent to the failure being recognised and the responsibility is transferred from the entrepreneur back to the system owner. This situation might result in latent failures, which are recognised when the system is started up again.

The technical system's maintainability will impact both the working conditions for the maintainers and the required time for Maintenance Execution. Therefore, it is most important to focus on the maintainability of the technical systems to be inspected as early as in the design phase. However, although the electric motor itself may be easy to inspect and maintain, surrounding equipment can often reduce the maintainability of the motor. A possible reason is that the motor is often encapsulated by the system it drives. For example, the motor's hatches may be covered by electrical cables, making it difficult to access. This is one example of where the requirements of the operational environment and of the Functional Testing and Maintenance Execution phases might be in conflict if they are not properly aligned. In order to protect the technical system from moisture, dirt, and corrosive substances, it is modified by being further encapsulated. However, this modification may reduce the maintainability of the technical system if the maintenance requirements not are properly considered. Hence, it is important to consider both operational requirements and maintainability requirements when designing the modification in order to avoid sub-optimisation. Furthermore, motors are often mounted so that the maintainers need to climb in order to reach them, e.g. overhead traverse cranes and some positions at a paper machines. This situation would be even worse if the working conditions were affected by factors such as unpleasant temperature and limited sight due to bad lighting and covering objects. Another example is oil and grease, which create a less safe workplace due to slippery surfaces that can cause fall accidents, but that also can impair the possibility to recognise and localize faults.

A system that is to be repaired must also be isolated, e.g. pressure or electricity must be released from the work area. Hence, both the design and the placement of the valves and switches used for isolation are important in order to reduce maintenance hazards. DC-motors are isolated at the interlocking installation or directly at the motor with a so-called safety switch. However, it should be noted that the safety switch is not fully reliable and only serves as an extra barrier, and that the only safe way is to cut the power at the switchgear insulator.

Failures to re-assemble the system correctly after maintenance work has been carried out may be triggered by insufficient maintainability. However, this is not a major problem with DC-motors, although there are several possibilities to complicate matters. If field cables are removed, in order to conduct measurement of the condition of the electrical insulation, they may be switched causing the motor to rotate at reverse speed. If a motor linked in a serial-system, takes a reverse rotation, the system may crash and probably cause losses.

Another important input to Maintenance Execution is material, which can be spare parts and different equipment, such as protective items and tools. One critical hazard is mix-up, such as incorrect and unspecified materials or items being used to replace items, which may lead to problems ranging from minor malfunctions to major losses. In DC-motors one very critical item is the electrical brush. Besides dimensions, there are several different grades, i.e. material and the ability to manage shifts between positive and negative currents (e.g. commutation in a commutator machine). Some examples of mechanical and electrical problems related to the brush are:

- Burning of commutator segments
- Wear of commutator (ditches and scratches)
- High wear of brushes, also creating extensive amount of brush dust
- Insulation problems (rotor and field windings)
- Brush failure due to over-current
- Brush unable to cope with oxidising environment.

When commutator segments are affected by burn marks, the operation of the motor is disturbed due to scintillations, which in turn affect the dependability of the technical system where the motor is installed. Wear of commutator is caused by lack of patina, which may be described as a non-functioning electrical and mechanical interface between the brush and commutator. Ditches and scratches are the result of a non-functional interface. The origin of burn marks, commutator wear and the ability to cope with oxidising environment are affected by the choice of a proper brush grade. In this situation maintenance is closely interlinked with system modification.

The use of items outside specification could be exemplified by the use of silicone gaskets or sealant with silicone ingredient. Here, different requirements, on a system level, for the different components are used at, or nearby, the motors. When external coolers (on DC-motors that require ‘forced draught’) are used, it is important to prevent water from entering the motors. This is especially crucial on high voltage motors, e.g. 6 kV, which are very sensitive to small amount of moisture. However, neither will DC-motors equipped with electrical brushes work properly if the air inside the motor is polluted by particles from the silicone gasket. It should be noted that even a very small number of particles is sufficient to degrade the motor’s performance. This is one example of a solution that fulfils the requirements of one specific subcomponent (leak prevention of the water coolant), at the same time as endangering the function of another subcomponent (the motor), which combined create a severe degradation of the paper machine’s performance. Another, rather unknown, effect of the silicone gasket is that released silicium particles become highly abrasive. These particles cause extensive wear of the electrical brush when mixed with the air in, or nearby, the motor.

Information is most important to reduce risks related to Maintenance Execution [9, 16]. This information may be found in maintenance documentation or transferred by verbal communication. One way to reduce the amount of human error contribution in maintenance is to follow routines and written procedures, such as predefined work sequences, which can be found in maintenance documentation, such as manuals or maintenance trees [19]. Lack of instructions regarding the repair or overhaul of the systems may lead to the loss of quality in the performed work. However, it may be possible for skilled personnel to perform the required work based on their experience [19]. Procedures, regarding maintenance should be checked and confirmed, i.e. have undergone a risk assessment, and then described in the maintenance process. Another example is the yearly maintenance shutdown, where several entrepreneurs, often with contradictory requirements are working in the paper-mill. In this situation, verbal communication plays an important role on the operational level. Teams working close to each other must communicate and share information to reduce the risks related to Maintenance Execution.

4.3 Functional Testing

The third maintenance process phase is Functional Testing, see Figure 1. The purpose of Functional Testing is to test the function of an item, in relation to some requirements. Functional Testing may be performed continuously, or periodically during scheduled checks, in order to establish the current health of the system and the actual need for maintenance. Functional Testing is also performed after Maintenance Execution, in order to verify that the system has been maintained in, or restored to, a state where it can deliver a required function. Functional Testing can also be applied iteratively with Maintenance Execution, in order to recognise and localise failures and faults by troubleshooting. The above description of Functional Testing is in line with different standards and includes inspection, monitoring, fault diagnosis, and function check-out, which will be defined in the next paragraph of this section. It should be noted that Functional Testing is a crucial maintenance phase since it is here that data and information about the actual health of the system is gathered. This data and information is feedback to all other process activities and should also be distributed to stakeholders outside the operating company, such as the Original Equipment Manufacturer (OEM). Hence, it should be noted that even though Functional Testing is illustrated as the third process phase in Figure 1, it is in reality often the first phase, which generates input to the other phases. The different data and information transferred between different process phases is further discussed in the next section, which covers the Feedback phase.

A test is a technical operation consisting of the determination of one or more characteristics of a given product, process, or service according to a specified procedure [5; IEV 191-14-01]. A test is carried out to measure or classify a characteristic or a property of an item by applying a set of environmental and operating conditions and/or requirements to the item [5; IEV 191-14-01]. An inspection is a check for conformity by measuring, observing, testing or gauging the relevant characteristics of an item, and can generally be carried out on before, during, or after other maintenance activities [17]. Monitoring, or supervision, is an activity that is performed either manually or automatically, and that is intended to observe the state of an item [5; IEV 191-07-26]. Automatic supervision may be performed internally or externally to the item [5; IEV 191-07-26]. Monitoring is distinguished from inspection in that it is used to evaluate any changes in the parameters of the item with time [17]. The monitoring may be continuous, over a specific time interval or after a given numbers of operations [17]. Fault diagnosis is a measure taken for fault recognition, fault localisation and cause identification [5; IEV 191-07-22]. Fault recognition is the event of a fault being recognised [5; IEV 191-07-20], while fault localisation is a measure taken to identify the faulty item at the appropriate indenture level [5; IEV 191-07-21]. In this paper, the identification of causes of faults includes the identification of failures, which is an event that can cause a faulty state. This is not mentioned in the standards, but is of great importance in order to perform condition-based maintenance, which is part of preventive maintenance. Function check-out is actions a measure taken after fault correction to verify that the item has recovered its ability to perform the required function [5; IEV 191-07-24].

Functional Testing is highly dependent on the maintainability of a technical system. When dealing with complex systems, the maintainability may be enhanced through proper testability design by different kinds of Built-in-Test (BIT). The BIT can, more or less continuously, monitor the technical system during operation, or test it in special off-line, maintenance modes. However, in the case of BIT design it is important to identify appropriate functions and items to monitor and assure that the received data can be converted into useful information about the health of the system [20, 21]. The importance of proper BIT design may be illustrated by the phenomenon of over lubrication, where too much grease is forced into the bearings of a DC-motor, either manually or by a centralised lubrication unit. This situation may occur if decisions are solely based on vibration measurements of bearings within the motor. As more grease is forced into the bearings, the vibrations may very well decrease, which indicates that everything is alright. However, due to over–lubrication, the temperature will probably rise considerably, at the same time as the motor may be filled with grease. Both these situations increase the risk of failure. In the first situation the failure will develop into a bearing fault within a few days, which in turn will cause motor fault and thereby faults to connected subsystems within the paper machine. This will further lead to extensive production losses and costly maintenance measures. The latter situation also causes an extensive need for maintenance of the motor, since the motor must be properly cleaned. Hence, one should perhaps monitor both vibrations and temperature, in order to gain proper information as input to the maintenance process. The example highlights the fact that it might be difficult to replace human experience and expertise by technological solutions.

Manual Functional Testing is to a large extent affected by the experience and skill of the maintenance technician. An experienced technician can diagnose the health of a DC-motor by smell, hearing, or touch without even entering the motor. If something seems to be wrong, a more detailed diagnosis may be necessary. A more detailed functional test might discover a non-functional brush, which is replaced with one that fulfils the intended purpose in the specific operational environment. Decisions about changed monitoring of different components or systems may also be based on the diagnosis. If a motor is judged to experience a failure event, the monitoring may be intensified by a shortening of the interval between inspections, in order to be able to execute maintenance before a fault develops. Another area where the expertise and training of the maintenance technician is crucial is fault localisation. When a DC-motor is in a faulty state, actions are often taken to replace the motor, in order to secure the dependability of the paper machine. However, it is of the utmost importance that the primary fault, and not a secondary fault, has been localised. A primary failure is the failure of an item, not caused either directly or indirectly by a failure or a fault of another item [5; IEV 191-04-15]. A secondary failure is the failure of an item, caused either directly or indirectly of the failure or fault of another item [5; IEV 191-04-16]. This is because latent faults can be present if Maintenance Execution has been directed towards a secondary fault. In order to achieve proper fault localisation, the interface between the DC-motor and other systems must be understood. The motor is driven by a static current changer, which is a complex system that converts Alternating Current (AC) to Direct Current (DC). Furthermore, the speed of the motor is controlled by the feedback unit (i.e. a tachometer generator or a pulse transducer). Hence, a fault in the DC-motor can actually be a secondary fault, while the primary fault is located at the feedback unit or the static current changer. This example highlights that the complexity of the system requires a deep understanding of technical, operational, and maintenance aspects. The requirements placed on the maintenance technician have increased to more than performing routine maintenance (defined as maintenance that does not require special skills) to the ability to recognise and locate faults in complex systems.

Manual Functional Testing is also affected by the system's maintainability. Hence, much of the description about the impact of maintainability on Maintenance Execution is also valid for Functional Testing. For example, when testing the function of the electrical brushes in a DC-motor, it may be difficult to reach them. This depends on the size of the motor, which can range from fairly small, where it is difficult to access it with two fingers, to rather large where the technician can climb into it with a ladder. It may also be difficult to perform a function check-out in order to detect if the maintenance was correctly executed, without causing damage to the brush or nearby internal cables. This situation is further influenced by the maintainability of the paper machine and the paper-mill. Functional Testing is also affected by environmental factors such as dirt, grease, and oil leakage, which make it more difficult to recognise and localise failures that might lead to future faults. The environmental aspect is also emphasised in TPM (Total Productive Maintenance) [22].

4.4 Feedback

The fourth phase within the maintenance process is Feedback of information, see Figure 1. This Feedback goes mainly from Functional Testing to Maintenance Planning and Maintenance Execution. The information in these feedback loops represents the current health of the system. However, there is also other important feedback from Maintenance Execution to Maintenance Planning, which establishes the progress of the Maintenance Execution. The actual progress should result in a follow-up and update of the original maintenance plan. There should also be a feedback loop from the operative maintenance process to stated maintenance objectives, strategies, and policies. This feedback loop should be applied in order to validate maintenance documentation, such as maintenance manuals, and when necessary perform changes. These changes should be recognised by both the operative organisation and the Original Equipment Manufacturer (OEM). However, the feedback loops that go outside the four phases of the proposed maintenance process are not covered in this paper. All the feedback loops mentioned are critical in order to achieve continuous improvement and continuous risks reduction in relation to the maintenance process. The following paragraphs will describe some hazards related to the Feedback phase, see Figure 2.

In Total Productive Maintenance (TPM) and Reliability-Centred Maintenance (RCM), modification, or continuous improvement, plays a central role. As described, modifications are common when adapting the electrical brushes to fit the current operational conditions for a specific electric motor. However, information regarding the changes must be transferred to the maintenance documentation, which may be partly found in a Computerised Maintenance Management System (CMMS). The approach to change the grade of the electrical brushes is quite straightforward, but may result in poorer performance. Hence, it is very important to monitor the result of the modification and feed this information back to the person that performed the change, so that any necessary countermeasures can be taken before the performance of the whole system is impaired. However, if the modification is actually an improvement, the updated documentation enables it to be maintained the next time the brush is exchanged. A related hazard is that maintenance decisions are based on old information regarding the configuration of the paper-mill. Another aspect of incorrect information about system status is constituted by safety issues in the Maintenance Execution phase. If the system is not correctly understood by the maintainers, there can be losses due to isolation problems, e.g. that the wrong part or incorrect subsystem is isolated before Maintenance Execution. Hence, the aspect of reconfiguration management and lateral process alignment is of most importance, especially when dealing with critical systems [11]. This requires the modification process to give feedback to both the maintenance process and the operational process, and vice-versa.

A critical hazard is an insufficient reporting system, which might lead to necessary maintenance being neglected. Maintenance entrepreneurs have a responsibility to ensure that the information regarding identified failures and defects is transferred to the maintenance system (if in place) or passed on verbally to the manager in charge. This information should influence Maintenance Planning. Otherwise there may be aspects of overseen, or lack of, maintenance that might endanger the fulfilment of critical stakeholder requirements. One example is the cancellation of planned shutdowns, which the entrepreneur must be informed about.

5 Discussion and conclusions

In this paper we have applied one process model of maintenance, in order to identify maintenance related hazards. The model is based on a generic process view of maintenance and consists of four interrelated activities of Maintenance Planning, Maintenance Execution, Functional Testing, and Feedback (see Figure 1). The process model is intended to support continuous improvement of and continuous risk reduction in maintenance activities. We have also illustrated some maintenance executors' perceived risks in relation to the four activities of the maintenance process (see Figure 2).

By applying a process view of maintenance, it is possible to identify its stakeholders, requirements and risks. This identification supports the management of both requirements and risks, which should contribute to business prosperity through continuous improvement and risk reduction.

It is also stressed that even though maintenance may be a solution to many problems, it actually may introduce risks that must be assessed and managed properly. One way to do this is to identify maintenance-related hazards in relation to the maintenance process. This approach has been demonstrated in this paper. The proposed approach for continuous risk reduction stresses that, even though the incidents and accidents may be manifested in maintenance execution, the underlying hazards may actually be located in other process phases. It is at these other phases that the conditions for maintenance execution are established. One example is the need for proper information during maintenance execution. In order to enable this, the requirements of the maintenance technician must be understood and considered already in the design of the technical system, e.g. through testability and maintainability. The maintenance technicians' situation must also be properly understood in order to plan the maintenance satisfactorily. This planning should include the maintenance technicians' requirements as regards time, resources, and information, and not only the operative requirements. By adapting the resources and technical system to maintenance requirements, the true hazards (or root causes) of maintenance are eliminated, and symptoms (or immediate causes) such as human error during Maintenance Execution do not become the focal point of the improvement efforts. Hence, the proposed process view can hopefully contribute to a deeper understanding of underlying maintenance-related hazards, which enables a cultural change from finding individuals to blame for accidents towards proactive risk awareness.

It should also be noted that even in today's industries, with information and communication technologies, verbal communication still plays an important role on the operative level. Teams working close to each other must communicate and share information to reduce the risks in maintenance execution. It is at the interfaces between different maintainers that hazardous situations occur, due to contradicting requirements of the maintenance task. These hazards may partially be reduced through proper planning, as discussed in the previous paragraph. However, independent of how good the maintenance planning is, unforeseen events that impact the execution and that must be managed at the shop floor level will occur.

Even though the system and process view of maintenance have been illustrated by examples derived from the maintenance of DC-motors in paper-mills, it is believed that they are mostly transferable to maintenance of other critical technical systems. One reason is that DC-motors have a wide diversity of applications and can be found whenever there is a need of transferring power into rotating movement, e.g. within steel mills, mining industry, marine applications, and trains. The same basic principles as for the DC-motor are also applicable when generating electricity from rotating movement, e.g. hydro power, wind mills, and steam generators. Further on, independent of what kind of philosophies, theories, and technologies are applied within an organisation, maintenance sooner or later comes down to maintenance execution, which still requires human intervention. Another reason is that maintenance is an approach that has generic characteristics independent of industrial application, and is more dictated by the complexity and criticality of the systems and the relationship between different stakeholders. For example, the authors have experience from projects related to maintenance within both the railway and the aerospace industries, where the ideas presented in this paper are considered to be applicable.

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PAPER III

Maintenance–related losses at the Swedish rail

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Maintenance-related losses at the Swedish Rail

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Abstract

Purpose – The purpose of this study is to identify maintenance related losses, and their causes, in order to describe different deviations in the maintenance process that contributes to incidents and accidents at the Swedish Railway.

Design/methodology/approach – In this paper incident and accident reports from 666 derailments and collisions at the Swedish Railway during 1988-2000, stored in a national database, are studied with respect to possible maintenance related causes.

Findings – The railway is a complex technical system used for both freight and passenger transportation. Maintenance is one way to achieve safety and dependability of the railway. However, at the same time badly performed maintenance may also cause accidents. The study shows that maintenance related causes represent 30 percent of all rail and track related incidents and accidents represented in the database. About 80 percent of the maintenance related accidents happen during the execution phase. The most common cause of maintenance related accidents is imperfect communication and information between the maintenance personnel and the operators. Rule violations, especially lack of permission to perform maintenance work on the track, are the second most frequent causes.

Originality/value – Identifies maintenance related losses, and their causes, on Swedish railways but is of value to all concerned with transport maintenance and safety.

Keywords Railways, Maintenance, Sweden, Accidents

Paper type Research paper

Practical implications

Maintenance is important not only to ensure dependability and it is essential for accident prevention. However, although maintenance is performed in order to increase the safety, incorrectly performed maintenance causes extensive loss. In order to avoid future losses one has to learn from history. In order to do so one has to analyse historical data. However, the means for doing this analysis may be inadequate. This paper presents a model that may be useful for the classification and analysis of different losses, in order to perform efficient and effective preventive measures.

Further on, this paper identifies different maintenance related losses, and their corresponding causes, in a Swedish rail context. It is important to understand the underlying causes of their occurrences, in order to know what to control, when maintenance is outsourced.

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The results may therefore be useful also for organisations outside the rail context, who are about to outsource their maintenance operations.

Introduction

The railway is a complex technical system[1] used for both freight and passenger transportation. The Swedish State Railways ("SJ") was the only railway operator on the Swedish rail network before 1988. Then the company was divided into an infrastructure authority, the Swedish National Rail Administr ation ("Banverket") and the state-owned passenger traffic operator (Bäckman, 2002). The Swedish Railway Inspectorate was now created in order to supervise and promote safety within all Swedish rail traffic, and to investigate the accidents[2] that may occur. The Swedish Railway Inspectorate is an independent governmental authority, but is associated with the Swedish National Rail Administration (Swedish Railway Inspectorate, 2003).

The Swedish National Rail Administration has to see that passenger safety is ensured and has therefore adopted a zero vision, meaning that nobody is killed or seriously injured as a consequence of a traffic accident (Banverket, 2003). Besides safety aspects, derailments and collisions affect the surroundings and may give the administrator and the operators a bad reputation. Therefore, maintenance[3] issues have been prioritized during the last few years.

Normal operation of the railway will gradually impair the performance of the railway system. Wear, dirt, corrosion and overloading are some contributing causes of the degradation of the track and switches. Therefore, the management must determine maintenance strategies and objectives to ensure the functioning of the railway system. Both preventive and corrective maintenance actions are performed to maintain or even increase the dependability[4] of the railway system.

Before 1988, maintenance work was performed only by the in-house maintenance personnel at the Swedish State Railways. This changed when the Swedish National Rail Administration decided to open up their maintenance to the free market in July 2001. Instead of conducting the work within their own organisation, entrepreneurs were invited to bid for maintenance contracts at some sections of the track in 2002 (Banverket, 2003). The use of contractors to undertake important work is not a new issue, and also it is not specific to the railways. It is common nowadays that companies worldwide focus on their core business and contract out other functions as a mean to achieve cost reduction (HSE, 2002). Although maintenance contractor's involvement in some cases may reduce the direct cost, it may affect the control by the administrator, especially if proper information about system changes and repair is missing (Kletz, 1993). The involvement of maintenance contractors may therefore increase the need to transfer adequate information and communication in order to control different risks due to maintenance activities.

However, although maintenance is performed in order to increase the safety, badly performed maintenance may reduce the safety and cause incidents[5] and accidents. A study performed by Edkins and Pollock (1996) shows that rail and track maintenance causes problems in Australia. Among 13 railway problem factors at the passenger division, staff attitude was the most important cause to problems followed by operating equipment and maintenance. At the freight division maintenance work was the second most important factor contributing to the problems regarding quality, consistency and delays.

In the United Kingdom, several accidents have occurred at Railtrack PLC[6] due to the involvement of maintenance contractors. Some recent examples are the derailments at Ladbroke Grove and Hatfield discussed below (HSE, 2002).

In October 1999, a major derailment and collision occurred at Ladbroke Grove. As a result of the collision 31 people died and 227 were taken to hospital. The investigators of that accident expressed concern about the privatisation and the use of contractors. Two major conclusions were drawn. Firstly, the process for the judgement of contracts was not operated with due regard for training and preparation of the contract workforce. Secondly, the managerial control of the work performed by maintenance contractors and sub-contractors was inadequate. Therefore, there was a need for improving the managerial control (HSE, 2002).

In October 2000, four people were killed in a derailment near Hatfield. The accident investigation showed that the immediate cause[7] of the derailment was a fragmentation of the rail caused by neglected maintenance actions. The contractor was recommended to review the procedures for the movement of managerial staff within contractor organisations and the recruitment of the contractors (HSE, 2002).

These accidents indicate that inadequately performed maintenance operations and routines may be an important cause of railway accidents. Accidents due to maintenance work may occur when there are deviations from an ideal maintenance process. The outcome of the process will differ from the desired result, when the steps are biased due to different reasons, resulting in losses that may be manifested in incidents and accidents. Holmgren and Akersten (2002) presents a discussion about different deviations that may occur in the preventive and corrective maintenance processes.

It is therefore important to identify the past deviations in the maintenance process, manifested in incidents and accidents, in order to get a basis for improvement in order to reduce the number of new undesired deviations in the future. As illustrated in the examples, maintenance contractor involvement may increase the risks at the railway, if not managed properly. The maintenance contractor situation thus requires higher demands on the transfer of information in order to control different risks due to their involvement.

Methodology

Data collection approach

This study is based on a database, created by Johan Bäckman, containing train derailments and collisions at the Swedish railways. The database was created in Microsoft Access and is called BOR. The database contains passenger train derailments for the period 1988-2000 and passenger train accidents with passenger or train crew fatalities for the period 1960-2000. The database contains the following five different data sources with the total amount of 973 incidents and accidents (Bäckman, 2002):

- BIS: The Swedish National Rail Administration has a computerised system called BIS, containing different modules for track information and for accident reporting from 1988 onwards.
- JAS: The Swedish Railway Inspectorate has a database called JAS which contains information from 1989 onwards. The criteria for the accidents to be

reported in the database are either fatalities or injuries or material costs of at least 100,000 USD.

- INCIDENT: SJ has a database called INCIDENT. SJ has been reporting accidents in that computerised database since February 1995, but the database was closed in December 1997.
- HÄR: The Swedish Railway Inspectorate administrated a database called HÄR between 1994 and 1998. It contains accidents as well as incidents.
- Sparre: A study conducted by Sparre on accident reports from the Swedish State Railways containing collisions, derailments and fires on the Swedish network between the years 1985 to 1994 has generated data that have been included in BOR.

Owing to the fact that the Swedish State Railways went through a major organisational change, data before 1988 is excluded from this study based on BOR. The database contains 666 incidents and accidents between 1988 and 2000, which were used in the study.

Data classification

In order to identify the maintenance related losses, all data represented in the database must first be classified. Thereafter, accidents and incidents are studied to identify the maintenance related causes.

The analysis work performed by professional railway investigators has resulted in accident reports with a description of the different causes of and consequences for the railway related accidents and in cidents, which are stored in the database, used for this study. The incidents and accidents have been classified based on the description of the incidents and accidents in the reports, and seen in relation to the modified Loss Causation Model (LCM).

However, there are additional problems with studying past accidents. There is, for instance, an excessive reliance on accident reports, which are usually incomplete or inaccurate, even when conducted by experienced accident investigators (Edkins and Pollock, 1996). The BOR-database has, in this study, been analysed without consideration of previous classification, made with a different purpose in mind, to avoid being biased, when searching for maintenance related causes. The accidents and incidents have instead been classified into three iterative steps, based on the stated causes and consequences. See Figures 1-3 for the three classification steps.

The first classification is performed with respect to all railway accidents and incidents reported to the database 1988-2000 (Figure 1).

The group track related causes are caused by or along the railway line including the ballast, switches, sleepers and rail or objects placed on or near the track. The group also includes work on the track such as maintenance and shunter actions.

The rolling stock causes are a collection of track bound vehicles such as trains and trolleys, but the group also includes human error aspects when operating the vehicles, such as driver error or when performing maintenance on the vehicles.

The group classified as insufficient information does have a serious lack of information of the causes and consequences in the accident and incident reports stored in the database. This fact created some uncertainty in the data material and might affect the validity of the results. This study aims at investigating the track related causes, and by that reason, the rolling stock causes and those classified as insufficient information were excluded from the second classification step.

In the second classification step, track related causes were divided into maintenance related causes, railway operation, sabotage and uncertain (Figure 2). This was mainly done in order to identify maintenance related causes. The other groups, e.g. mainly railway operation and sabotage, were created to gain comprehension of their occurrences.

The group maintenance related causes consists of events caused by direct maintenance execution and indirect maintenance impact, such as lack of proper maintenance. Maintenance execution is, for example, repair work on the track or the switches. Note that the vehicles used for the execution of maintenance tasks such as rail adjustments are classified as track related causes due to the fact that they are on the track to support the maintenance execution. When these vehicles are involved in collisions it may be due to maintenance work, and not due to railway operation. However, the causes to the accidents or incidents may be similar to driver error at normal operation of the railway.

The group railway operation causes are collections of various other events that have its origin within the normal operation of the track. One example of railway operation is actions performed by the shunters to switch gears on the track. Another example is the problem with snow, which is treated as normal operation, since snow is very common in the northern parts of Sweden. Snow may cause the railway switches to malfunction, due to the inability to close the switch when filled with snow, which in turn may cause derailments or broken switches.

The group sabotage consists of accidents caused by objects which are deliberately placed on, or, nearby the track with the intention to cause harm. Some examples of such objects are bathtubs, sandboxes and snowmobiles. When classifying these causes, some objects may have been left out of the group sabotage. These objects are, for example, trees and rocks, which may have been placed on the track deliberately, but appears as environmental causes.

The group uncertain contains various events with insufficient information presented with the description of the causes or the consequences in the database. Although it has been possible to identify that the causes of the accidents are track related, it is hard to draw further conclusions of data in that group with respect to the

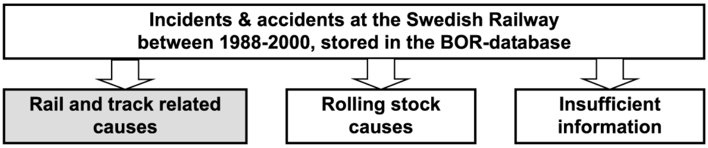


Figure 1.
The first classification of the data aims at breaking down the railway-related accidents and incidents between 1988 and 2000

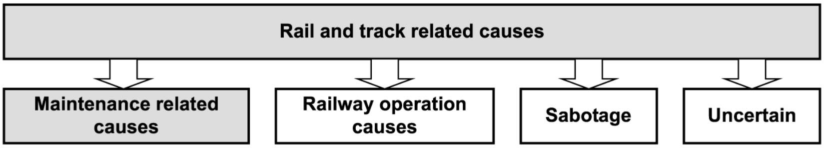


Figure 2.
The second classification of the data is a further breakdown of the track-related causes

purpose of this study. This uncertainty may affect the reliability of this study. All groups except maintenance related causes have been excluded in the third classification step for the purpose of identifying the causes of the maintenance related losses.

In the third classification step, maintenance related causes have been divided into maintenance execution and lack of maintenance execution (Figure 3).

The group maintenance execution is a collection of direct maintenance related causes, which have their origin in relation to the execution of maintenance tasks at the railway track. Examples of maintenance execution are repair of switches, adjustments of the ballast and the rail. Other examples are collisions with track bound vehicles which are used to support the maintenance execution.

The group lack of maintenance execution is a collection of various indirect events caused by overseen maintenance tasks. Some examples are wear and tear at the switches, and fragmentation of the rail. It is difficult to pinpoint these causes in this category to overseen maintenance planning or routines. However, due to the fact that there is degradation, which has not been detected, there may be some kind of gap between the maintenance planning and execution.

Data analysis models

British Rail[8] did use a model called REVIEW developed by Reason (1993) in order to identify deficiencies in the managerial activities, which may result in accidents. The model measures latent failures that have been common denominators in major accidents. The model assumes that accidents arise from fallible decisions and line management deficiencies, organisational policies and procedures. However, there are other loss LCMs as well. In 1931, Heinrich presented a domino theory, which is a precursor to more recent LCMs (Heinrich *et al.*, 1980). Bird and Loftus (1976) presented an LCM, based on Heinrich's domino theory, but they updated Heinrich's approach to reflect the direct management relationship involved in the causes and effects of all incidents that could result in losses, which are manifested in accidents. The steps in the LCM are briefly described in Figure 4. See also Akersten (2000) and Holmgren and Akersten (2002) for a description of LCM applications in the maintenance domain.

The LCM model is designed to systematically identify the chain of events from the incidents to lack of control that is leading to the losses. However, the author has modified the LCM model, to reflect the reverse chain of events from losses, which are seen as both incidents and accidents, to the lack of control, which initiates the LCM (Figure 4).

The modified LCM model serves as a tool in this study, to analyse the data stored in the investigated database and to identify the causes of the maintenance related incidents and accidents. The focus is on the immediate and basic causes[9] due to the fact that they initiate the loss producing chain of events that has its origin in

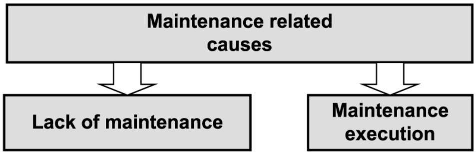


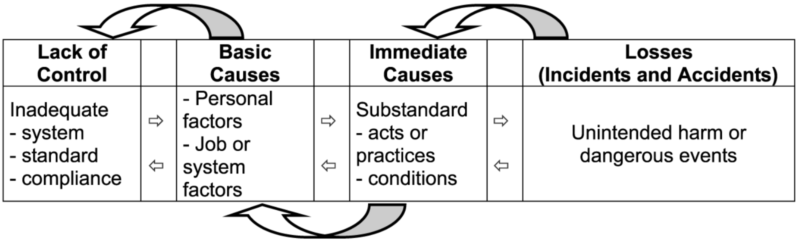
Figure 3.
The third classification aims at breaking down maintenance-related causes

inadequate managerial control. The category immediate causes, acts as the direct trigger of maintenance-related accidents. However, the accidents directly initiated by the front line operators are merely the inheritors of system defects created higher up within the operating system (Edkins and Pollock, 1996). These deficiencies can be found in the categories basic causes and lack of control.

Data analysis

The two groups, lack of maintenance and maintenance execution, which were created at the data classification, have been carefully studied in order to identify the causes to the loss initiation chain, shown in Figure 5. However, the analysis of the maintenance related losses, classified as maintenance execution and lack of maintenance, is then structured according to the modified LCM, shown in Figure 4, in order to identify loss producing events, which are deviations from the ideal situation in different steps in the maintenance process. The modified LCM model illustrates the reverse chain of events from the consequences to the lack of control.

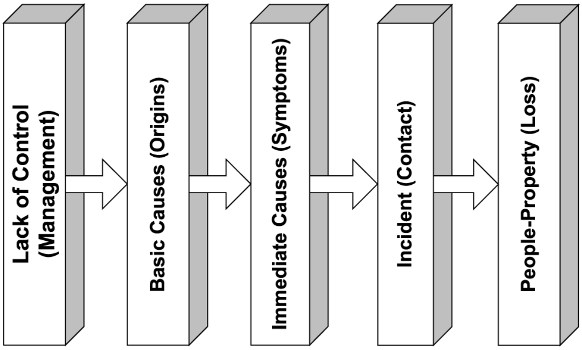
The most abstract level in the model is lack of control, which can be related to the maintenance management. It would be desirable to identify the causal connection from



Lack of Control		Basic Causes		Immediate Causes		Losses (Incidents and Accidents)
Inadequate - system - standard - compliance	⇨ ⇦	- Personal factors - Job or system factors	⇨ ⇦	Substandard - acts or practices - conditions	⇨ ⇦	Unintended harm or dangerous events

Note: The model is a modification of the Loss Causation Model, originally developed by Bird and Loftus (1976). The basic idea is to start the investigation at the losses, manifested in both incidents and accidents in order to find the chain of events leading to lack of control

Figure 4.
The data analysis model used for identification of causes of maintenance-related losses



Source: Bird and Loftus (1976)

Figure 5.
The LCM, an updated Heinrich model, reflecting the direct management relationship involved in the causes and effects of all incidents

the losses to the lack of control in all maintenance related accidents and incidents, but due to the variety of the quality of the data, this is not possible. However, the causes and effects have been studied in order to find the immediate and the basic causes, according to Figure 4.

The "five why" methodology has been used supplementary to the structure in the modified LCM model to find the immediate and the basic causes of the accidents and incidents. See, for example, Tetsuichi and Kazuo (1990) for a description of the "five why" methodology. The first question is why the rail and track related incident or accidents occurred. If the cause was maintenance related, a second question was asked to identify if the cause was due to the execution of maintenance work or caused indirectly by lack of maintenance work. The result of the first two questions is shown in Figures 6-8, and the results of the first "two why" in Figure 9.

The third to fifth why-questions expose the underlying, or basic causes, of the maintenance related course of events, described in the database. These basic causes have been identified due to the stated description of the causes and consequences of the incidents and accidents. The results of this analysis can be found in the "third to fifth why" squares shown in Figure 9.

Results

The result of the first three classification steps shown in Figures 1-3 are shown in Figures 6-8. The result is based on the distribution of the 666 railway related incidents and accidents in Sweden during 1988-2000 stored in the database.

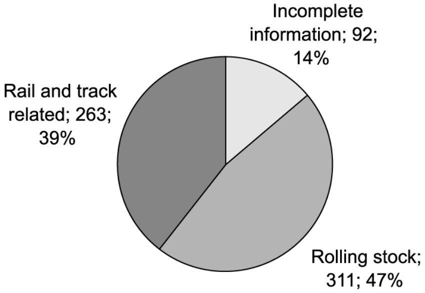


Figure 6.
The causes of the 666 railway-related accidents and incidents in Sweden, between the years 1988-2000, stored in the BOR-database

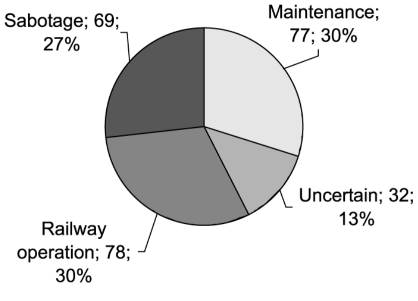


Figure 7.
Different causes of the rail- and track-related accidents stored in the BOR-database. The distribution and percentages are related to the rail- and track-related accidents and incidents in Figure 6

The result of the second and third classification steps fulfils one purpose of this study, namely to identify the maintenance related losses at the Swedish railway. The result is shown in Figures 7 and 8.

The purpose of this study was also to identify the causes of the maintenance related losses. These causes are structured according to the "five why" methodology, where the first two "why" identifies the immediate causes in the modified LCM model and the third to five "why" reveals the basic causes to the maintenance related losses. The result of that classification is shown in Figure 9.

Discussion

The results show that 30 percent of the total number of track related incidents and accidents in the database are maintenance related. Among the maintenance related accidents, the execution of maintenance work is the immediate cause in 79 percent of all maintenance related accidents and incidents. Only 19 percent of the accidents found in the database are caused by neglected maintenance, such as wear and tear on the track and switches. It is clear that most of the maintenance related accidents happen during the execution phase. The most common basic cause of the maintenance related incidents and accidents is imperfect communication and information between the maintenance personnel and the train dispatcher or the operators. The defective communication between the maintenance personnel and rail operators indicates the need for better exchange of information between them. The future involvement of maintenance contractors, especially foreign ones who may lack local knowledge, increases the demands for communication and the transfer of adequate risk information. Proper information must be communicated in order to maintain, or increase, the safety level found today at the railways. The continuous improvement work should focus on ways of achieving better communication between the maintenance executor and the operator of the railway. Kletz (1993) describes the importance of clearly writing or explaining what should be done and how it should be done. Vague instructions for the recondition or overhaul of the broken equipment may lead to losses, and to the skills of the maintenance personnel not being fully used. Experienced personnel perform the required work acquired by experience, but inexperienced personnel may possibly perform the work badly according to the unknown demands of the system. This is an important aspect to consider when

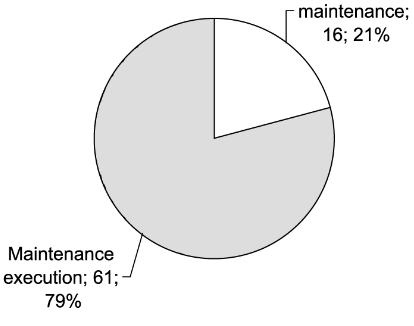


Figure 8.
The causes of the maintenance-related accidents. The percentages are related to the maintenance-related accidents and incidents in Figure 7

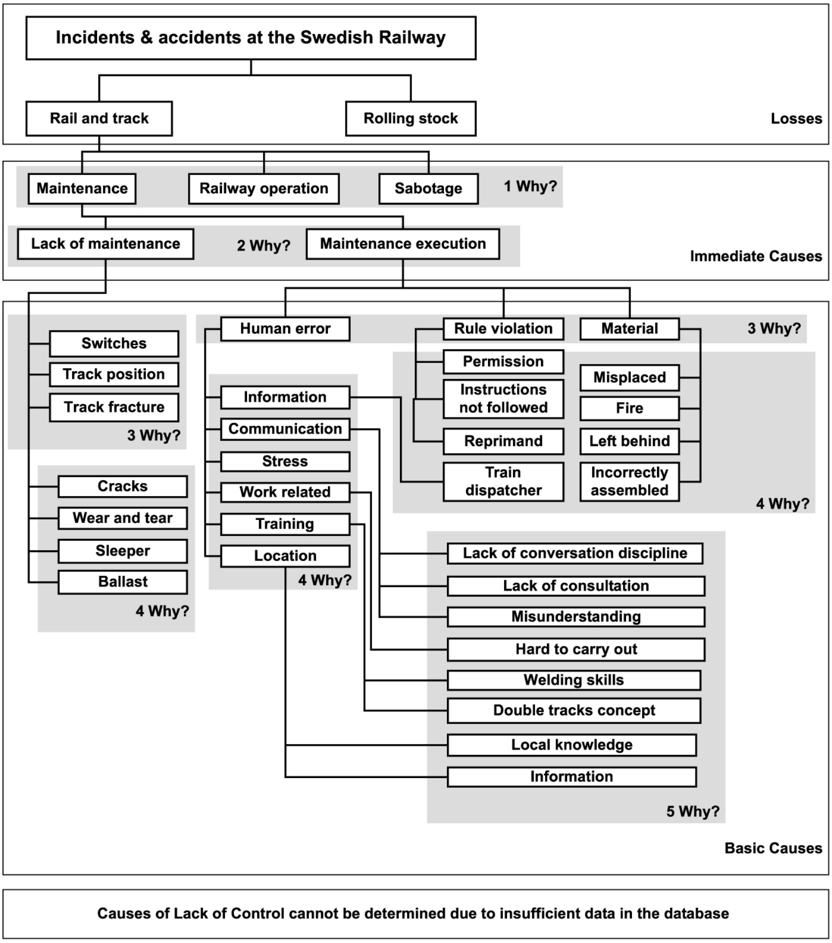


Figure 9.
A schematic description based on the modified LCM model, illustrating the immediate and basic causes of the identified maintenance-related losses at the Swedish Railway network during the period 1988- 2000. The basic causes precede the immediate causes in the loss causation chain of events

maintenance work is to be bought from maintenance contractors without local knowledge.

According to the modified LCM, the causes of the incidents and accidents can be traced to the immediate, and in some cases the basic, causes. The information stored in the used database has shortcomings because detailed information of the causes is sometimes missing. Therefore, it is hard to find what causes the lack of control, which is the most abstract level of the maintenance management. However, the chain of events can in most cases be traced back to the basic causes in the LCM. It is important to remember that these immediate causes are the direct trigger of the accidents, but these are in turn caused by the basic causes and lack of control of the operations, which are managerial responsibilities.

Rule violations, especially lack of permission to perform maintenance work at the track, are the second most dominating basic cause, as shown in Figure 9. Human error due to various causes is a common trigger of maintenance related accidents. One way of reducing the human error contribution in the accidents is to follow routines and written procedures. It is, on the other hand, very difficult to adopt a necessary but not over-regulated permit-to-work system to ensure system safety. Kletz (1988) describes some incidents involving a permit-to-work system and the lesson learnt when the procedure does not cover all circumstances or when the permission has been withdrawn without further notice to the maintenance personnel.

On the other hand, Lawton (1998) discusses the aspects of over-regulation and the human reluctance to follow written procedures when they make it more difficult to perform the required work. Troublesome rules and routines may tempt the personnel to take shortcuts in order to get the job done, when there is lack of time to perform the work properly.

Some causes due to lack of maintenance have also been found in the study (Figures 8 and 9). Of these 16 accidents, the most dominating basic cause is defect switches. Other basic causes are incorrect rail positions, rail fractures and broken sensors. This aspect of indirect maintenance causes is twofold, either an explanation of natural degradation is possible or overseen maintenance work. On the other hand, if some causes can be explained by natural degradation, maintenance routines should cover these and ensure rail safety.

Although not included in this study, an indication was given that maintenance activities at the rolling stock also cause some accidents. These accidents were demarcated in the first classification step, due to the purpose of this study. When looking at the numbers presented, we must be aware that insufficient data in the database were deleted in the first and the second classification steps (Figures 1-2). This underlines the importance of the clear reporting both incidents and accidents, with an accurate and extensive description of the related causes and consequences.

Conclusions

In total, 666 derailments and collisions were reported at the Swedish State Railways between the years 1988 and 2000 to the BOR-database. Among these derailments and collisions, 263 were track related. Maintenance, direct or indirect, caused 77 of these accidents. In this study, 61 of the accidents were caused by incorrect maintenance execution. The execution of maintenance work is guided by the maintenance process, which is found in the maintenance strategy. Different deviations from the desired maintenance process will affect the outcome of the process creating losses, some manifested in incidents and accidents, although other smaller deviations from the ideal maintenance process may still remain hidden.

The most frequent cause of accidents during the execution phase is imperfect communication and information between the maintenance personnel and the train dispatcher or the operators. Rule violation is the second most important basic cause of accidents during the maintenance execution. Bearing in mind that, if the procedure is covered by the rulebook, deviations from maintenance procedures in a regulated business will cause rule violations.

The Health and Safety Executive in the United Kingdom has listed the following issues that may contribute to a major accident due to maintenance (HSE, 2003):

- failure of safety critical equipment due to lack of maintenance;
- human error during maintenance;
- incompetence of maintenance staff; and
- poor communication between maintenance and production staff.

The result of this study confirms three of the above four categories. Human error during the execution was, in some cases, explained by the lack of proper information due to communication issues. Another possible explanation of human error is, according to Kletz (1993), lack of time, which may contribute to an increasing amount of human error. In the case of railway maintenance, stress may occur when work should be done during a short gap in the timetable when the track is available for repair.

In some cases dealt with in this study, no explanation of human error can be found other than unconscious slips and lapses, which contribute to human error. See Kirwan (1994) for a description of slips and lapses. These are commonly called the "human factor". The category incompetence of the maintenance staff, as stated by HSE, has only been found in one accident of the maintenance related causes. This may be explained by the long experience and proper education the Swedish National Rail Administration's own maintenance personnel have. During the years 1988-2000 maintenance work has mainly been performed by Banverket Production, a division of their own management. When maintenance is to be bought from contractors this can change if unclear demands are stated in the maintenance contracts. Some fundamental demands are already claimed in the TransQ, a joint prequalification system for suppliers to Scandinavian transport organisations in which the Swedish National Rail Administrator is one of the participating organisations.

Further research

The increasing globalisation affects the national markets. The railways, which are being opened up to foreign ownership are no exception. Competition is also increasing, bringing changes in how to manage safety in the newly privatised railway companies (Hale, 2000). The Swedish Rail Administrator has already begun to purchase maintenance from contractors, and foreign ones will not be excluded in the future. The maintenance contractor situation, especially with the involvement of contractors that lack local knowledge, will further increase the need for transfer of adequate risk information and requirements. Therefore, further research should focus on the identification of requirements for different stakeholders to the maintenance process that affect rail safety. Different activities that affect lack of control and the basic causes are important to focus on due to their pre-initiation of the accident sequences presented in this paper.

It is the managerial responsibilities to design and evaluate the inquiries for maintenance contracts. An interesting aspect to investigate is if these inquiries for maintenance contracts cover, or clearly express, safety critical demands. In the future it is important to focus on how to make the existing regulations clearer, not to create new regulations. The reason for this is, according to Hale (2000), the railway industry already has, together with the nuclear and the chemical industries, a long tradition of extensive regulation. Accidents have, according to Hale (2000), traditionally been analysed up to the point where it became clear that someone had broken a rule or that there was no rule for this causality. It is therefore important to identify all the causes in the loss causation chain of events, leading to lack of control, in order to prevent similar occurrences in the future. If the investigation stops after the immediate causes, which are merely triggers to the accidents, is a great possibility that the basic causes are still present!

Notes

1. A system is a network of interdependent components that work together to try to accomplish the aim of the system (Deming, 1994).
2. An accident is here defined as an unplanned and uncontrolled event in which the action or reaction of an object, substance, person, or radiation results in personal injury or the probability thereof (Heinrich *et al.*, 1980).
3. Maintenance is defined as the combination of technical and administrative actions such as supervision actions intended to retain an item in or restore it to a state in which it can perform a required function (IEV191-07-01, 2002).
4. Dependability is here defined as a collective term used to describe the availability and its influencing factors: reliability, maintainability and maintenance supportability.
5. An incident is here defined as an undesired event that can, or does, result in losses (Bird and Loftus, 1976).
6. Railtrack PLC is now owned by Network Rail.
7. Immediate cause may also be called primary cause.
8. British Rail is now Network Rail.
9. Basic cause may also be called underlying cause.

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PAPER IV

Loss causation analysis of accidents linked to maintenance on the Swedish state railways

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Loss Causation Analysis of Accidents Linked to Maintenance on the Swedish State Railways

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ABSTRACT

Railways are used to transport goods and passengers as an alternative to other types of transportation, such as road and air traffic. A well-maintained track infrastructure is hence important and safety must be guaranteed. The use of the infrastructure causes wear on the track. Maintenance is therefore required to retain or restore the condition of the track. However, if this is not performed as intended, lack of maintenance activities may cause accidents. It is, for this reason, important to identify maintenance-related hazards, which then can be managed in order to avoid future accidents.

The aim of this paper is to study maintenance related accidents in order to identify and quantify causes contributing to losses due to collisions and derailments on the Swedish railway. In this paper, 666 descriptions of accidents occurring on the Swedish rail system between 1988-2000 are studied. The analysis is based on a modified version of the Loss Causation Model.

Among these accidents, 81 were caused by improper infrastructure maintenance. These were in turn classified as being caused by 'maintenance execution' and 'lack of maintenance'. The main causes for accidents due to 'maintenance execution' were classified as 'human error' and 'rule violation'. Different types of 'wear' caused uncorrected faults at the 'turnouts' and 'track', which were classified as due to 'lack of maintenance'.

KEYWORDS

Railway Accidents, Maintenance, Loss Causation Model, Derailment, Collision

1. RAILWAY TRANSPORTATION, MAINTENANCE AND ACCIDENTS

Efforts being made towards a sustainable environment, with reduced emissions of carbon dioxide, require 'environmentally friendly' transportation. The choice of rail transport rather than other types of transportation using fossil fuels, might be a good way to reduce the environmental impact. This is one reason for increasing interest in investing in and enlarging rail traffic, in Sweden and other countries.

The competition from other means for transportation thus forces rail traffic to be safe, punctual and economically efficient. Availability of the track is hence important and safety must be guaranteed. To increase safety and punctuality different forms of maintenance are important.

Derailments and collisions result in financial losses, which include the cost of repairing the train and the infrastructure. Severe collisions and derailments may also result in injuries and fatalities, either for the train operators and travellers or other persons on or nearby the track, such as maintenance personnel or third parties. Two such examples are the derailments at Ladbroke Grove (1999) and Hatfield (2000) in the UK.

The collision and derailment at Ladbroke Grove, resulted in the death of 31 persons and left 227 persons injured. Inadequate managerial control of the work performed by maintenance and sub-contractors was one cause for this accident. The accident investigators pointed out the need for improving managerial control. (HSE, 2001)

One year after the accident at Ladbroke Grove, another severe collision and derailment occurred in Hatfield, which resulted in the death of four persons. According to the investigators, one cause contributing to the accident was a fragmentation of the rail, which in turn was caused by insufficient maintenance. (HSE, 2002)

In order to transform the Swedish rail traffic into a safe, competitive and economically viable alternative for transportation of people and goods the Swedish Railway Administration was restructured in 1988 (Espling & Kumar, 2004). The Swedish Railway Administration was then divided into one organisation responsible for infrastructure[1] management (Banverket) and a state owned train operator, which must compete with other train operators on an open market (Banverket, 2005). The infrastructure management became responsible for design and construction, as well as maintenance, including renewal and modification of the track. Hence, the infrastructure management runs the day-to-day operation and infrastructure maintenance together with long term development of the assets (Espling & Kumar, 2004).

The infrastructure management must manage the risks associated with maintenance to avoid economic losses and serious accidents. There are different aspects to consider, including not only recognising failures, before they cause punctuality problems and develop into faults that impair the safety of the railway system, but also controlling maintenance execution. Therefore, it is important to identify the causes of un-recognised maintenance needs or neglected maintenance, and the causes of biased maintenance execution.

The aim of this paper is to study maintenance related accidents in order to identify and quantify causes contributing to losses due to collisions and derailments on the Swedish railways. The analysis is based on a modified version of the Loss Causation Model presented by Bird & Loftus (1976). The study contributes with knowledge about the causes of maintenance-related accidents within a railway infrastructure context. This will result in ways to manage maintenance hazards by a proactive approach.

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[1] Infrastructure consists of the railway track, turnouts (or points), overhead wires and signalling equipment. The railway track consists of two parallel steel rails, which are laid upon sleepers which are embedded in ballast. In this study the track also includes the ground or space from the rail to a distance at 2.2m on each side of the rails. A switch is here defined as a mechanical installation provided at a point where the rail track divides into two tracks. Each switch contains a pair of linked tapering rails that can be moved laterally into one of two positions. Overhead wires are used to transmit electrical energy to trains at a distance from the energy supply point. (Wikipedia, 2005)

2. TERMINOLOGY AND STUDY APPROACH

2.1 Empirical Data

In Holmgren (2005), a database containing 666 Swedish railway accidents, which occurred between 1988-2000, were classified in order to identify those caused by infrastructure maintenance. The data was classified and divided in three steps, which are briefly presented below. See Holmgren (2005) for description of the database used and details regarding that classification.

In the first step, the data was classified with respect to where in the rail system the accident cause originated. Here the following three categories were created:

- Infrastructure
- Rolling stock
- Incomplete information

The purpose of the first classification was to identify those accidents that had their origin in the railway 'infrastructure'. The group 'rolling stock' consists of accidents related to the operation of, or caused by, the track bound vehicles running on the track. The group 'incomplete information' consists of those accidents, to which it was impossible to determine the cause or causes due to insufficient information in the database. Accidents in this category may therefore have their origin from the rolling stock, infrastructure or a combination thereof.

In the second step, the accidents in the group 'infrastructure' were further classified into the following groups:

- Maintenance
- Railway operation
- Sabotage
- Incomplete information[2]

In the group, called 'maintenance', all accidents caused by incorrectly performed maintenance or lack of suitable maintenance of the infrastructure were identified for further investigation. The group 'railway operation' consists of causes due to tasks included in the normal operation of the infrastructure, such as shunting operations and snow clearing (common in the northern parts of Sweden). Snow cleaning may, due to the definition of maintenance as *"the combination of all technical and administrative actions, including supervisory actions, intended to retain an item in, or restore it to, a state where it can perform a required function"* (IEV 191-01-07), be regarded as maintenance. However, the Swedish Railway Administration treats snow cleaning as 'railway operation', even though its purpose is to ensure that the railway is in a functional state. This is the reason for excluding those causes from the 'maintenance' group in the classification.

The group 'sabotage' consists of causes due to objects on the track that are placed there deliberately to interrupt operation. Examples of such objects are sand boxes or snow mobiles. Here, a distinction is made between natural causes and sabotage. A tree on the track, for instance, may be sabotage if it is placed deliberately to cause harm but not sabotage if it is the result a windy day. The group 'incomplete information' consists of those 'infrastructure' accidents, where further details could not be determined due to the lack of information in the data.

In the third step, the accidents in the 'maintenance' group from the second step, were classified into one of the following groups:

- Maintenance execution
- Lack of maintenance

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[2] In Holmgren (2005) the term 'uncertain' is used. To reach better consistency we prefer to use 'incomplete information'.

Here a distinction is made between the causes of the accidents linked to maintenance. If the accident is caused by actions taken within the maintenance work to retain or restore the infrastructure, it is classified as ‘maintenance execution’. If maintenance of the track is required, but not performed, the cause of the accident is classified as due to ‘lack of maintenance’.

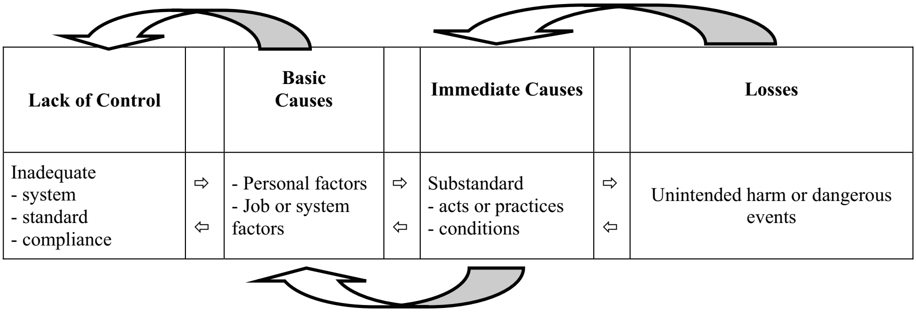
The discussion in the rest of this paper is mainly based on those accidents, which in the second step are classified as ‘maintenance’ related.

2.2 Loss Causation Model for Data Analysis

In order to determine the hazards and to understand in what way they should be controlled, it is important to understand how an accident comes about. There are several ways to illustrate this using different representations of accident causation models; see Heinrich et al. (1980); Reason (1997); Groeneweg (1998); Ridley & Channing (1999); Reason & Hobbs (2003) and Leveson (2004).

The accident causation model used as a data analysis model in this paper is a modified version of the Loss Causation Model (LCM), developed by Bird & Loftus (1976). The modified LCM version is illustrated in Figure 1. The Loss Causation Model by Bird & Loftus (1976) originates from the early ‘Domino Theory’ (Groeneweg, 1998).

Our modification means that the model excludes pre-contact ‘incidents’ situated between ‘immediate causes’ and ‘losses’. Our model also emphasizes the causation route from the ‘losses’ to ‘lack of control’, instead of the other way around in the original model. The modified Loss Causation Model is used to structure the empirical data classified as ‘maintenance’ in the third classification step. The approach used here is an analysis based on accidents that have already occurred. It is one way to identify and illustrate why things went wrong.



Lack of Control		Basic Causes		Immediate Causes		Losses
Inadequate - system - standard - compliance	⇨ ⇦	- Personal factors - Job or system factors	⇨ ⇦	Substandard - acts or practices - conditions	⇨ ⇦	Unintended harm or dangerous events

Figure 1. The figure illustrates the data analysis model used for identification of the causes for maintenance-related rail accidents. The analysis starts at the ‘losses’, with the intention to first identify the ‘immediate causes’ and thereafter carry out deeper analysis of the accident descriptions to determine the ‘basic causes’, in order to identify what to control to prevent future ‘losses’ manifested in accidents. (Adapted from Bird & Loftus, 1976)

The data analysis starts at the ‘losses’, as illustrated in Figure 1. The ‘losses’ can be identified in the accident descriptions. The ‘loss’ is the consequence of the accident which is manifested in material damage, injuries and causalities. The losses are identified to determine the extent of each accident.

The ‘immediate causes’ in the model are the events or conditions that occur just before the accident. However, ‘immediate causes’ can be seen as symptoms of causes, often of a more intangible nature, such as personal and work place factors. For that reason, it is interesting to identify the ‘basic causes’ that lead to such conditions or individual acts that are underlying factors for the ‘immediate causes’. The ‘basic causes’ are also referred to as ‘root causes’ (Groeneweg, 1998).

The most abstract level in the model is ‘lack of control’, which here is related to the maintenance management. ‘Lack of control’ is the initiating event of the sequence that starts the domino chain, which first enables the ‘basic causes’. The drawback of this representation is that, *“... since fundamentally uncontrollable factors were not considered, this model suggests that all accidents are avoidable if the management exerts enough control”* (Petersen, 1988). However, in a railway context, lack of control is a significant cause, since the railway is highly controlled and regulated. These regulations aim to supervise and control the execution of the maintenance jobs.

In order to identify what to control it is important to identify the relation between ‘losses’, ‘immediate causes’ and ‘basic causes’. The causes in the LCM model represent hazards at different stages of the accident sequence. These hazards must be identified and means to control them suggested, in order achieve improved safety within rail infrastructure maintenance.

3. RESULTS OF CLASSIFICATION AND QUANTIFICATION

Based on the descriptions of the 666 accidents, 263 were classified as due to causes related to the ‘infrastructure’. Examples of information related to this category are different objects placed on the track; geometrical deviations and wear of the track; shunting operations and maintenance work performed on the track.

The accidents caused by the rolling stock, or their operation, are excluded. This group is not studied further in this paper, due to the purpose of this study. However, there is an interaction between the condition of the vehicles and the track, e.g. wheel-rail interface problems, see Granström (2005) and Larsson (2005). Therefore, improper maintenance of the track bound vehicles may cause damage to the rails, such as cracks and wear. Another interface of concern is the one between the overhead wires and the pantograph[3], which may impact on the infrastructure maintenance, see Granström (2005) and Lagnebäck (2006). In this study, maintenance of overhead wires is included in ‘infrastructure’ maintenance, but the impact of defective pantographs situated at the ‘rolling stock’ on the ‘infrastructure’ is not studied further here. There may also be an interaction between the way the track bound vehicles are operated and the need for corrective maintenance, for instance, intense breaking causing wheel flats or passing through turnouts that are not in position. However, such interactions were not considered in the classification.

Of the 263 infrastructure related accidents, 81 were classified as caused by ‘maintenance’. Of these 81 maintenance-related accidents, 58 were classified as due to ‘maintenance execution’ and 23 were classified as due to ‘lack of maintenance’. No distinction was made between corrective or preventive maintenance tasks. See Figure 2. Some examples of causes in ‘maintenance execution’ are incorrectly performed tasks, such as improper repair work and driver error while handling maintenance vehicles. Here, the maintenance personnel has two roles, one as maintenance operators and the other as drivers of maintenance vehicles. However, errors made by the train drivers were classified as related to the ‘rolling stock’ in the first classification step, when they were related to freight or passenger trains[4]. The reason for this is that such errors are made during train operation, and not during maintenance or transportation of maintenance vehicles

‘Lack of maintenance’ may be expressed as neglected or overseen maintenance. For instance, the infrastructure was in a state that required corrective maintenance actions to perform the required function or in a state requiring preventive maintenance in order to avoid a fault. Maintenance inspections of the infrastructure should be able to handle such degradation problems.

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[3] A pantograph is the name commonly given to the arms that collect current from overhead wires on electric trains. (Wikipedia, 2005)

[4] In rail transport, a train might be defined as a set that “consists of a single or several connected rail vehicles that are capable of being moved together along a guide-way to transport freight or passengers from one place to another along a planned route.” (Wikipedia, 2005)

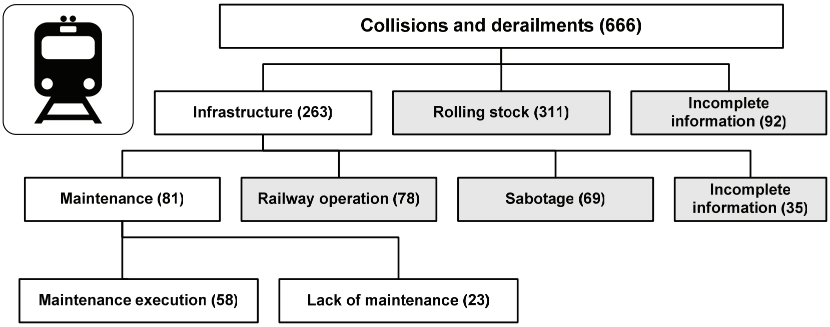
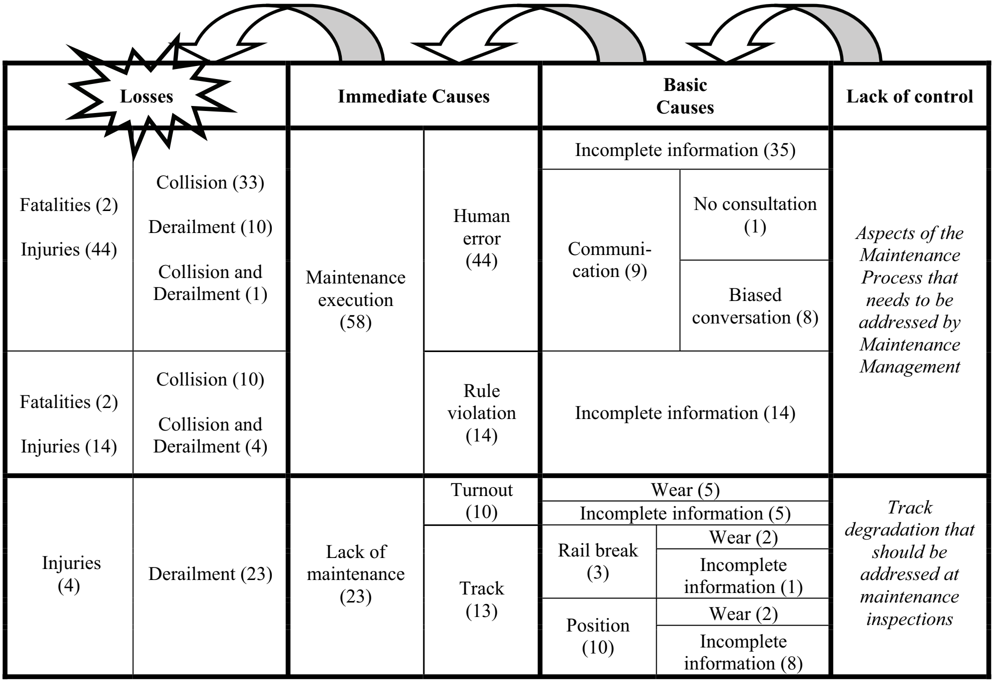


Figure 2. The figure illustrates the distribution of the 666 collisions and derailments on the Swedish state railways 1988-2000. The events leading to lack of control of the maintenance operations derive from various causes and results in either incorrect maintenance execution or lack of maintenance. The shaded boxes illustrate categories that have been excluded from further studies in this paper.

4. RESULTS OF LOSS CAUSATION ANALYSIS

All identified causes for the 81 maintenance-related accidents, were classified as ‘maintenance execution’ and ‘lack of maintenance’. The classification was based on the descriptions of events contributing to the accident. Hence the Loss Causation Model provided logic for classification of the different causes to which different events were related, in order to describe the combination of causes leading to an accident.

In Figure 3, the causes are illustrated as dominos, starting from the right in the model at ‘lack of control’ and leading to different ‘losses’ or consequences at the left side of the model. In Figures 4 and 5, the ‘immediate causes’ and ‘basic causes’ are illustrated separately, in order to highlight possible management actions that could reduce a ‘lack of control’.



Losses		Immediate Causes		Basic Causes		Lack of control
Fatalities (2) Injuries (44)	Collision (33) Derailment (10) Collision and Derailment (1)	Maintenance execution (58)	Human error (44)	Incomplete information (35)		*Aspects of the Maintenance Process that needs to be addressed by Maintenance Management*
				Communication (9)	No consultation (1)	
					Biased conversation (8)	
Fatalities (2) Injuries (14)	Collision (10) Collision and Derailment (4)		Rule violation (14)	Incomplete information (14)		
Injuries (4)	Derailment (23)	Lack of maintenance (23)	Turnout (10)	Wear (5)		*Track degradation that should be addressed at maintenance inspections*
				Incomplete information (5)		
			Track (13)	Rail break (3)	Wear (2)	
					Incomplete information (1)	
				Position (10)	Wear (2)	
					Incomplete information (8)	

Figure 3. The figure illustrates the loss causation chain of events starting from 'lack of control' and leading to collisions or derailments, which in turn cause 'losses' manifested in accidents causing injuries, fatalities and economical harm.

Besides economical harm, the collisions and derailments due to 'maintenance execution' resulted in 'losses' consisting of four fatalities and 58 injured persons.

The 58 'maintenance execution' accidents resulted in 43 collisions, five derailments and five cases with both collisions and derailments. These cases resulted in four fatalities and 58 injuries. These accidents were classified as being caused by 'human error[5]' in 44 cases and by 'rule violation[6]' in 14 cases, see Figure 4. 'Communication' problems were classified as the cause for 'human error' in nine of the accidents. Two types of communication problems were identified. In eight cases the communication had been established, but interrupted or misinterpreted in some ways, classified as 'biased conversation'. In one case, necessary consultation was lacking completely, classified as 'no consultation'. The other 35 cases of 'human error' could not be explained, due to the insufficient accident descriptions in the database.

'Rule violation' was classified as the cause for 14 cases of incorrectly performed maintenance work. Here, established rules existed, but were somehow ignored by the maintenance personnel. However, the reasons for these rule violations could not be identified due to insufficient information in the database.

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[5] 'Human error' is here defined as: "… occasions in which a planned sequence of mental or physical activities fails to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some chance agency" (Reason, 1990).

[6] 'Rule violation' is here defined as deviations from safe and established procedures, standards or rules to control a system (Reason, 1997).

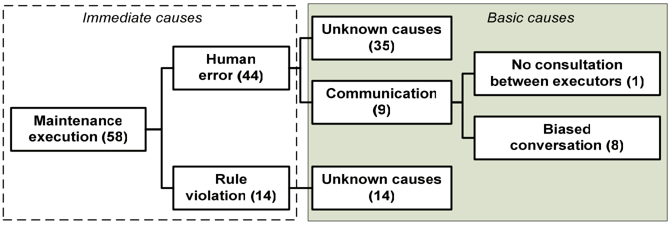

Figure 4. The figure illustrates the causes contributing to improper 'maintenance execution'. The 'immediate causes' are the trigger events for the accidents. The 'basic causes' illustrates the underlying reasons for improper 'maintenance execution'.

The 23 accidents classified as 'Lack of maintenance', resulted in 23 derailments, see Figure 3. These derailments resulted in 'losses' consisting of four injuries and economical harm. However, the magnitude of these economical losses was not established within this study.

The 23 derailments were caused by defective 'turnouts' in 10 cases and by 13 cases of 'track' deficiencies. The 'turnout' problems were due to 'wear' in five cases. The other five cases could not be further explained due to insufficient information provided by the database. The 13 track deficiencies were caused by 10 cases of incorrect 'position' or alignment of the track. These alignment problems were in turn caused by 'wear' in two cases, or could not be further explained in the other eight cases. The three identified 'railbreaks' were due to 'wear' in two cases, one case could not be further explained due to the limitations of the data.

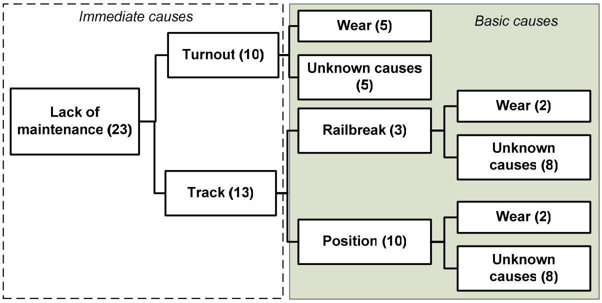

Figure 5. The figure illustrates the causes contributing to 'lack of maintenance'. The 'immediate causes' are here just the trigger events for the accidents. The 'basic causes' illustrate the underlying factors leading to 'lack of maintenance'.

5. CONCLUSIONS AND DISCUSSION

When deciding about effective maintenance strategies, it is important to identify the causes of past accidents and the hazards associated with maintenance execution. Analysis of past accidents defines the areas that need special attention so that measures can be implemented for hazard reduction to achieve safer operations due to improved maintenance.

Maintenance-related accidents within the Swedish railway accounted for about 30% of the infrastructure related accidents between 1988-2000. Causes arising from aspects of incorrectly executed maintenance and uncorrected faults within the infrastructure were identified. Different types of ‘wear’ caused uncorrected faults at the ‘turnouts’ and ‘track’, which were classified as reasons for ‘lack of maintenance’.

This study shows that improper infrastructure maintenance was one major cause for the derailments and collisions. Of the 263 infrastructure related accidents, 81 (31 %) were caused by ‘maintenance’. These results are largely in agreement with the conclusions reached by Reason (1997) that maintenance errors play a dominant role in organisational accidents.

Some examples of other maintenance-related accidents are the chemical plant disaster at Bhopal (India, 1984), the Piper Alpha oil platform fire (North Sea, 1988), the Clapham Junction Rail Collision (U.K., 1988) and the disaster at Philips petrochemical plant in Texas (USA, 1989).

Of the 81 identified maintenance-related accidents 58 (72 %) were classified as being caused by ‘maintenance execution’, and 23 (28 %) were classified as being caused by ‘lack of maintenance’. The ‘immediate causes’ of the accidents, due to ‘maintenance execution’ were identified and classified as ‘human error’ in 44 cases (76 %) and ‘rule violation’ in 14 cases (24 %). The ‘immediate causes’ of ‘lack of maintenance’ problems could be pinpointed down to unrecognised faults at the ‘turnouts’ and ‘track’. The only explanation that can be given, based on the available data, is different types of ‘wear’.

The identified causes represent hazards to the rail system due to the infrastructure maintenance. These hazards may arise when there are deviations from the ideal situation in the maintenance process. See Holmgren & Söderholm (2005) for a description of steps involved in a generic maintenance process.

The resolution of the available data does not allow deeper analysis of the causes. This results in a quite generic explanation of the immediate and basic causes for ‘maintenance execution’ as well as ‘lack of maintenance’. We can see that different forms of individual ‘errors’ or ‘violations’ have been committed by the maintenance personnel. However, we can not explain, with support from the data, the reasons why the execution of maintenance tasks and fault recognition has deviated from the ones intended in the maintenance process. It is therefore of interest to discuss some reasons for uncorrected faults (resulting in ‘lack of maintenance’) as well as ‘human error’ and ‘rule violations’ (resulting in incorrect ‘maintenance execution’), with support from theoretical propositions, and based on that, give suggestions of some countermeasures that can be implemented within the Swedish rail context.

5.1 Aspects of lack of maintenance

‘Lack of maintenance’ may be due to a number of different causes. A reasonable assumption is that a maintenance activity starts with recognition of a failure or fault that needs to be addressed if corrective or condition-based maintenance strategies are applied. A failure on system level may require preventive maintenance. A fault on a component level needs to be counteracted by corrective maintenance, but a fault on a component level can be a failure on a system level.

A consequence of this is that ‘lack of maintenance’ may be caused by incomplete inspection of the system, which in turn, may be caused by a lack of resources needed to recognise faults causing problems within the infrastructure. A second possibility is that the motivation to perform these activities is lacking. A third possibility is that the awareness of maintenance-related risks in the system is too low.

These three possibilities correspond fairly well to the three basic factors important for system safety, presented by Reason (1997): 'commitment' (motivation and resources), 'competence' and 'cognisance' (awareness of risks), that all play an important role to achieve a safe system.

5.2 Aspects of improper maintenance execution

5.2.1 Human error

A distinction can be made between errors having their origin in problem solving (what?) and the development of a plan to solve a certain problem (how?), storage of the plan to be used (remember!), and the execution of the plan (do!). (Reason, 1990)

Reason (1990, 1997) makes a distinction between different kinds of errors. One is when the plan behind an action is incorrect ('knowledge based' mistakes). Another when the rule used to solve a problem is incorrect ('rule based' mistakes) and 'slips' and 'lapses' that may occur due to failures in the execution of an action or failures in the storage of a plan for the execution of an action. This distinction is important because different types of errors will call for different solutions.

To counteract 'knowledge based' mistakes it may be necessary to design a system so that an operator may form a correct mental representation or mental model of it. A correct mental model of the system will make it possible for an operator to understand what may happen when a certain action is performed to control the system. To counteract 'rule based' mistakes it is necessary to design a system in a way that maximizes correct selection of appropriate rules to control the system.

'Slips', or execution failures, may be avoided if distracting information or disturbances are eliminated during the process when the system is controlled. 'Lapses', or memory failures, may be avoided in the same way as 'slips' and also by adding different memory aids to support the storage of a plan to control a system. Here, a mental representation of the maintenance process may be helpful, to relate different actions with the information needed at each step.

5.2.2 Rule violations

Hale et al. (2003) define a rule as *"a correct or preferred way of carrying out a task in defined circumstances to achieve a defined goal"*. Violations to a rule may be either deliberate or not deliberate, without awareness, such as driving too fast but being unaware of that.

'Rule violations' may be divided into 'routine' (corner-cutting or taking short cuts), 'optimizing' (violations motivated by more or less rational motives, such as thrill) and 'situational' violations (due to insufficient recourses such as optimal tools, equipment and time necessary to get the job done). (Reason & Hobbs, 2003)

Different violations require different preventive strategies. In the case of 'routine', or corner cutting violations, it may be possible to either reinforce behaviour that follows established procedures or rules, or to supervise behaviour and punish deviations from established procedures or rules. 'Optimizing' violations motivated by more or less rational motives, such as thrill, may be prevented by information and supervision of behaviour. 'Situational' violations may be counteracted by providing adequate resources to get the job done. Here the different demands of the rail system as well as the needs of the maintenance operators must be considered. See Holmgren & Söderholm (2005) for a discussion about hazards linked to maintenance execution. One recurring hazard was lack of feedback.

6. FURTHER RESEARCH

One way to get more detailed information than available in the studied database is to study documentation generated by the accident investigations. A selection of investigations, based on the identified accidents from the database, would therefore be of interest to explain causes of ‘human error’ and the circumstances preceding and enabling their occurrence. ‘Rule violations’ could also be further analysed, in the same way as ‘human error’, in order to explain their occurrence.

The data provided in the database enabled analysis to identify the immediate causes for the accidents. It is of interest to further identify underlying factors, the ‘basic causes’, for accidents.

The reasons for incorrectly executed maintenance tasks were classified as ‘human error’ and ‘rule violation’. However, it was not possible to make a distinction between the different types of ‘human error’ divided into ‘knowledge based’; ‘rule based’; ‘slips’; and ‘lapses’, due to lack of available information in the database. In nine cases, it was possible to identify, ‘communication’ problems as likely basic causes of ‘human error’. Furthermore, it was not possible to explain the causes for ‘rule violations’, divided into ‘routine’; ‘optimizing’; and ‘situational’ violations and suggest countermeasures.

As the next step, an investigation has been started, to increase our understanding of the different types of errors and violations committed by the maintenance personnel in the execution of different maintenance tasks. The intention is to be able to suggest countermeasures in order to support a prevention of future maintenance-related accidents and losses.

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PAPER V

Human failures in maintenance execution within a railway context

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Human Failures in Maintenance Execution within a Railway Context

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ABSTRACT

Even though maintenance is intended to ensure safety and dependability of transportation systems, there are several examples of when it has resulted in accidents with extensive losses. Similarly in the railway sector, improper maintenance execution and lack of maintenance result in unwanted events such as collisions and derailments. Traditionally, human failures have often been identified as contributory factors in these accidents. However, human failure as an explanation for accidents is unsatisfactory, since there are organisational and operational causes that lay the foundation for these failures. The main purpose of this study is to identify causes contributing to human failures during maintenance execution, in order to help prevent maintenance-related losses. Twenty-six investigations of severe railway accidents and incidents within Sweden are analysed through a process approach supported by HAZOP-influenced (Hazard and Operability studies) guidewords. This analysis describes causes contributing to human failures and pinpoints them in relation to a generic maintenance process. The study also indicates that the applied analysis approach facilitates the interpretation of existing accident investigations. Hence, the analysis approach is also believed to be valuable when investigating future incidents and accidents, in order to identify hazards contributing to human failures in maintenance execution.

Keywords: Maintenance Execution, Human Failures, Accident Prevention, Railway

1. Maintenance and Accident Prevention

Maintenance is used to ensure the safety and dependability of railway systems. However, insufficient railway maintenance may result in collisions and derailments with negative consequences for humans, property, and the environment. Two examples of severe maintenance-related accidents on the railways are Ladbroke Grove in 1999 and Hatfield in 2000 [1, 2]. The collision and derailment at Ladbroke Grove caused 31 deaths and 227 injuries. Inadequate managerial control of the work performed by maintenance and sub-contractors was one cause of this accident [1]. The accident investigators pointed out the need for improving managerial control. The collision and derailment in Hatfield resulted in death of four persons [2]. According to the investigators, one cause contributing to the accident was a fragmentation of the rail, which in turn was caused by not identifying and replacing a cracked rail, i.e. lack of maintenance.

In Sweden, 40 percent of 666 railway accidents with collisions and derailments between 1988 and 2000 were infrastructure-related, i.e. caused by deficiencies in the infrastructure, such as the track or overhead wire, and not in the rolling stock. Of these infrastructure-related accidents, 30 percent were caused by insufficient maintenance or human failures during maintenance execution. These 58 maintenance-related accidents resulted in four fatalities, 62 injuries, and extensive economical losses. [3, 4]

Clearly, it is important to reduce the number of equipment failures that are being caused by improper maintenance execution. When adopting effective maintenance strategies, it is important to identify the causes of past accidents and the incidents associated with maintenance execution. Analysis of past accidents identifies areas that need special attention so that measures can be implemented for hazard reduction to achieve safer operations due to improved maintenance.

In the investigations related to the maintenance-related accidents cited above, one common factor is human failure. However, human error as an explanation for accidents is unsatisfactory, since there are always organisational and operational aspects that lay the foundation for these errors [5]. Hence, errors are consequences, rather than causes [6]. In other words, human errors are the result of a network of actions and conditions which involve people, teams, tasks, workplace and organisational factors [7]. Hence, discovering a human error is the beginning of the search for causes, not the end [6, 8]. The intention should be to identify and control hazardous conditions, instead of focusing on single causes of accidents and trying to eliminate them [9]. The purpose of this study is therefore to identify causes contributing to human failures during maintenance execution, in order to help prevent maintenance-related losses.

2. Definitions and Study Approach

'Human failures' are defined as consisting of both 'human errors' and 'rule violations'. 'Human error' is defined as: "… occasions in which a planned sequence of mental or physical activities fails to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some chance agency" [10]. 'Rule violation' may be defined as deviations from safe and established procedures, standards or rules to control a system [6]. Hence, rule violation may be either deliberate or erroneous [6]. In this paper, rule violations are seen as deliberate actions, even though the outcome is unintended. If the outcome is intended, the human action is classified as sabotage and excluded from this study.

Maintenance is defined as the combination of all technical and administrative actions, including supervisory actions, intended to retain an item in, or restore it to, a state where it can perform a required function [11].

An accident is defined as an unplanned and uncontrolled event in which the action or reaction of an object, substance, person, or radiation results in personal injury or the probability thereof [12]. An incident is defined as an undesired event that can, or does, result in losses [13]. The term loss is defined as an undesired event that affects people or property creating physical or economic harm [14].

If the cause of a maintenance-related accident or incident is an action taken during maintenance work to retain or restore the railway infrastructure, it is classified as caused by 'infrastructure-related maintenance execution'. The railway infrastructure consists of the railway track, points, overhead wires, and signalling equipment. [3]

2.1 Empirical Data

In Holmgren [3, 4], a database containing 666 Swedish railway accidents and incidents, which occurred between 1988 and 2000, were analysed. Out of these unwanted events, 58 were classified as caused by infrastructure-related maintenance execution. The main causes for accidents and incidents due to 'maintenance execution' were classified as 'human error' or 'rule violation'. However, only 27 investigations were accessible through the Swedish Rail Agency (Järnvägsstyrelsen). The reason for this is probably the division of accidents and incidents into two different severity groups, of which only the more severe events are reported to the Swedish Rail Agency. These 27 investigations have been analysed in the study presented in this paper. Furthermore, it turned out that one of the investigations was not maintenance-related, so the main analysis is founded on 26 investigations. The average number of pages for the analysed investigations is 30, varying between 11 and 154 pages.

2.2 Data Analysis

The accident and incident investigations have been analysed using two complementary approaches. The first approach is a generic maintenance process, as described by Söderholm et al. [15] and applied by Holmgren & Söderholm [16], see Figure 1. The applied maintenance process is based on the four phases of the Improvement Cycle (Plan-Do-Study-Act), as described by Deming [17]. The second approach was the application of guidewords, similar to those used in Hazard and Operability studies (HAZOP), as described by the Health and Safety Executive [18], see Table 1.

The process model was applied to illustrate contributory factors in the accidents' ultimate loss in relation to different maintenance activities, i.e. Maintenance Planning (Plan), Maintenance Execution (Do), Functional Testing (Study), and Feedback (Act), see [15] for further details. The purpose of using a generic maintenance process influenced by the Improvement Cycle in the analysis is to promote continuous improvement, and hence continuous risk reduction by hazard elimination.

In order to pinpoint the causes in relation to the steps of the maintenance process, the classification according to Table 1 was applied as a support. This classification was selected as a support in the analysis since it was developed with the purpose to identify possible human failures.

It is also important to note that the analysis was performed from a Maintenance Execution perspective. The reason for this is that the studied material consists of investigations of accidents and incidents, which primarily are manifested during maintenance execution. However, the underlying causes of the incident and accident may often be found in other maintenance activities, e.g. planning and testing [16].

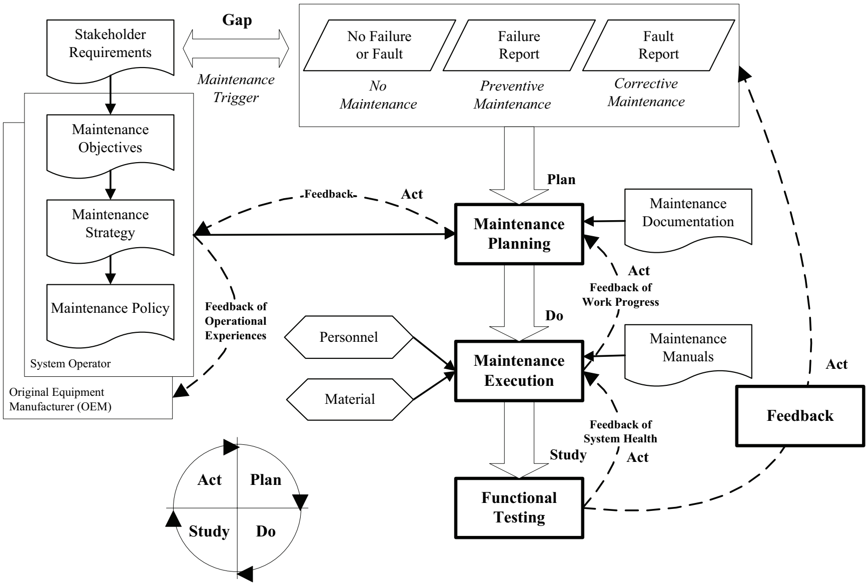


Figure 1. Maintenance as a process consisting of the four activities: Maintenance Planning, Maintenance Execution, Functional Testing, and Feedback. These activities and their relations are associated to the Improvement Cycle (Plan-Do-Study-Act), as described by Deming [17]. The activities are supported by information and different resources, such as personnel, time, and material. From Söderholm et al. [15].

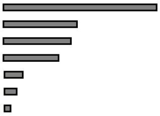
Table 1. A classification of human failures akin to Hazard and Operability studies (HAZOP) guidewords. [18]

Action Errors	A1 Operation too long/short A2 Operation mistimed A3 Operation in wrong direction A4 Operation too little/much A Operation too fast/slow A6 Misalign A7 Right operation on wrong object A8 Wrong operation on right object A9 Operation omitted A10 Operation incomplete A11 Operation too early/late
Checking Errors	C1 Check omitted C2 Check incomplete C3 Right check on wrong object C4 Wrong check on right object C5 Check too early/late
Information Retrieval Errors	R1 Information not obtained R2 Wrong information obtained R3 Information retrieval incomplete R4 Information incorrectly interpreted
Information Communication Errors	I1 Information not communicated I2 Wrong information communicated I3 Information communication incomplete I4 Information communication unclear
Selection Errors	S1 Selection omitted S2 Wrong selection made
Planning Errors	P1 Plan omitted P2 Plan incorrect
Violations	V1 Deliberate actions

3. Results

Some background information about the analysed incidents and accidents and the results of the analysis are summarised in Table 2.

Table 2. The result of the classification of human failures according to the applied maintenance process and the Health and Safety Executive (HSE) classification.

Accident or Incident*	Losses	Process Phase	Failure Classification
1	F=0, I=0, M=Yes	D/ADP	A3/I1
2	F=1, I=0, M=Yes	P/D	A2
3	F=0, I=0, M=Yes	P/D/ADP	A5/A9/R3/I4/P2
4	F=0, I=2, M=Yes	D/ADP	C1/R3/I3/I4
5	F=0, I=3, M=Yes	P/D/ADP	A9/R4/I3/I4/P2
6	F=0, I=8, M=Yes	D/ADP	R4/I2/I3
7	F=0, I=0, M=Yes	P/D/ADP	A10/I1/P2
8	F=1, I=0, M=Yes	D/ADP	A2/R3/R4/I1/I3/I4
9	F=0, I=0, M=Yes	D/ADP	A9/R4/I1/V1
10	F=0, I=5, M=Yes	P/D/ADP	A5/R4/I2
11	F=0, I=0, M=Yes	D/ADP	A3/A9/R4/I1
12	F=0, I=0, M=Yes	P/D	A9/P2
13*	F=0, I=0, M=No	P/D/ADP	I3/I4
14	F=0, I=1, M=Yes	P/D	A9/I4/P2
15	F=0, I=1, M=Yes	D/ADP	A9/I1
16	F=0, I=0, M=Yes	P/D/APD	A2/C1/I4
17*	F=0, I=0, M=No	D/S/ASP	C2
18	F=0, I=0, M=Yes	D/S/ASP	C2
19	F=0, I=1, M=Yes	D/ADP	A2/I3/P1
20	F=0, I=0, M=Yes	D/S/ASD	A8/C2
22	F=0, I=5, M=Yes	D/ADP	A2/R4/I4
23	F=1, I=0, M=Yes	D/ADP	A2/V1
24*	F=0, I=0, M=No	P/D/APD	A8/A9/R4/I3
25*	F=0, I=0, M=No	P/D/ADP	R4/I4
26	F=0, I=2, M=Yes	P/D/APD	I1
27	F=0, I=1, M=Yes	D	A5
Summary of incidents and accidents Country: Sweden Years: 1988-2000 Selection of investigations: collisions and derailments related to maintenance of railway infrastructure. Number of investigations: 26 Number of incidents: 4 Number of accidents: 22 Full investigations are accessible through the Swedish Rail Agency (Järnvägsstyrelsen).	 I=29 F=3 M= In 22 cases out of 26 **Abbreviations** I: Injury F: Fatality M: Material loss	 D=25 P=12 APD=11 ADP=9 S=3 ASP=2 ASD=1 **Abbreviations** P: Maintenance Planning (Plan) D: Maintenance Execution (Do) S. Functional Testing (Study) ADP: Feedback from Do to Plan APD: Feed forward from Plan to Do ASP: Feedback from Study to Plan ASD: Feedback from Study to Do See Figure 1 for the relationships between different process phases.	 R4=9 I4=9 A9=8 I1=7 I3=7 A2=6 P2=5 A5=3 C2=3 R3=3 A3=2 A8=2 C1=2 I2=2 V1=2 A10=1 P1=1 **Abbreviations** See Table 1.

The majority (51%) of human failures in maintenance were related to information deficiencies, i.e. communication errors (I, 34%) or retrieval errors (R, 17%), see Figure 2. These information deficiencies were located in Feedback (Act) between different steps of the maintenance process, or within the Maintenance Execution (Do) phase, see Table 2. The next largest group of human failures consisted of action errors (A) with 31%, see Figure 2. These action errors are located in the Maintenance Execution (Do) phase of the maintenance process. Thereafter, the groups are in descending order: planning errors (P, 8%), which are located in the process phase of Maintenance Planning (Plan), checking errors (C, 7%) located in the Maintenance Execution (Do) phase, or violations (V, 3%). The checking errors are, in addition to Maintenance Execution (Do), also connected to the process phases of Maintenance Planning (Plan) or Functional Testing (Study) through Feedback (Act). The violations are all located in the Maintenance Execution (Do) phase, but are also related to both the Feedback (Act) and Maintenance Planning (Plan) phases, see Table 2.

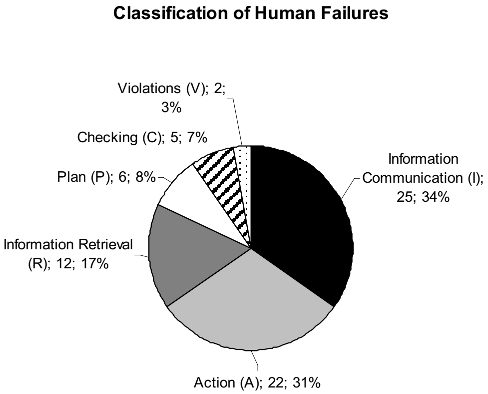


Figure 2. *Classification of human failures causing maintenance-related incidents and accidents on the Swedish railways between 1988 and 2000.*

3.1 Information Communication and Retrieval Errors

The 25 information communication errors were caused by unclear communication (I4, 36%), information not communicated (I1, 28%), information communication incomplete (I3, 28%), or the communication of wrong information (I2, 8%). The 12 information retrieval errors (R) were caused by incorrectly interpreted information (R4, 75%) or incomplete information retrieval (R3, 25%). All information-related errors involved more than one process phase through Feedback (Act) or feed forward. See Figure 3 and Table 2.

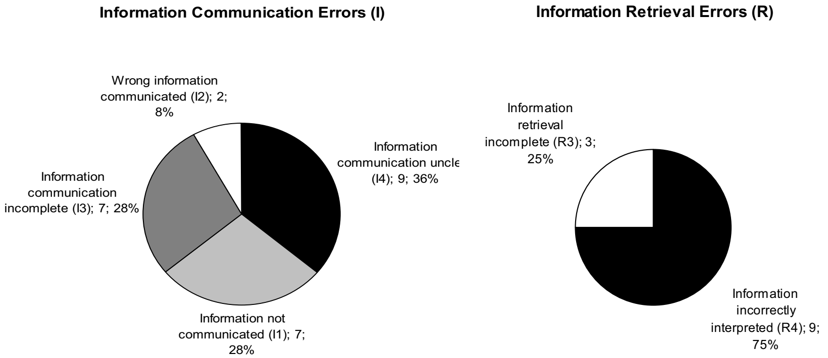


Figure 3. *Classification of human failures during railway maintenance execution related to information communication errors (I), on the left, and information retrieval errors (R), on the right.*

The most common cause of unclear information communication (I4) in the analysed investigations was lack of conversation discipline, which in turn caused misunderstanding. One example of this situation was when work-related communication was interrupted by a private telephone call. Another example was when a guard, part of whose job is to warn for trains, did not communicate with flags or signal horn, since this equipment was missing.

Human failures classified as information retrieval incomplete (R1) were all related to radio communication. These communication failures could in turn be linked to technological or organisational factors. The technological factor can be linked to poor audible quality, which in one case was caused by a known problem related to the terrain, which blocked good communication quality. One accident was the result of incomplete information retrieval, caused by lack of conversation discipline.

Some examples of human failures classified as information incorrectly interpreted (R4) were related to aspects of geographical location of track sections, vehicles, and personnel. A further example was insufficient system knowledge, leading to wrong assumptions about how to use double tracks and on which sections maintenance vehicles could be manoeuvred without disrupting normal operation. Incorrectly interpreted information was also often related to lack of conversation discipline, e.g. no repetition of communication, disturbed conversation (private telephone call), and conversation with wrong persons (e.g. with local train dispatcher instead of central train dispatcher).

Another class of information communication errors was information not communicated (I1). One example of such an error was a lack of conversation discipline, which led to missed information. Another example was when the train dispatcher did not tell the maintenance driver that there was already another maintenance vehicle on the track, which in turn led to lack of consultation. There are also examples of when the wrong information was communicated (I2).

Another form of information communication error was incomplete information communication (I3). One example was when only one instead of two parties was consulted. Another was no, or incomplete, repetition of safety conversation, leading to severe misunderstanding. A third example was lack of consultation leading to misinterpretation of each others' positions leading to a collision. A further example of incomplete information communication was when the driver of a ballast plough made an unplanned stop without informing the train dispatcher.

3.2 Action Errors

After the information errors (I or R), actions errors (A) turned out to be most frequent in the investigations. The 22 action errors were classified in the following groups in descending order: operation omitted (A9, 36%), operation mistimed (A2, 27%), operation too fast or too slow (A5, 14%), operation in wrong direction (A3, 9%), wrong operation on right object (A8, 9%), and operation incomplete (A10, 5%). All the action errors are located in the Maintenance Execution (Do) phase of the maintenance process. See Figure 4 and Table 2.

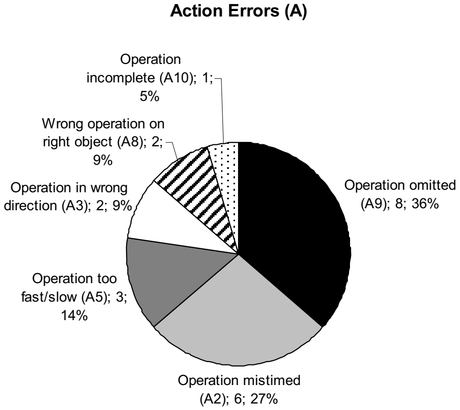


Figure 4. *Classification of human failures during railway maintenance execution related to action errors (A).*

The largest class of action errors (36%) was omitted operation (A9). A typical cause of these errors was the omission of obstruction signs or short circuit devices on the track. Another example was a forgotten communications radio. The second largest class of action errors (27%) was mistimed operation (A2). One example of this was maintenance personnel on the track being hit by a train, but no explanation or possible cause could be identified. Another example was maintenance personnel being supposed to ask for permission to start work when the train has passed. However, in some cases maintenance staff asked for permission without having seen the train pass. A version of this situation was when maintenance work was initiated before permission was given, while the train was still approaching. In the latter situation, contributory causes were the absence of obstruction signs and short circuit devices, which should have been put up by the maintenance personnel. A further example was when the driver of a ballast plough made an unplanned stop on the track to clean the vehicle's conveyor. The driver was obstructed by a track survey car, which drove behind the ballast plough brake van. One contributing cause was the lack of automatic brake lights on the plough.

Of the actions errors 14% were classified as operation too fast or too slow (A5). The most common factor found within the investigations was maintenance vehicles travelling too fast. One example was a ballast plough going too fast while performing track maintenance, leading to a collision with a track survey car, an additional factor being a lack of local knowledge. Another example was when a maintenance vehicle exceeded the speed limit on a track where the maximum speed had been reduced due to track geometry problems.

In two cases the action errors were classified as operation in wrong direction (A3). One case was when a maintenance vehicle performed a turn without checking the opposite track for clearance and collided with a small track vehicle. In the other case, a mini digger was left at the wrong location after completing digging for the day, in combination with the absence of a short circuit device, an insufficient understanding of the meaning of double track, and omitted communication with the train dispatcher before leaving the vehicle.

There were also two occasions where the action errors were classified as wrong operation on right object (A8). One case was a ballast plough travelling too fast while performing track maintenance. Another example was when the maintenance personnel isolated track at a wrong signal box, of which a contributory factor was the absence of a short circuit device. In one case the action error was classified as incomplete operation (A10), i.e. when no ballast was placed at the track on a section during maintenance.

3.3 Planning Errors

The human failures related to planning errors (P) are located in the Maintenance Planning (Plan) phase or the Maintenance Execution (Do) phase of the maintenance process. Five planning errors (83%) are classified as incorrect plan (P2), derived from the Maintenance Planning phase. One error (17%) is related to an omitted plan (P1) during Maintenance Execution (Do). See Figure 5 and Table 2.

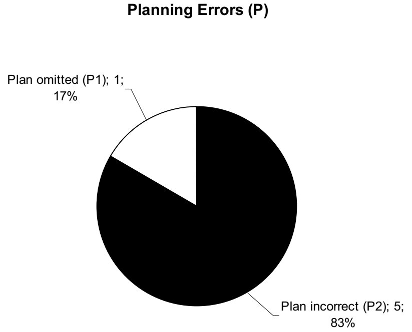


Figure 5. *Classification of human failures during railway maintenance execution related to planning errors (P).*

One example of incorrect plan (P2) was that the plan did not consider the plough driver's lack of local knowledge. Another example is when a person responsible for safety was not appointed in the plan. A third example is that the plan did not include ballast operation (ballast inserted on track) before a train was allowed to pass through, which would reduce the risk of sun curves. A further example of incorrect plan (P2) was when the plan did not consider the fact that work could not be performed with short circuit device inserted since current was needed. Train protection comprised a point that had been turned manually. However, had the track been short-circuited, the accident would have been avoided. In one case the plan was omitted (P1), i.e. an unplanned action was performed.

3.4 Checking Errors

There are two classes of checking errors (C) identified in the analysis of the investigations: check incomplete (C2, 60%) and check omitted (C1, 40%), see Figure 6. The checking errors are all related to the processes phase of Maintenance Execution (Do), see Table 2. There are also connections to Feedback (Act) or feed forward to other process phases such as Functional Testing (Study) and Maintenance Planning (Plan), see Table 2.

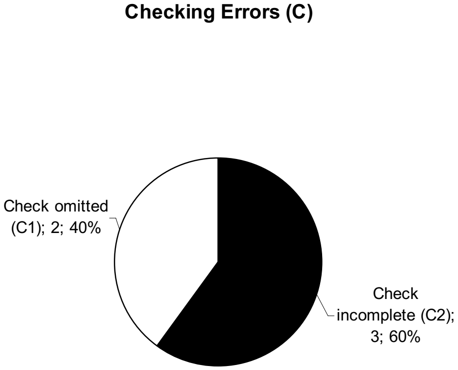


Figure 6. *Classification of human failures during railway maintenance execution related to checking errors (C).*

There were three cases of incomplete check (C2). One example was when a contractor marked a check-list as “OK” even though ballast was missing. Another example of incomplete check was undetected bad track geometry after adjustment and ballast cleaning. A third example of incomplete check (C2) was when the wrong type of claws had been inserted into a switch.

There were also two cases when the check was omitted (C1). One case was when the maintenance operator did not check that he was talking to the right person on the radio. The second case was when the maintenance personnel received permission to start work on track. However, before giving the permission the train dispatcher did not check if there was a train on track, which there was.

3.5 Violations

In the analysed investigations it was only possible to, without doubt, identify two rule violations, i.e. deliberately actions (V1) where the outcome was unintended. The rule violations are located in the process phase of Maintenance Execution (Do), but also involve insufficient Feedback (Act) to Maintenance Planning (Plan). See Table 2.

One example of rule violation was when the track was intentionally not short-circuited in order “to get the job done”, i.e. to be able to operate a level-crossing gate. If the gate had to be operated manually, it would have taken a long time to perform the work. The second example was when a maintenance operator failed to obey a direct order not to drive up on the track in order to turn a digger around. The maintenance operator was subsequently run over by a train and died.

4. Conclusions and Discussion

The study presented in this paper has identified contributory factors in human failures during maintenance execution leading to incidents and accidents within the Swedish railway between 1988 and 2000. The study shows that 51% of the human failures in maintenance are related to information deficiencies, i.e. communication errors (34%) or retrieval errors (17%). These information deficiencies are located in Feedback between different steps of the maintenance process, or within the Maintenance Execution phase. The reason for information deficiencies within Maintenance Execution is that the focus of the performed analysis was on maintenance execution. At the same time the accidents and incidents are manifested in this process phase even though the contributory causes may be located in other process phases. It can also be noted that the studied investigations often do not cover other phases of the maintenance process.

Action errors are the second largest group of human failures (31%). These action errors are located in the Maintenance Execution phase of the maintenance process. Thereafter, the groups are in descending order: planning errors (8%), which are located in the process phase of Maintenance Planning, checking errors (7%) located in the Maintenance Execution phase (and connected to Maintenance Planning or Functional Testing through Feedback), or violations (3%). The violations are all located in the Maintenance Execution phase, but are also related to the Feedback to Maintenance Planning. Hence, the process approach highlights that human failures may occur at different phases of the maintenance process. The further away in space or time, i.e. 'blunt end', a failure occurs, the more intangible it is. However, the impact at the 'sharp end' (Maintenance Execution) may be significant. See Hollnagel [9] for a discussion about 'sharp' and 'blunt' ends.

As discussed above, the study indicates different forms of individual 'errors' or 'violations' that have been committed by maintenance personnel. This identification was supported by the HAZOP guidewords. Hence, these guidewords provide an understanding of 'what' kind of errors had been committed. However, it was not possible to distinguish between the different types of 'human errors' divided into Reason's [10] 'knowledge based', 'rule based', 'slips', and 'lapses', due to insufficient resolution of available information in the studied investigations. Hence, in order to achieve a deeper understanding of the human failures and to implement proper preventive measures, future investigations should preferably be on a more detailed level.

In addition to the HAZOP guidewords-inspired classification, the performed analysis is based on a generic process model. The process model provides an understanding of 'where' different causes contributing to human failures are located. Hence, the combination of the guidewords and the process approach provides information about both 'what' and 'where' aspects of causes contributing to human failures. This combination gives a preliminary understanding about the network of contributory factors in human failures during maintenance execution, i.e. 'how' the causes are interlinked with each other and together contribute to human failures. Hence, the applied analysis supports the proposition that human failures are consequences of a network of actions and conditions which involve people, teams, tasks, workplace, and organisational factors, rather than single causes of accidents.

One thing that could be noticed when analysing the investigations was that the focus seems to have changed over time. Earlier investigations (1989-1997) seem to have focused on finding someone responsible for the accident, i.e. a 'blame' focus, while later investigations (1998-1999) seem to have an MTO-influenced (Man, Technology, and Organisation) focus, see Rollenhagen [19]. The next step of investigation development would be to have a deeper focus on human errors, as described by Reason [10]. It is also worth noticing that the Swedish National Rail Administration (Banverket) has initiated a special group, the task of which is to analyse incident and accident reports to obtain a holistic view of the railway context and accordingly act more proactively in the future.

In summary, the findings of this study support a proactive risk management process. This is achieved by indicating causes contributing to human failures during maintenance execution, as well as where in the maintenance process these causes are located. Furthermore, the applied and described analysis approach includes appropriate methodologies and tools that can complement the ones applied today within the Swedish railway sector. Hence, continuous risk reduction is facilitated and maintenance-related losses measured in fatalities, injuries, and economical consequences can hopefully be avoided in the future.

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