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DOCTORAL THESIS

RELIABILITY ANALYSIS AND COST MODELING OF DEGRADING SYSTEMS

Saurabh Kumar

Luleå University of Technology
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To my parents for believing in me...

PREFACE

The study and research work presented in this thesis has been carried out at the Division of Operation and Maintenance Engineering, Luleå University of Technology, Luleå, Sweden. The research work was sponsored by the Luleå Railway Research Centre (JVTC) and the Swedish National Rail Administration (Banverket). I would like to thank Banverket and JVTC for providing the financial support throughout my research work.

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Saurabh Kumar
March, 2008,
Luleå, Sweden

ABSTRACT

Degradation is an on-going process in systems, equipments and components subjected to various stresses and adverse operating conditions. The factors influencing the degradation process may adversely affect the system or component performance. A study of these factors will provide a basis for making correct decisions concerning corrective and preventive measures. Such a study is also useful for reliability analysis of the degrading systems/components for making maintenance decisions or for initiating measures for changes in the design.

Many times it is not possible to implement design changes due to complexities and cost considerations, as in the case of railway infrastructures, etc. In such situations operational reliability is assured through effective maintenance actions. Knowledge of the technical condition of components is important to achieve the optimal maintenance policy in order to minimize the total system risk. A methodology for rail defect prioritization and risk assessment is developed to support the decision-making process during the effective scheduling of the inspection frequency based on the type of defect and its risk of developing into a rail break.

The present research work also demonstrates an application of reliability analysis to improve system reliability based on design changes. This has been illustrated with an example from a manufacturing industry. The objective is achieved using cost-benefit analysis in combination with failure data and root cause analysis. The analysis of failure data with the different cost elements involved in the operation and maintenance of the complex systems is presented as a basis for choosing between alternative designs.

Furthermore, an optimization model has been developed to estimate the optimum inspection frequency required at the minimum maintenance cost based on the technical condition of the component. The model has been validated by a case study of an offshore oil and gas platform. The consequences of not choosing the right distribution have also been discussed in the thesis. The concept of the virtual failure state has been introduced to estimate the failure distribution of highly critical components. The factors influencing the degradation process have been identified and studied in detail. A framework for classification of rail failure data has also been developed for rail life estimation using reliability analysis.

In short, the thesis discusses the application of reliability analysis and cost modeling techniques to support the decision-making process in operation and maintenance activities and demonstrates its usefulness in real life.

Keywords: *Degradation process, influencing factors, reliability analysis, maintenance, classification framework, failure distributions, risk estimation, inspection, pairwise comparison, cost modeling and estimation, design changes, rail breaks, rail defects, flowlines, maintenance optimization.*

LIST OF APPENDED PAPERS

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

PAPER I: **Kumar, S., Espling, U. and Kumar, U.** (2007). A holistic procedure for rail maintenance in Sweden. *Accepted for publication in Journal of Rail and Rapid Transit: Proceedings of the Institution of Mechanical Engineers, Part F.*

PAPER II: **Chattopadhyay, G. and Kumar, S.** (2008). Parameter estimation for rail degradation model. *Accepted for publication in International Journal of Performability Engineering.*

PAPER III: **Kumar, S., Gupta, S. and Ghodrati, B.** (2007). Rail defect prioritization and risk assessment using a hybrid approach. *Submitted to an International Journal.*

PAPER IV: **Kumar, S., Chattopadhyay, G. and Kumar, U.** (2007). Reliability improvement through alternative designs: a case study. *Reliability Engineering and System Safety,* 92(7), 983-991.

PAPER V: **Kumar, S., Dandotiya, R., Kumar, R. and Kumar, U.** (2008). Inspection frequency optimization model for degrading flowlines on an offshore platform. *Accepted for publication in the International Journal of Reliability, Quality and Safety Engineering.*

LIST OF RELATED PUBLICATIONS

Publications related to the research, but not appended in the thesis.

Kumar, S. (2006). *A Study of the Rail Degradation Process to Predict Rail Breaks.* Licentiate Thesis. Division of Operation and Maintenance Engineering, Luleå University of Technology, Luleå, Sweden, ISSN 1402-1757; 2006:73.
Link: http://epubl.ltu.se/1402-1757/2006/73/LTU-LIC-0673-SE.pdf

Kumar, S., Chattopadhyay, G., Reddy, V. and **Kumar, U.** (2006). Issues and challenges with logistics of rail maintenance. *In Proc. of 2nd International Intelligent Logistics Systems Conference,* Brisbane, Australia, 22-23 February, 16.1-16.9, ISBN (CD-Rom) 0-9596291-9-X.

Chattopadhyay, G., Kumar, S., Larsson-Kråik, P.O. and **Kumar, U.** (2006). Estimation of parameter for degradation of rails. *In Proc. of 19th International Congress on Condition Monitoring and Diagnostic Engineering Management (COMADEM),* Luleå, SWEDEN, 12-15 June, 605 – 612, ISBN 978-91-631-8806-0.

Kumar, S. (2006). *Study of Rail Breaks: Associated Risks and Maintenance Strategies.* Technical Report. Division of Operation and Maintenance Engineering, Luleå University of Technology, Luleå, Sweden, ISSN 1402-1536; 2006:07.

Kumar, S., Chattopadhyay, G., Kumar, U. and **Kumar K.** (2005). Application of design changes for improvement of system reliability: a case study. *In Proc. of 18th International Congress on Condition Monitoring and Diagnostic Engineering Management (COMADEM)*, Cranfield, U.K., 31-2 Aug/Sept, 83 – 92, ISBN 1871315913.

Kumar, S., Mishra, N.M. and **Mukherjee, P.S.** (2005). Online condition monitoring of engine oil. *Industrial Lubrication and Tribology,* 57(6), 260 – 267.

Kumar, S., Mishra, N.M. and **Mukherjee, P.S.** (2005). Additives depletion and engine oil condition: a case study. *Industrial Lubrication and Tribology,* 57(2), 69 – 72.

CONTENTS

Chapter 1

1. INTRODUCTION

A brief introduction to the importance of reliability analysis and performance improvement of systems or components is discussed in this chapter. It covers the underlying background and problem areas of the research study. It also discusses the research questions and the scope of the research. Finally the structure of the thesis is discussed.

1.1. Background and Problem Discussion

Competitiveness has increased demands on production systems (Miyake and Enkawa, 1999). Customer satisfaction depends upon the production systems' capability to deliver goods and services on time, meeting the required quality specifications. To do so, the systems must be reliable. However, the operation and aging of the systems gradually reduce their performance, reliability and safety. Wear, corrosion, erosion, fatigue and crack generation are major contributors to system/component degradation (Clifton, 1974). A degraded state is a state of a system/component whereby that system/component continues to perform a function to acceptable limits, but which are lower than the specified values or continues to perform only some of its required functions (SS-EN 13306, 2001). There may exist several states of degradation under which the efficiency of the system may decrease (Li and Pham, 2005). In some cases, if the degradation level exceeds a particular limit, the system may not operate successfully; this may be considered as a system failure[1]. Improvement in inspection techniques and skills may reduce failures, but they cannot be avoided completely.

A failure can sometimes be catastrophic in nature. Relevant examples from the railway and the oil & gas industry have been taken to illustrate the catastrophic consequences of a failure. The *German ICE train derailment* at Eschede on 3rd June 1998 took more than one hundred lives. The accident was caused by a fatigue fracture which started on the underside of the rim of a wheel. The derailment caused one of the carriages to swing out of line and to strike a support of a bridge, prompting its collapse (Smith, 2003). The *Hatfield derailment* (UK) in October 2000 killed four and injured 34 people. The damages in terms of consequential costs to Railtrack Company (acquired by Network Rail in 2002) were about £733 million (The Guardian, 2005). The derailment happened because a rail in which there were multiple cracks and fractures due to RCF (rolling contact fatigue) fragmented when a high-speed train passed over it (ORR, 2002).

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[1] Failure is the termination of the ability of an item to perform a required function (IEV 191-04-01, 2001).

The *Alexander Kielland accident* in March, 1980 killed 123 of the 212 men on board the platform at the time of the accident. The accident occurred during poor weather conditions, and was initiated by a fatigue fracture on a weld on the lower horizontal bracing of one of the legs. Soon the remaining five bracing members connected to the column failed in quick succession, because they were loaded almost immediately beyond their capacity. This led to the overturning of the rig after some time (HSE, 2006). The direct expenses amounted to USD 80 million and considerable loss originated in the disruption and deferment of petroleum production (Amundsen, 1992). There will always be some risk associated with failures, but it can be reduced by precise knowledge of the technical condition[2] of systems/components.

Even if failures are not catastrophic, they may lead to production loss through downtime, extending the delivery deadlines (for example in the manufacturing industry). This might cause a number of rejections and reworks leading to material wastage and additional costs for the products. The profit margin drops and thus the product becomes less competitive in the market. Sometimes this leads to a reduction in the market share (Blischke and Murthy, 1994). Therefore, the company might be forced to reduce production (underutilization of plant capacity), which ultimately increases the cost of production. On the other hand, problems with poor quality also add cost, the effect of which is in-line with the loss of productivity. In addition to this, there is a probability of losing customer goodwill (Kumar *et al.,* 2007).

There is an uncertainty involved in the occurrence of failures in a system or component which depends on its technical condition, age and the degradation rate. Therefore, reliability is an aspect of engineering uncertainty which describes the system's or component's condition in terms of probability. Reliability is defined as "the probability that an item can perform a required function under given conditions for a given time interval" (IEV 191-02-06, 2006).

Earlier (i.e. in the nineteenth and early twentieth century), components were less severely constrained by cost, usage, high production demands, etc. Consequently, in many cases, high levels of reliability were achieved as a result of over design (Smith, 2005). Therefore, the need for reliability analysis was not essentially felt. The necessity of expressing reliability as a quantitative measure first arose during the Second World War. The need for reliable defense equipment was realized and basic reliability concepts were used to improve missile reliability (Dhillon, 2002). The concept of reliability has existed for a very long time in qualitative terms, but it was quantitatively specified during the early 1950's (Barlow and Porschan, 1965; Smith, 2005). An advisory group on the reliability of electronic equipment (AGREE) was established by the U.S. Department of Defense in 1957 (O'Connor, 1991). This led to the recognition of reliability as an independent specialized field.

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[2] The technical condition is defined as the degree of degradation relative to the design condition. It may take values between a maximum and a minimum, where the maximum value describes the design condition and the minimum value describes the state of total degradation (Steinebach and Sørli, 1998).

Reliability analysis helps to identify the technical condition and predict the remaining useful life of degrading systems/components. Information about the current and future condition of the system/component becomes an important indicator in the operation and maintenance decision-making process. Alternative design options can improve system reliability (Petersen, 1986), but detailed analysis of failure data with the different costs involved in the operation and maintenance of complex systems is required. Cost modeling and cost-benefit analysis provide essential information for decision making.

Many times it is not possible to implement design changes due to complexities and cost considerations, for example in the case of oil platforms or railway infrastructures, etc. In such situations operational reliability is intended to be assured through effective maintenance actions. Knowledge of the technical condition of the components is crucial to decide upon the type and frequency of maintenance actions required.

The performance of systems/components depends on the decisions taken during their life cycle. Decision making is a complex process that differs a great deal from industry to industry. The thesis deals with three different case studies, related to the manufacturing industry, railway infrastructure and offshore oil & gas platform infrastructure, describing case-specific approaches based on reliability analysis and cost modeling. Components of machines used in the manufacturing industry have very different performance criteria compared to infrastructural components such as rails or pipelines. An important aspect of infrastructural components is that they are costly investments that have a long and useful life (Larsson, 2004). Therefore, once installed, it is very difficult to modify the initial design. Consequently, the performance of the infrastructure depends on the maintenance and replacement decisions taken during its life cycle. On the other hand, machine components are cheaper and have a relatively shorter life expectancy. Therefore, decisions on design alternatives in the case of machine components are practically more feasible than such decisions in the case of infrastructure.

A great deal of literature is available on maintenance, replacement and design changes related to systems and components, and the role of reliability analysis in improving system or component performance (see Barlow and Porschan, 1965; Ross, 1970; Billinton, 1983; O'Connor, 1991; Yadav *et al.,* 2003; Jardine, 2006; Hagmark and Virtanen, 2007). In the case of railway infrastructure, many researchers are involved in developing cost-effective maintenance models to improve track performance (see, for example, Fazio and Prybella, 1980; Hargrove, 1985; Acharya *et al.,* 1991; Zarembski, 1991; Martland *et al.*, 1994; Zhang *et al.*, 1999; Larsson, 2004 and Podofillini *et al.*, 2006). Reliability analysis techniques have also been widely proposed to improve the performance of offshore oil and gas platform infrastructures (see Garbatov and Soares, 2001; Rajasankar *et al.,* 2003; Moan, 2005; Castanier and Rausand, 2006; Khan and Howard, 2007). However, most of the maintenance and renewal decisions are based on past experience and expert estimations. Evaluation methods based on expert judgments have been developed from experts' experience of system/component failure patterns over the years. Expert judgment is mostly applied when it is difficult to obtain the required data or where great precision in prediction is not required (for details on expert judgment, see Saaty, 1987; Meyer and Booker, 1991).

In most of the safety-critical and process/manufacturing industries, the accurate prediction of failures and other reliability parameters is essential to make effective maintenance or design change decisions which can avoid undesired consequences. Therefore, a systematic approach is required for guaranteeing the defined levels of performance of the system/component during its operation and maintenance phase.

1.2. Research Purpose

The purpose of the research work is to study and analyze the performance of degrading systems/components using a reliability engineering approach and cost modeling techniques to support the maintenance decision-making process.

1.3. Research Objectives

The research objectives are:

1. Identification of the different factors influencing the degradation process of systems/components.
2. Development of a framework for classification of the degradation and failure data for reliability analysis and cost modeling.
3. Development of a maintenance optimization model to arrive at the optimal maintenance policy for a component during its useful life.

1.4. Research Questions

To fulfill the research purpose and achieve the research objectives, the following research questions need to be answered:

1. What are the factors influencing the degradation process?
2. How can the performance of a degrading system be improved/assured using reliability analysis techniques?
3. How can integration of reliability analysis based on failure data and expert judgment be used to estimate the system risk?
4. How can reliability analysis help in optimization of the maintenance policy?

1.5. Scope and Limitations

The research work covers failures due to degradations in systems and components related to complex mechanical systems and infrastructures. The degradation process in electronics and electrical systems is not considered. Failures initiated on account of human errors are not considered. In this study, the application of reliability analysis and cost modeling techniques is limited to the operation and maintenance phase.

1.6. Structure of the Thesis

The thesis consists of six chapters and five papers appended in full. Chapter 1 introduces the research, giving a brief background dealing with the importance of the reliability of systems/components by presenting some examples of the catastrophic accidents due to system/component failure. The chapter also discusses the research problem and outlines the research purpose, research objectives, research questions and limitations.

Chapter 2 discusses the state-of-the-art concerning the concepts, the theories and the empirical studies included in the thesis.

Chapter 3 briefly describes the factors influencing the rail and flowline degradation process. The chapter also discusses the concept of virtual failure state.

Chapter 4 describes the methodology that has been used in this research. It explains the different phases of research, which include the research purpose, the research approach, the research strategy, data collection, data analysis and evaluation of the research quality.

Chapter 5 presents the summary of the appended papers, highlighting the important findings of each of the appended papers.

Finally, Chapter 6 discusses the approach to reliability-based analysis for degrading systems and the contribution of each paper to fulfill the research purpose, objectives and answering the research questions. The effect of assuming a wrong failure distribution is also discussed in this chapter. The chapter also contains the conclusions, research contributions and recommendations for future research.

Chapter 2

2. LITERATURE REVIEW

This chapter discusses the state-of-the-art concerning the concepts, the theories and the empirical studies discussed in the thesis.

Reliability analysis is very important to maintain the performance (i.e. quality, reliability and safety) of systems/components, as discussed in Chapter 1. However, the performance of a system/component may change due to process or demand variation (Liyanage and Kumar, 2003). A process variation may be a change in the operational condition; for example a change in the sand particle level or water content in an oil and gas pipeline may cause fairly rapid erosion or corrosion respectively. Demand variation can be seen in the railway infrastructure, where, for example, the axle load and traffic density change according to the stakeholders' demands. In addition, aging, overloading and various stresses degrade the systems and components (Valdez-Flores and Feldman, 1989). Degradation may take place in the form of wear, corrosion, erosion, fatigue and crack generation. Any of these factors or their combination can become a cause of a failure. Degradation issues are very critical in many industries, for example, the railway, oil and gas, manufacturing industry, etc.

In the railway industry, as rail degradation is one of the prime issues for rail infrastructure managers, it is important to understand the rail degradation process. Rail degradation is an inherent process which leads to a rail defect. Olofsson and Nilsson (2002) classified the rail defects which occur due to RCF (rolling contact fatigue) into the surface-initiated and subsurface-initiated defects. Other classifications were given by Cannon *et al.* (2003) and Marais and Mistry (2003). A detailed study of the different types of rail defects has been performed by a number of researchers over the years (see Grassie and Kalousek, 1993; Matsumoto *et al.*, 1996; Kalousek and Magel, 1997; Nielsen and Stensson, 1999; Zhang, 2000; Esveld, 2001; Ishida *et al.,* 2003; Zarembski *et al.*, 2005). Residual stress accumulation is also an important factor which accelerates the rail degradation process. The use of improved welding technology and post-weld heat treatment considerably decreases the extent of weld-initiated residual stress (see for details Esveld, 2001; IHHA, 2001). Most of the critical defects manifest themselves in the form of cracks which finally lead to a rail break. An interesting insight into the phenomenon of crack propagation during fluid entrapment was given by Bower and Johnson in 1991 (see also Bogdanski *et al.*, 1997). Bower and Johnson stated that manufacturing defects in the rail subsurface and in the direction of the crack mouth on the rail surface both dictate the crack development direction. The presence of water, snow or lubricant on the rails may increase the crack propagation rate. When these minute head checks are filled with water or lubricants, they do not dry up easily. During wheel-rail contact, these liquids get trapped in the crack cavities and build up very high localized pressure, which may even be greater than the compressive stress of the material. If the head checks are in the direction of the train traffic, crack growth takes place due to liquid entrapment, but when the head checks are in the opposite direction to that of the train traffic, the liquid is forced out before its entrapment (Ringsberg, 2001).

Wear and fatigue in rails are significant problems for the railway industry. They are major contributors to rail deterioration depending on the operational conditions, such as the train speed, axle load, rail-wheel material type, size and profile, track construction, the characteristics of the bogie type, MGT (million gross tonnes), curvature, traffic type, climate and operational environment (see Chattopadhyay and Kumar, 2008). A detailed study of the process of rail wear can be found in the articles of Jendel (1999), Zakharov (2001), Olofsson and Nilsson (2002) and Chen *et al.* (2005). Wear is a form of degradation which cannot be completely eliminated but can be reduced by lubrication. Effective lubrication can only be achieved if adequate monitoring methods are available (Peters and Reiff, 1989). Analysis and modeling of RCF initiated defects have been undertaken by many researchers to find out ways of reducing the initiation and propagation of these defects (see Fletcher and Beynon, 2000; Ekberg *et al.,* 2001; Ringsberg and Bergkvist, 2003; Ishida *et al.,* 2003; Sawley and Kristan, 2003; Jeong, 2003). A small reduction in the initiation of these defects will save a great amount of maintenance, replacement and consequential costs (in the case of derailments caused by RCF-initiated defects), but an appreciable level of reduction still needs to be achieved. Rail grinding is performed mainly to control RCF defects and rail wear, and became increasingly recognized as a way of reducing RCF defects from 1980 onwards. Prior to that, rail grinding was mainly focused on corrugation removal (Cannon *et al.,* 2003). A noticeable contribution to the rail grinding process and grinding strategy can be found in Kalousek *et al.* (1989) (see also Kalousek and Magel, 1997; Magel and Kalousek, 2002; Magel *et al.,* 2003).

Similarly, for the offshore oil and gas infrastructure, pipeline or flowline degradation is a critical issue for the infrastructure managers. Khan and Howard (2007) classified pipeline or flowline degradation into uniform and non-uniform/localized degradation. Degradation of offshore structures takes place mainly in the form of corrosion, erosion and crack generation due to fatigue and thermal stresses (Rajashankar *et al.,* 2003; Moan, 2005; Castanier and Rausand, 2006). Moan (2005) further classified the corrosion types commonly occurring on offshore structures as general corrosion, pitting corrosion, grooving corrosion and weld metal corrosion. Corrosion in pipelines becomes significantly more aggressive in the presence of erosion (Castanier and Rausand, 2006).

Maintenance of systems/components not only increases the life length but may also reduce the failures and the degradation rate. Maintenance can be defined as a combination of all the technical and administrative actions, including supervisory 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, 2001; see also BS ISO, 1999). The focus on maintenance has changed over time from being an issue of low priority, to becoming an important management factor influencing the overall safety, quality, reliability and profit of an organization (Andersen, 1999). Maintenance today is viewed as a value adding concept (Liyanage and Kumar, 2003) because it contributes efficiently to the companies' strategic objectives in profitability and competitiveness (Al-Najjar and Kans, 2006). Achieving more efficient maintenance depends on the capability of the implemented maintenance policy to provide and employ effectively the relevant information about the factors affecting the life of the component/system being considered (Al-

Najjar and Alsyouf, 2003). If we wish to realize the benefits from an investment, maintenance is the prerequisite (Andersson, 2002).

The railway infrastructure owners' cost for operation and maintenance, including reinvestment costs, for the Swedish railway was €447 million during the year 2006 (Banverket, 2006). The asset value of the railway infrastructure is also very high, which probably makes maintenance efforts highly valuable (Larsson, 2004). Reasonably structured track maintenance planning started to develop in the early 1980's. Fazio and Prybella (1980) described a track maintenance approach in which they highlighted some of the prerequisites for track maintenance. Hargrove (1985) proposed a track degradation model considering the degradation of different components of the track. Separate degradation models of all the track components together form the track degradation model. An application of his approach can be found in Paper I, appended to the thesis. Hargrove further calculated the track maintenance cost by life cycle estimation for different components of the track. However, Hargrove's model lacked the prioritization of different maintenance activities which should be performed in order to control the degradation rate in different components of the track.

By the beginning of the 1990's, many researchers and rail infrastructure managers had felt the need for an economical and efficient rail infrastructure maintenance model. Considerable work was undertaken during the 1990's on the development of effective maintenance strategies for rail infrastructure. REPOMAN (Rail Expert Planning, Organization and Maintenance) and TRACS (Total Right-of-Way Analysis and Costing System) were developed in the early 1990's at MIT (Massachusetts Institute of Technology), USA, with the aid of rail infrastructure owners/managers like BN (Burlington Northern Railroads) and the AAR (Association of American Railroads). REPOMAN was based on maintenance planning, while TRACS was based on track degradation analysis and life-cycle costing (see for details Acharya *et al.,* 1991; Martland and Hargrove, 1993; Martland *et al.,* 1994). During this time, many rail infrastructure managers collaborated with academic/research institutions to develop the rail infrastructure maintenance strategies which further produced useful track maintenance models like ECOTRACK (Economical Track Maintenance), developed jointly by UIC (Union Internationale des Chemins de fer: International Union of Railways), ERRI (European Railway Research Institute) and rail companies, ITDM (Integrated Track Degradation Model), developed at Queensland University of Technology, Australia and DECOTRACK (Degradation Cost on Track), developed jointly by Damill AB, Banverket (Swedish National Rail Administration) and JVTC (Luleå Railway Research Centre) at Luleå University of Technology (see ERRI, 1995; Zhang *et al.,* 1999; Zhang, 2000; Larsson, 2004).

Ebersöhn (1997) discussed the need for track maintenance management and outlined some of the prerequisites for the track maintenance decision-making process, such as traffic data, cost information, an asset inventory and historical data. Ebersöhn's approach provided useful data for the development of track maintenance strategies (see Ebersöhn *et al.*, 2001). His approach has been implemented in AMTRAK (National Railroad Passenger Corporation and Subsidiaries). Zarembski (1991) emphasized the use of automated inspection systems and well-structured databases, which should provide all the information required and enable proper planning to improve the efficiency of rail infrastructure management systems. Zarembski tried to give a general view of developing an effective track maintenance strategy. However, his approach lacked some of the factors affecting rail degradation, like the axle load and the characteristics of the bogie type. Most of the factors influencing rail degradation have been identified (see Paper I) and described in detail in Section 3.1 in the thesis. In addition, the degradation behavior of flowlines on an offshore oil and gas platform in the North Sea is also studied as a separate case study presented in the thesis. Flowlines are the topside piping systems on the platform taking the well-stream from the well head to the production manifold (Kumar *et al.,* 2008). Flowlines are also subjected to different stress and adverse operating conditions, as are the rails. The factors influencing the flowline degradation are also described in Section 3.2.

The application of reliability analysis techniques for the assessment of technical conditions, maintenance planning and model development for offshore structures is not new (see Fjeld, 1977; Lloyd and Karsan, 1988; Moses and Liu, 1992; Moses, 1997; Lotsberg *et al.,* 2000; Garbatov and Soares, 2001; Rajashankar *et al.,* 2003; Moan, 2005; Castanier and Rausand, 2006). However, there has not been much research work performed on maintenance planning and optimization based on the flowline condition (Khan and Howard, 2007).

Maintenance optimization modeling has attracted many researchers since the early 1960's and its importance has continuously grown over the years. This is because it is the only approach which combines reliability with economics in a quantitative way (Dekker, 1996) and it is applicable in diversified areas (Cho and Parlar, 1991). A wide range of maintenance optimization models have been developed and reviewed from time to time (see Sherif and Smith, 1981; Cho and Parlar, 1991; Dekker, 1996; Dekker *et al.,* 1997; Kuo and Prasad, 2000; Ben-Daya *et al.,* 2000). Complexity and increasing demands on component reliability and cost-effective maintenance of systems have led to the development of more sophisticated models. However, applications of the developed maintenance models using reliability or statistical analysis techniques are not common, largely because they require specialist knowledge (HSE, 2002). This is also due to the models mainly focusing on mathematical analysis and techniques rather than solutions to real-world problems and practical applicability (Dekker, 1996; Castanier and Rausand, 2006). Therefore, the development of the maintenance approach and models should be practical and as simple as possible, so that they can be easily grasped and interpreted by the technicians and managers.

Another important issue which needs to be looked into is the detection of defects and failures. If the defects and failures are not detected and recorded properly, the results obtained by reliability analysis may be misleading, which will provide wrong inputs for the maintenance decision-making process. In the case of rails as well as offshore structures, the detection of defects in the form of cracks is very important, as it directly concerns safety issues. A rail defect may call for safety measures (for example the imposition of speed restrictions), leading to considerable traffic disruption and ultimately passenger dissatisfaction (Kumar, 2006). Similarly, a pipeline defect in the form of a leak or a crack may require an immediate shutdown of the concerned system on the production facility for safety reasons. This may also affect the production capacity. Cannon *et al.* (2003) described the shadowing effect of ultrasonic sound waves when detecting head checks and squats in rails. Some of the defects which are left undetected by non-destructive testing (NDT) techniques are due to the problem described by Cannon. There is a need for a reduction in undetected defects and wrongly detected defects (Kumar, 2006; Söderholm, 2007). Frequent and skillful handling of effective inspection equipment can increase the probability of detection. Inspection (in the operational phase) is a maintenance activity carried out at predetermined time intervals in order to reduce the probability of failure (or the performance degradation) of the system/component (Bahrami-Ghasrchami *et al.,* 1998). The inspection cost increases when the inspection interval is shortened (or the inspection frequency is increased), as inspection is one of the cost elements (Jardine and Tsang, 2006). For example, the rail inspection costs alone (assuming annual ultrasonic vehicle-based inspections followed by manual verification of detected defects) are estimated at about €70 million per year for a 0.5 million kilometer track system in the European Union (Cannon *et al.,* 2003).On the other hand, the risk or loss caused by failure will increase when the inspection interval is lengthened (Rajasankar *et al.,* 2003; Okumura and Okino, 2003). Therefore, appropriate scheduling of inspection activities is important for a reduction in the maintenance cost. The rail infrastructure managers are looking for cost and risk reduction by modeling the inspection, grinding and maintenance intervals (Chattopadhyay and Kumar, 2008). An inspection frequency optimization model for the flowlines of an offshore oil and gas platform has been developed and described in Paper V. A similar optimization model can also be developed for the railway infrastructure.

For a manufacturing company, the failure of a component may cause production loss due to downtime, besides affecting reliability and safety. Frequent failures may affect the quality of the product being manufactured. Rejects, reworks and downtime lead to wastage and additional costs for the products, the profit margin drops and thus the product becomes less competitive in the market. Sometimes this leads to a reduction in the market share (Blischke and Murthy, 1994). Consequently, the company has to reduce production forcibly (underutilization of plant capacity), which ultimately increases the cost of production.

Detecting failure causes at an early stage, provides opportunities to control component and machine condition before the deterioration becomes intolerable (Al-Najjar and Wang, 2001). In such situations, a system approach is required to identify the root cause and find out alternative technical solutions to improve the reliability of the system.

From the review of previous discussions, it was found that there is a need to monitor the technical condition of systems/components and initiate measures to reduce their degradation and failure rate. The simple and effective application of reliability analysis techniques can predict system/component life and failure probability, which can help in development of the optimal maintenance models required in the decision-making process or alternative designs for enhancement of the performance of systems/components.

Chapter 3

3. FACTORS INFLUENCING THE DEGRADATION PROCESS

There are many factors which influence the degradation process. These factors have been identified during the study of rails and flowlines and are briefly described in this chapter. The concept of the virtual failure state is also highlighted in this chapter.

3.1. Identification of the Factors Influencing Rail Degradation

In order to identify the factors influencing the rail degradation process, various sources of information have been examined. These included a literature survey, inputs from various railway-related conferences attended, and discussions and consultations with rail maintenance experts from Banverket and JVTC. The identified factors responsible for rail degradation are illustrated using a cause and effect diagram in Figure 3.1 and are briefly described below.

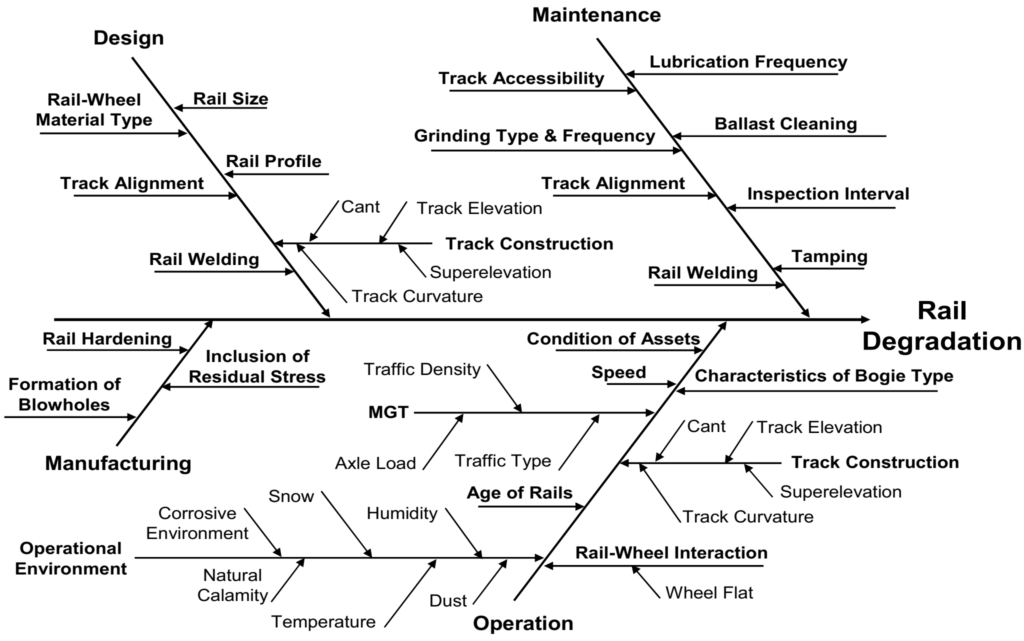

Figure 3.1: Cause and effect diagram for the factors influencing rail degradation

The identified factors are:

<u>Condition of Assets:</u> Assets in a poor condition (for example sleepers, fastenings, ballast, etc.) accelerate the rail degradation rate. Fishplates having a degraded condition or loose fishbolts

will cause the rail joint gap to close or fully open, even at minor temperature changes (Lichtberger, 2005). This may result in rail buckling or rail end degradation.

Age of Rails: Sometimes rail replacement becomes essential due to degradation in the rail's material properties over a period of time and usage. This is known as ageing in rails and replacement is required, as aged rails may degrade the wheel material during rail-wheel interaction or vice versa.

Axle load: This is a measure of the deterioration of track quality and as such provides an indication of when maintenance and renewal are necessary (Esveld, 2001). A heavy axle load causes static and dynamic stress at the rail-wheel contact patch, which may accelerate rail degradation (IHHA, 2001).

Speed: Vehicle speed can adversely influence the curving performance of the vehicle and, in turn, lead to wear and stress in the rail and wheel (IHHA, 2001). The running speed has a certain influence on the dynamic interaction between the vehicle and the track, because the point of application of the load moves with the running speed.

Tamping: This is a process whereby the ballast under the ties (sleepers) is compacted to provide proper load bearing. Ties are the portion of the track structure generally placed perpendicular to the rail to maintain the track gauge, distribute the weight of the rails and rolling stock, and keep the track properly aligned. The majority of ties are made of wood. Other materials used to manufacture ties include concrete and steel (IHHA, 2001).

Ballast Cleaning: Despite an identical track structure, the same year of construction and the same traffic load, the rates of deterioration may differ widely even between adjacent sections. One of the reasons is the non-homogeneity of the ballast beds (Lichtberger, 2005). Infrequent ballast cleaning may result in undesirable changes in the track position, which may cause more stress generation and more wear.

Traffic Density: The more frequently trains pass over a rail section, the more rail-wheel interaction takes place leading to more wear and RCF generation.

Traffic Type: The type of traffic passing over the rail (passenger or freight traffic) defines the axle load and thus influences the rail degradation rate.

Characteristics of the Bogie Type: In Sweden, railway operators and maintenance contractors have been deregulated, which has led to a tendency for operators to introduce low-cost rolling stock. This may increase track degradation (Larsson, 2004). Therefore, the characteristics of the bogie type influence rail degradation.

Grinding Frequency: Preventive grinding leads to a significant increase in the service life of the rails, delay in the occurrence of rail corrugation and a decrease in traffic noise levels (Van

Den Bosch, 2002). An optimal grinding frequency helps to increase the rail life (Rippeth *et al.,* 1996).

Rail-Wheel Interaction: Rail-wheel interaction is a very complex phenomenon. Repetitive wheel loads on the rail result in rolling contact fatigue (RCF). Rail wear occurs due to rail-wheel interaction and is more common on curves where maximum rail wheel shearing occurs (IHHA, 2001).

Million Gross Tonnes (MGT): All types of track degradation features, such as an increase in geometrical deviations and an increase in rail fractures and rail wear, can be expressed as a function of the tonnage, which is often expressed as Million Gross Tonnes (MGT). It is used to express the intensity or capacity of rail traffic on a specific line (Esveld, 2001).

Track Curvature: The optimal wear rate depends on the differences in the traffic type and density, axle load, rail metallurgy, and track curvature (IHHA, 2001). (For example, the rail degradation rate on a curve with a curve radius of 500 meters will be different from that on a curve with a 1200-meter curve radius).

Track Elevation: More traction force is required to overcome gravitational force when vehicles travel in an uphill direction. Limited lubrication is required to avoid slippage on uphill tracks causing more wear on this section of track.

Inspection Interval: More frequent ultrasonic inspection is required to manage/reduce the risk of internal defects (IHHA, 2001).

Superelevation: This is the difference in elevation between the two edges of the track; it allows vehicles traveling through the turn to go at higher speeds than would normally be possible. Superelevation helps to prevent overturning of the vehicle (IHHA, 2001). It is provided to overcome the centrifugal force of the vehicle at the curves. Degradation on either the high rail or low rail lying in the same curve radius depends on the speed of the vehicle. If the vehicle speed is higher than the designated speed limit of the curved track, considering the superelevation, more degradation will take place on the high rail. This is because the wheel flange is more in contact with the inner surface of the high rail than the inner surface of the low rail due to centrifugal force acting on the vehicle (see Paper II). If the vehicle speed is lower than the designated speed limit of the curved track, considering the superelevation, more degradation will take place on the low rail.

Operational Environment: Wear is highly dependent on third-body properties, which are strongly influenced by lubrication, environmental conditions (humidity, rain and snow), and the presence of sand. During winter in North America and Russia, there is more wheel shelling damage than in the summer time; this is evident because of an increase in track stiffness and thus the impact of track distortions on forces between the wheel and the rail (see IHHA, 2001). Another cause of this phenomenon is the influence of liquid. Water in the form of rain or melted snow considerably enhances the crack propagation rate due to the hydrostatic effect of liquid trapped in the crack (Bower and Johnson, 1991; Bogdanski *et al.*, 1997). The worst conditions occur when a dry period (when cracks are initiating) is followed by a wet period, when water enhances crack propagation. Dust and a corrosive environment accelerate rail wear. A high ambient temperature (greater than 25˚C) may cause the longitudinal expansion of rails, which may result in track buckling. This poses a serious risk of derailment (Zarembski *et al.*, 2005).

Rail-Wheel Material Type: The rail-wheel material plays a very important role in rail degradation. The mechanical properties of a pearlitic rail steel structure are governed by the distance between the cementite (Fe_3C) layers and the grain size. These are controlled by the cooling rate of the steel. The yield point and tensile strength are inversely proportional to the distance between the cementite layers and grain size. There are different types of heat-treated, alloyed or plain carbon steel rails being used around the world. Apart from the usual manufacturing process of the rails, the tensile strength and toughness are increased by heat treatment. Heat treatment is usually carried out on the rail head, turnouts and at the ends of non-welded rails to address the issue of maximum stress concentration (Esveld, 2001).

Rail Hardening: Rail hardening aims to reduce wear and to increase the resistance to RCF of rails in operation, particularly in tight and medium curves (Lichtberger, 2005). A head-hardened rail is a rail where only the rail head has been heat-treated to provide harder steel for locations of extreme service, such as curves (IHHA, 2001).

Inclusion of Residual Stress: Residual stresses can be built up in rails during the rail manufacturing process, during the rail welding process or as a result of contact stresses generated by the wheels rolling on the rails (Esveld, 2001). The maximum longitudinal and tensile residual stress in the rail foot, formed during rail manufacturing, should be less than 250 MPa (Cannon *et al.*, 2003). Residual stress formation can accelerate rail defect initiation and propagation.

Formation of Blowholes: Blowholes are possible defects formed during rail manufacturing. The presence of blowholes weakens the rail section causing further development of other types of defects. Today, new rails have to pass through several quality checks, including ultrasonic inspection, before their commissioning. Therefore, it is very rare to find blowholes or other manufacturing defects in rails.

Rail Size: The weight of the rail in kilograms per meter denotes the rail size (Esveld, 2001). Rails of different sizes will have different degradation rates.

Rail Profile: Many different rail profiles are in use. Different rail infrastructure owners use different standards for rail profiles. Different rail profiles are designed according to their operational requirements.

Track Construction: A track is constructed according to the requirements of the axle load, speed, required service lifetime, amount of maintenance to be done, operating conditions and availability of basic material (Esveld, 2001). For example, the condition of the sub-grade and soil properties should be analyzed during track construction.

Lubrication Frequency: Applying lubricant at the wheel/rail interface significantly reduces the wheel and rail wear, as well as dramatically decreasing the locomotive fuel consumption (Diamond and Wolf, 2002). Lubrication can be optimized for rails to effect a reduction in the flange wear so that maintenance resources are minimized and the rail/wheel life maximized (Wilson, 2006).

Rail Welding: Rail welding results in residual stresses that are distributed in a very complex manner with respect to their magnitude and direction. In many cases, these stresses are the cause of rail web failure. The use of improved welding technology and post-weld heat treatment considerably decreases the extent of weld-initiated residual stresses (IHHA, 2001).

Track Accessibility: Poor track accessibility leads to delayed maintenance, which causes more degradation.

3.2. Identification of the Factors Influencing Flowline Degradation

The degradation rate of a flowline can be affected by a number of factors. Under the continuous influence of these factors, different types of degradation can be observed in the flowline. Khan and Howard (2007) have classified the flowline degradation into uniform and non-uniform/localized degradation. A uniform corrosion is an example of the uniform degradation process. In uniform degradation, the material life is defined as the time taken for the material thickness to reach the minimum allowed thickness. Pitting, crevice corrosion and stress corrosion cracking are the best known examples of non-uniform degradation. In the case study described in Paper V, the degradation process mostly results in non-uniform loss of material, which is precisely measured as the maximum reduction in the thickness level at a point using non-destructive testing (NDT) techniques.

Adverse climatic conditions corrode the flowlines externally, whereas undesirable contents flowing in the flowlines corrode them internally. The potential for flowline failure caused either directly or indirectly by corrosion is perhaps the most familiar hazard associated with steel pipelines (Muhlbauer, 1996). Corrosion is an electrochemical process. It is a time-dependent mechanism and depends on the local environment within or adjacent to the pipeline (Cosham *et al.,* 2007). The flowline material plays an important role in withstanding the degrading conditions, both internally and externally. Flowline degradation takes place mainly due to stress generation, corrosion or erosion. A higher sand particle level can accelerate the erosion rate of the internal surface of the flowline. Erosion is the accelerated mechanical removal of surface material as a result of relative movement between, or impact from solids, liquids, vapor or any combination thereof. Erosion-corrosion is a description of the damage that occurs when corrosion contributes to erosion by removing protective films or scales, or by exposing the metal surface to further corrosion under the combined action of erosion and corrosion (API, 2003).

There are a number of factors which influence the flowline degradation process. Figure 5.5 illustrates the important identified factors influencing flowline degradation. The identification of the factors influencing flowline degradation is based on an extensive survey of the articles, reports and discussions and consultations with Aker Kvaerner personnel.

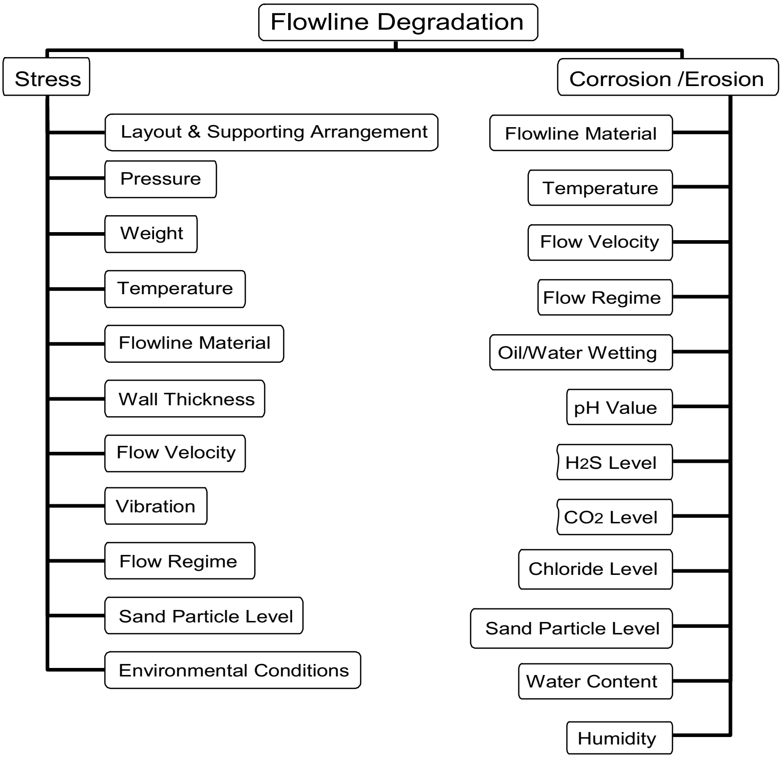

Figure 3.2: Factors influencing flowline degradation

The identified factors influencing flowline degradation are briefly described as follows:

<u>Layout and Supporting Arrangement:</u> The layout and supporting arrangement of the flowline plays an important role in pressure, temperature and stress distribution. Streamlining of bends reduces the impingement due to sand particles present in the well stream (API, 2003). Correct positioning of the supporting arrangement evenly distributes the weight of the flowline components, along with the well stream content, which reduces the stress on the flowline material.

<u>Pressure:</u> Flowline pressure is a critical factor inducing stress on the pipe walls. Some of the points on the flowline surface which have been weakened by corrosion or microscopic crack generation have a high risk of failure at high pressures. Pressure also exerts an effect on

chemical reactions, but in the oil production process its effect is greater on dissolved gases (Ayazi *et al.,* 2006).

Weight: When designing and fabricating the flowlines and their components, due consideration is given to their weight, which depends on the flowline material and the safety specifications. A flowline material more resistant to corrosion will require less wall thickness and, therefore, will be lighter than more corrosive flowline materials. An increase in the weight increases the requirement of supporting structures. Moreover the likeliness of an uneven stress distribution also increases.

Temperature: The operating temperature in the present case is defined as the temperature of the equipment under a steady-state operating condition, subjected to a normal variation in operating parameters (Norsok M-001, 2004). Variation in temperatures may cause thermal fatigue in the flowline material. A form of thermal fatigue cracking (thermal shock) can occur when high and non-uniform thermal stresses develop over a relatively short time in a piece of equipment due to differential expansion or contraction. If the thermal expansion/contraction is restrained, stresses above the yield strength of the material can result. Thermal shock usually occurs when a colder liquid contacts a warmer metal surface. Temperature changes can also result from water quenching as a result of rain (API, 2003).

Flowline Material: The flowline material is exposed to various chemicals, like H_2S, chlorides, acids, salts, CO_2, SO_2, etc., together with an air-water mixture, which acts as a perfect environment for corrosion and oxidation. Sand particles erode the flowline material internally. The erosion rate can be very fast, depending on the flow velocity and the sand particle level in the well stream. Besides, humidity and temperature also attack the flowline material. Currently duplex or carbon steel is used/recommended as the flowline material (Norsok M-001, 2004).

Wall Thickness: The initial/nominal wall thickness and the degradation rate affect the probability of the failure of the flowline. The wall thickness level decreases due to the degradation and aging of the flowline and other components attached to it. The initial wall thickness level is specified by various safety standards (for example ASME B31.32) based on the tolerance level.

Flow Velocity: The fluid flow velocity is another important parameter influencing the corrosion rate. Fluids with a low velocity cause a low corrosion rate. A high fluid velocity increases the rate of corrosion, especially with the presence of solid particles (Ayazi *et al.,* 2006).

Vibration: Different flow regimes of the well stream induce random shocks on the flowline material internally, whereas a high wind velocity and high sea waves induce external vibration on platform structures, causing mechanical fatigue in the components. Vibration-induced fatigue can be eliminated or reduced through design and the use of supports and vibration dampening equipment. Material upgrades are not usually a solution (API, 2003).

Flow Regime: For oil, water and gas mixtures, the most common regimes are bubble flow, slug flow and emulsion flow. In horizontal wells, there may be stratified or wavy stratified flow in addition to many of the regimes observed in vertical wells. The presence of air bubbles, cavitations or air gaps in the well stream induces random shocks generating stress on the pipe walls. This may lead to the development of microscopic cracks on the pipe walls. Cavitations can be prevented by streamlining the flow path (by decreasing the flow velocity) to reduce the turbulence (API, 2003).

Sand Particle Level: Sand particles form a part of the well stream content and are mainly responsible for erosion in flowline material. Erosion is the removal of pipe wall material caused by the abrasive or scouring effects of substances moving against the pipe wall (Muhlbauer, 1996). The size, shape, density and hardness of the impacting medium, along with the flow velocity of the well stream, affect the metal loss rate (API, 2003).

Environmental Conditions: Environmental conditions are those conditions which impact the pipe wall internally as well as externally. The marine environment is considered to be one of the most corrosive environments. Structural assessment should be performed by considering the worst case as the governing condition (Muhlbauer, 1996).

Oil/Water Wetting and Water Content: Internal corrosion of flowlines made from carbon steel is always associated with the presence of water, and the likelihood of corrosion generally increases with the volume fraction of water. Water wetting is one of most important factors in our current understanding of internal corrosion in oil and gas carbon steel pipelines. The findings of Tang *et al.* (2007) demonstrate that no corrosion occurs in the pipe wall when it is fully wetted by the oil, whereas intermittent wetting and full water wetting lead to significant corrosion, the latter being twice the rate of the former.

pH Value: pH is another influential factor in water corrosion. A low pH value is a sign of the existence of acidic agents, which increases the corrosion rate (Ayazi *et al.,* 2006). Stress corrosion cracking usually occurs at pH values above 2. At lower pH values, uniform corrosion generally predominates. The stress corrosion cracking tendency decreases toward the alkaline pH region (API, 2003).

H_2S level: Crude oils and other hydrocarbon streams contain sulfur at various concentrations. The corrosion of carbon steel and other alloys results from their reaction with sulfur compounds in high-temperature environments. Sulfidation is primarily caused by H_2S and other reactive sulfur species as a result of the thermal decomposition of sulfur compounds at high temperatures. The presence of hydrogen in H_2S streams increases the severity of high-temperature sulfide corrosion at temperatures above 260 $^{\circ}$C (API, 2003).

CO_2 Level: An increase in the carbon dioxide (CO_2) level in the well stream increases flowline corrosion. CO_2 corrosion results when CO_2 dissolves in water to form carbonic acid

(H_2CO_3). The acid may lower the pH level and sufficient quantities may promote general corrosion and/or pitting corrosion of carbon steel (API, 2003).

Chloride Level: Salts of crude oil include 85-90% sodium chloride and 10-15% magnesium or calcium chloride (Ayazi *et al.,* 2006). Chlorine species in the well stream form hydrogen chloride, which at low enough temperatures combines with the water vapor in the flowline to form hydrochloric acid, which can lead to severe corrosion (API, 2003).

Humidity: Moisture can be a primary ingredient of the corrosion process; higher air moisture content is usually more corrosive and attacks the external surface of the flowline material (Muhlbauer, 1996).

Apart from the factors discussed above, aging is also a significant contributor of flowline degradation. Aged components need to be constantly upgraded with new ones, as the probability of failure increases due to aging (see Paper V).

3.3. Virtual Failure State

Generally, gradual degradation in the form of material loss, an increase in crack or defect dimensions, etc. is observed in mechanical components due to aging. However, the process is sometimes accelerated due to the other factors discussed, causing, for example, excessive wear or erosion within a very short period of time, resulting in rapid material loss. A sudden accelerated degradation cannot be generalized, even for similar components operating under similar conditions. Figure 3.3 shows the degradation behavior in the form of thickness reduction (i.e. material loss) of similar flowline components. Each of these components shows a unique degradation behavior. However, all of them eventually proceed towards failure.

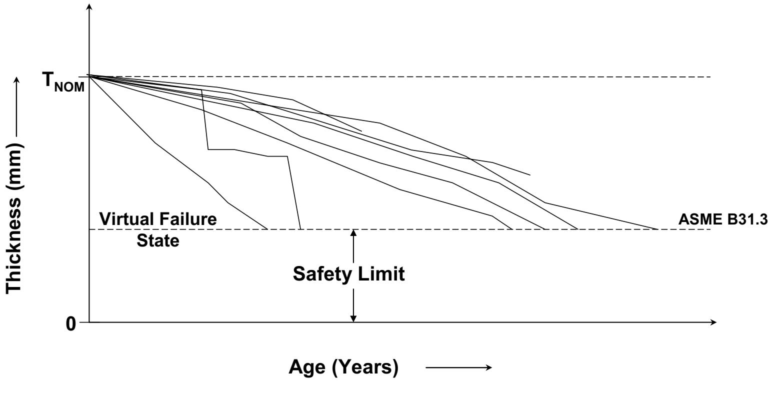

Fig. 3.3: Degradation in flowline components in the form of thickness reduction

In the case of safety-critical components, a failure may be extremely serious and unacceptable. Therefore, replacement or repair actions are taken long before the real failure state is reached. Performing reliability analysis based on failure data will be difficult as the occurrence of real failures in safety-critical components is very rare. In such a case, a component can be assumed to fail virtually when its degradation reaches a safety limit specified by a standard (for example, ASME B31.32). The failure state in this case may be called a “virtual failure state”. The concept of the virtual failure state has been used in Paper III (where different rail defect types defined by UIC Code-712 R (2002) are assumed as rail failures) and Paper V (where the flowline components are assumed to have failed when their thickness level progressively decreases to reach a safety limit defined by a standard ASME B31.32).

Chapter 4

4. RESEARCH METHODOLOGY

In this chapter some research options and methods are described briefly. The chosen research approach and methodologies for achieving the research objectives are discussed.

4.1. Introduction

Research is a way of thinking, critically examining the various aspects of our professional work, understanding and formulating the guiding principles that govern a particular procedure and developing and testing new theories for the enhancement of our practice/knowledge. In other words, research is a systematic examination of the observed information to find answers to the problems. Research methodology is the link between thinking and evidence (Sumser, 2000). It also refers to the way in which the problem is approached in order to find an answer to it (Taylor and Bogdan, 1984). Good research generates dependable data and information that are derived by professionally conducted practices and that can be used reliably for decision-making (Cooper and Schindler, 2006).

4.2. Research Purpose

There are three different ways of conducting research in terms of its purpose, viz. exploratory, descriptive and explanatory research.

- Exploratory research is useful when researchers lack a clear idea of the problems that they will meet during the research (Cooper and Schindler, 2006). Exploratory research rarely yields definitive answers (Neuman, 2003). It addresses the “what” question.
- Descriptive research is used when the knowledge level is moderate and it is possible to categorize the existing knowledge into models or approaches. The aim of this kind of research is to describe a few aspects either one by one or together in the area of interest by using more or less the same technique. Descriptive research focuses on “how” and “who” questions.
- Explanatory research is performed to examine and explain the existence of an observed pattern. This type of research is used to analyze the relationships and causes of a certain phenomenon (Sullivan, 2001). Explanatory research looks for causes and reasons (Neuman, 2003) and addresses the “why” question.

The chosen research methodologies in the thesis are exploratory and descriptive as the purpose of the research has been developed by exploring the different issues related to system/component reliability and its effect on maintenance decisions. The exploratory research helped in building up the knowledge required to choose and develop the three different case studies discussed in the thesis and identify the different factors influencing the degradation process in both rails and flowlines. The development of the approaches for rail failure prediction, parameter estimation and risk estimation is the result of descriptive research. We know that the performance of a system/component deteriorates with time due to the factors discussed in the previous chapters, but descriptive research is applied to show how it can be improved.

4.3. Research Approach

Research may be fundamental or applied in nature depending upon the knowledge about a certain area and the solution intended. Fundamental research aims to widen the knowledge of a particular subject so that future research initiatives can be based on it. It is research which is designed to solve problems of a theoretical nature with little direct impact on strategic decisions. Applied research addresses existing problems or opportunities (Cooper and Schindler, 2006).

This thesis is the documentation of applied research, the purpose of which is to study and analyze the performance of degrading systems/components using a reliability engineering approach and cost modeling techniques to support the maintenance decision-making process. The knowledge gathered from the extensive literature survey, discussions and consultations with maintenance experts from Banverket, JVTC, Queensland University of Technology, Brisbane, Australia and Aker Kvaerner, Norway was applied to meet the research objectives.

The research approach can be categorized into the deductive or the inductive approach (Sullivan, 2001).

- The deductive approach can be applied to generate hypotheses based on existing theories, the results of which are derived by logical conclusions.
- The inductive approach uses observations, the knowledge base and empirical data to explain and develop theories and establish relationships. The approach involves inferring something about a whole group or class of objects from our knowledge of one or a few members of that group or class.

The research approach can be quantitative or qualitative. In simple terms, quantitative research uses numbers, counts and measures of things, whereas qualitative research adopts questioning and verbal analysis (Sullivan, 2001).

In the present work, both deductive and inductive research approaches have been applied. The deductive approach is initially applied during the process of the literature review and to build up the theoretical frame of reference required for the research. Thereafter, the inductive approach is applied in the analysis, model development and validation phases (Figure 4.1). A model has been developed for component inspection frequency optimization and has been validated using empirically obtained data. Both quantitative and qualitative research methodologies have been applied in this research.

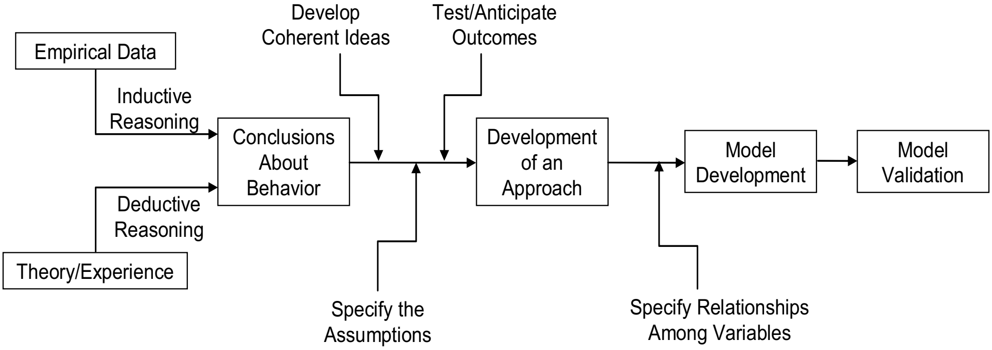

Figure 4.1: The process of model development and its validation [adopted from Cooper and Schindler (2006]

In the present context, it becomes essential to have a clear concept of a model. A model is defined as a representation of a system that is constructed to study some aspects of that system or the system as a whole. Models are important means of advancing theories and aiding decision makers (Cooper and Schindler, 2006).

4.4. Data Collection

In the present context data can be defined as the facts presented to the researcher from the study's environment. Data may be divided into primary and secondary types. The data collected by the researcher through various experiments or on-site data recording for the purpose of the study are called primary data. Primary data are sought for due to their proximity to the truth and control over error. Data collected by other people/organizations and used by the researcher are called secondary data. They have at least one level of interpretation inserted between the event and its recording (Cooper and Schindler, 2006).

An enormous amount of data is collected by various companies, but little use is made of this data. The maintenance personnel spend a great deal of time and money on data collection and report preparation, without being able to utilize the data for knowing the present or future condition (Steinebachh and Sørli, 1998). Analyzing these data to obtain meaningful information is a tedious job. At present, rail inspection data are interpreted by the experience of the technical people performing non-destructive testing and visual checks (Clark, 2003). The accuracy of the collected data depends on the skill level of the inspectors. The thesis discusses the improvement areas in Banverket's database management system, highlighting what to measure and record, and the reason behind it. Empirical data have been used in all the case studies described in the thesis. A framework has also been developed in Paper II for classification of rail failure data.

Different databases were searched to extract both qualitative and quantitative data. Relevant scientific papers and articles were extracted from online databases, such as Elsevier Science Direct, Blackwell Synergy, Emerald, IEEE Xplore, Proquest science journals, Inspec and Compendex, etc. Some of the articles were searched from the references of other relevant articles. Different keywords were used for searching these articles as mentioned in the abstract. Different combinations of these keywords were also used to narrow down the number of hits. Some of the known articles were searched directly from the journal databases. Technical journals like European Railway Review were also examined. Some of the railway and oil & gas accident investigation reports were also studied. Many times the required articles were not available in the library, and in such cases interlibrary loans were obtained. Relevant books were searched for in Lucia (Luleå University Library's online catalogue) and relevant reports and licentiate and PhD theses from various universities were also studied.

Empirical data were collected from three different companies for the case studies described in the thesis.

Rail degradation data were provided by Banverket (North Region), from its NDT car inspection reports, hand-held ultrasonic inspection reports, and an unpublished internal research report, for Malmbanan (the Swedish Iron Ore Line - Section 111) from Kiruna to Riksgränsen. The collected data were then verified with Banverket's centralized databases BIS, BESSY and 0felia.

BIS: This is Banverket's infrastructure register (computerized database) containing information about infrastructure or facilities, arranged geographically in accordance with Banverket's facility structure. In BIS, for example, information is collected prior to work on train timetables and before work in connection with inspections (Karlsson, 2005). Apart from this, information about agreements, accident reports, the history of tamping and grinding, curve-information can also be obtained.

BESSY: This is an inspection system in which comments are registered per facility on completion of inspection. Data are also registered directly during the course of inspection with the aid of a palm computer.

0felia: This is a database containing information on all the faults in the infrastructure that have been registered for a particular railway facility. The faults are sorted on the basis of the structure used in BIS (Karlsson, 2005).

Apart from the data collection and its verification with the above-mentioned databases, information was also collected through discussions and consultations with experts from Banverket and JVTC. On-site trips were also made to Malmbanan (the Iron Ore Line), Section 111, to gain a better understanding of the rail degradation process and the rail maintenance procedures followed. Some of Banverket's documents and reports were also studied to understand the different databases.

A survey was also performed to find out the severity of rail defects. Expert judgment was used as a qualitative assessment tool to find out the severity of different defect types which can develop into a rail break. The assessment by field experts was carried out based on a pairwise comparison technique. A pre-study was performed by sending the questionnaire to three experts individually, to obtain some suggestions for improvement. Thereafter, a suitable team of experts working at different positions in Banverket were invited to assess the (improved) questionnaire. When selecting the experts more stress was placed on the experience of the candidate. Eight experts were selected for judging the questionnaire, of whom only five were consistent enough throughout their judgment. The short list of these five experts was based on their consistency ratio (CR), as explained in Paper III.

Flowline degradation data were gathered from the different inspection databases of the oil & gas company. Inspection data measuring the reduction in the thickness level at different degraded points were classified according to their degradation behavior. These data were then transformed owing to their confidentiality. Transformed flowline degradation data and cost data were used to validate the developed inspection frequency optimization model. Similar to the rail inspection methodology, ultrasonic and visual inspection methods are used for detection of defects on offshore oil and gas structures. Details about the databases cannot be described in the thesis due to confidentiality issues.

For the case study based on the bearing manufacturing industry, one year’s failure and cost data were collected for the different components of the automatic internal grinding machine from the production report and log book. The time-to-repair (TTR) and time-to-failure (TTF) data were collected and analyzed to find out the causes behind failures.

4.5. Data Analysis

Data analysis is an important step in the research process which includes the aspects of examining, categorizing, tabulating, or recombining the evidence to address the propositions of a study (Yin, 2003). Data analysis usually involves the reduction of accumulated data to a manageable size, developing summaries, looking for patterns, and applying statistical techniques. Further, the researcher must interpret these findings in the light of the research questions or determine if the results are consistent with the hypotheses and theories (Cooper and Schindler, 2006).

In the present research, reliability analysis has been performed to know the technical condition of systems/components, predict their lives, estimate the risk and, based on these input parameters, decide upon the design alternatives or the maintenance actions required for assuring or improving their reliability. In practice, components are subjected to different design, manufacturing, maintenance and operating conditions and will fail at different time intervals in the future. Consequently, these failures obey a probability distribution which may, or may not be known and which describes the probability that a given component will either fail within a certain specified time or survive beyond that time (Billinton and Allan, 1983). Different probability distributions are used for failure analysis and prediction, but before using them, it is essential to conduct a formal verification that the failure data are independent and identically distributed (i.i.d.). In reliability prediction and analysis, failure data are usually based on the assumption that they are independent and identically distributed in the time domain. The details regarding the testing of the i.i.d. assumption have been described in the appended papers. It may not be appropriate to use classical statistical techniques if the failure data are not i.i.d. (Kumar and Klefsjö, 1992). Section 6.2.1 describes the effect of choosing an inappropriate distribution when performing reliability analysis.

In the thesis, an analysis of failure data for the best fitting distribution is also carried out. In most of the cases, Weibull distribution is the best fitting distribution. Weibull distribution is often used to represent the problems related to mechanical component aging, wear and degradation (Billinton and Allan, 1983). This is because Weibull distribution has a very important property: the distribution has no specific characteristic shape and depending upon the values of the parameters in its reliability functions, it can be shaped to represent many distributions (Billinton and Allan, 1983). The great adaptability of Weibull distribution results in accurate failure analysis and prediction. The slope or shape parameter β has an effect on the failure rate of a component. The value of β being less than one indicates the infant mortality stage, while β being equal to one means that the component has a constant failure rate (follows an exponential distribution). This stage is the normal operating or useful life of the component. If β is greater than one, it indicates the wear-out stage of the component. The scale parameter η is also known as the characteristic life of the component and is defined as the age at which 63.2 percent of the units will have failed (Abernethy, 2003).

4.6. Evaluation of Research Quality

The research quality can be evaluated in terms of the reliability of the procedures and data collection techniques adopted. A good explanation of the techniques and the procedures adopted improves the quality of the research performed.

4.6.1. Reliability and Validity

A reliable operation means that the procedures, when repeated in a very similar or identical manner, will give the same results. One condition for high reliability is that the methodology used for data collection is clearly described (Yin, 2003). Validity is concerned with whether or not the system/component actually produces or explains the intended information.

The data and information used in this research have been collected either from reputed peer reviewed journals, refereed conference proceedings and reports or from company databases, which positively contributes to the research's reliability. Well-established reliability analysis techniques have been applied through simple approaches in different case studies, which also contribute positively to the reliability of the research.

With regard to the validity of the present research, the analysis technique and the developed model have been validated by using real failure and cost data from industry. The model can be used for other degrading components under similar operating conditions. The obtained results are believed to support the validity of the research as they matched the theoretical and logical expectations.

Chapter 5

5. SUMMARY OF APPENDED PAPERS

This chapter includes an extended summary of the papers appended to the thesis. The followed approaches, the results and the conclusions of the appended papers are summarized in this chapter. For detailed information the reader is referred to the appended papers. The following five papers are appended in full to the thesis.

Paper I: Kumar, S., Espling, U. and Kumar, U. (2007). A holistic procedure for rail maintenance in Sweden. *Accepted for publication in Journal of Rail and Rapid Transit: Proceedings of the Institution of Mechanical Engineers, Part F.*

Paper II: Chattopadhyay, G. and Kumar, S. (2008). Parameter estimation for rail degradation model. *Accepted for publication in International Journal of Performability Engineering.*

Paper III: Kumar, S., Gupta, S. and Ghodrati, B. (2007). Rail defect prioritization and risk assessment using a hybrid approach. *Submitted to an International Journal.*

Paper IV: Kumar, S., Chattopadhyay, G. and Kumar, U. (2007). Reliability improvement through alternative designs: a case study. *Reliability Engineering and System Safety,* 92(7), 983-991.

Paper V: Kumar, S., Dandotiya, R., Kumar, R. and Kumar, U. (2008). Inspection frequency optimization model for degrading flowlines on an offshore platform**.** *Accepted for publication in the International Journal of Reliability, Quality and Safety Engineering.*

5.1. Paper I: A Holistic Procedure for Rail Maintenance in Sweden

The paper describes a procedure for collection, classification and analysis of rail failure data so that rail maintenance can be performed effectively. There is a need for describing an effective rail maintenance procedure considering the factors influencing the rail degradation process, so that the risk of rail breakage and the inspection cost can be reduced. A number of factors which influence the rail degradation process have been identified in the paper. A detailed description of these factors can be found in Section 3.1. The current rail maintenance and reporting procedure followed by Banverket for the Swedish Iron Ore Line is also described. The necessary data required to perform the analysis and prediction of failures are discussed, along with the improvement areas in Banverket's database management system.

The objective of this paper is to help the infrastructure managers to understand better the existing rail maintenance procedure, and the improvements which can be incorporated in the existing procedure to make it more effective.

In order to predict rail failures considering most of the factors influencing rail degradation, it is essential to develop a well-defined procedure. The procedure should be explained to the contractor so that he/she knows what to collect/record and the reason for this. The procedure can be briefly described in the following steps (the details of each step are described in the paper).

Step 1: Identify the different factors influencing the rail degradation process.

Step 2: Collect and classify the rail failure data depending on the conditions under which the failure occurred and the factors which played a dominant role in causing that failure. In the case of a deficiency of field data, modeling of the actual conditions followed by simulation can be carried out to generate data.

Step 3: Perform a trend test followed by a serial correlation test to verify if the data are independent and identically distributed (i.i.d.), once an appreciable data sample size under a particular category is available

Step 4: Predict the failures and estimate the component life using the most suitable failure distribution.

Step 5: Allocate a maintenance budget during the decision-making process based on an analysis and interpretation of the results.

The procedure of analyzing and predicting the rail failures is demonstrated using real data for the frequently occurring defects on the rail section under study (section 111, the Iron Ore Line) to estimate the probability of failures at different intervals of time (i.e. at different tonnage accumulation) for the failure data sets of each of the considered defect types.

Data provide valuable information which delivers knowledge. Knowledge of the rail degradation and defect formation process can help the infrastructure managers to understand the kind of information required under specific conditions.

5.2. Paper II: Parameter Estimation for Rail Degradation Model

Wear and fatigue in rails are the major contributors of rail degradation depending on the operational conditions, the track, the characteristics of the bogie type, Million Gross Tonnes (MGT), curvature, traffic type and environmental conditions. The estimation of parameters for failure models is necessary for the accurate prediction of the expected number of rail defects over a period of time based on the MGT of traffic and the operating conditions, in order to develop cost-effective maintenance strategies.

This paper focuses on the collection and analysis of field data over a period of time for the estimation of parameters for predicting rail life. The parameters of the failure models are estimated using real-life data. Failure data have been collected from Banverket's different databases as discussed in Chapter 4. Failure modeling is defined by the probability distributions and performed by applying a stochastic approach. A framework for the classification of rail failure data is developed and trend and serial correlation tests are carried out to justify the analysis procedure.

As ageing in rails takes place due to tonnage accumulation on the track resulting from traffic movement, rail break data analysis is based on the MGT of traffic flow. As per Banverket's inspection and failure databases, rail replacements and ageing are estimated by assuming 25 MGT per year of traffic flow on the Swedish Iron Ore Line (Malmbanan). The age of rail segments having a rail break is calculated by multiplying the annual MGT of traffic flow with the difference between the year when a rail break is detected in the rail segment and the year when it was last replaced.

The estimation of parameters for failure models is necessary for accurate prediction of the expected number of rail defects over a period of time based on the MGT of traffic and the operating conditions, in order to develop cost-effective maintenance strategies. The estimated parameters could be useful when allocating the maintenance budget for different activities such as rail inspection, grinding, rectification and replacement, and planning maintenance actions based on the technical condition of the various rail segments in the track network.

5.3. Paper III: Rail Defect Prioritization and Risk Assessment Using a Hybrid Approach

Increasing demands on passenger and freight transportation have increased the axle loads and traffic density, which has caused rail defects to appear in a greater variety and with a greater frequency. Many of these rail defects, if left undetected, can develop into rail breaks which may lead to train derailments. In order to reduce the number of such catastrophic events, huge investments are made to inspect and maintain the rails. Proper maintenance planning and risk assessment are required to reduce the maintenance cost of the rails. Frequent rail inspection intervals and rectifications (rail maintenance actions) require huge investments. Therefore, in this paper, a methodology for rail defect prioritization and risk assessment is developed to support the decision-making process during the effective scheduling of the inspection frequency based on the type of defect and its risk of development into a rail break. Fault tree analysis has been used in the paper to identify logically the possible causes of a train accident.

The possible causes of rail defect initiation and propagation include rolling contact fatigue (RCF), shear stress, wear, ratcheting and weld problems, which depend upon the different factors influencing the rail degradation process. These causes initiate a variety of defects in rails, such as surface/subsurface cracks, head checks, squats, spalling, shelling, etc. As these defects are considered as part of an ongoing degradation process, their probability of occurrence can be modeled if their state of degradation can be clearly defined. The UIC rail defect classification standard (UIC Code-712 R) divides the different types of rail defects up into different degradation states based on their location and propagation characteristics and assigns them a defect code. In this paper, the different defect types which are assigned defect codes are considered as failure states.

The paper presents the methodology with the aid of a case study from Banverket. Empirical data related to the defect type, age and frequency have been extracted from Banverket's inspection and failure reports. Qualitative assessment of the severity of different types of defects is carried out according to their likeliness to develop into a rail break based on expert judgment using a paired comparison technique. This technique is used for estimation of severity, because the severity of a defect depends on a number of influencing factors for which the data are difficult to obtain. As both a quantitative and a qualitative analysis technique has been used in this paper, the developed methodology is considered as a hybrid approach.

In order to calculate the risk of the occurrence of a rail defect and its development into a rail break, the probability of occurrence of failure and the severity of each of the defect types need to be calculated. The first part (i.e. the probability of occurrence of failure) is calculated from the data extracted from Banverket's ultrasonic car inspection reports, hand-held ultrasonic equipment inspection reports and visual inspection reports on section 111 (the Iron Ore Line from Kiruna to Riksgränsen in Sweden). The line allows a 30-tonne axle load with mixed traffic.

Expert judgment is used as a qualitative assessment tool to find out the second part (i.e. the severity of different defect types which can develop into a rail break). The assessment by field experts is performed based on a pairwise comparison technique. The severity of a defect type depends on a large number of factors influencing the initiation and propagation of a defect. It is difficult to calculate the severity of a defect quantitatively, as to do so, one would have to know the extent of the effect (i.e. percentage of contribution) of each of these factors influencing a rail defect. Many of these factors are subjective in nature and it is difficult to model their influencing function. However, it is easier to compare the relative importance between two factors, as is done in the pairwise comparison approach.

The methodology will help in reducing the overall rail maintenance cost, as it helps in making effective decisions related to the inspection frequency (i.e. resource allocation according to the need). However, the minimal inspections required should always be performed, as the deductions of the paper are purely probabilistic in nature. The grinding campaigns can also be scheduled according to the inspection frequencies of different defect types. Furthermore, more detailed analysis is required to look into the cost aspects of inspection and grinding intervals for making optimal decisions. Risk assessment of rail defects can provide cost-effective options for the infrastructure managers for scheduling inspection, grinding, lubrication and replacement intervals.

5.4. Paper IV: Reliability Improvement through Alternative Designs: A Case Study

In today's competitive world, the reliability of equipment is extremely important to maintain quality and delivery deadlines. Reliability is assured by using proper maintenance and design changes for unreliable subsystems and components of a complex system. It is important to develop a strategy for maintenance, replacement and design changes related to those subsystems and components. An analysis of the down-time, along with its causes, is essential to identify the unreliable components and subsystems.

Downtime often leads to both tangible and intangible losses. These losses may be due to some unreliable subsystems/components, and therefore an effective strategy for maintenance, replacement or design changes related to those subsystems and components needs to be framed out. The paper describes the reliability improvement of systems by looking into alternative designs of components based on failure and repair data and cost-benefit analysis. A case study in the manufacturing industry was carried out to meet the objective of the paper. The paper presents an analysis of failure data for the solenoid coils of an automatic internal grinding machine used in a bearing manufacturing plant. It analyses various replacement and design change options during the operation phase, such as the introduction of a pneumatic system in place of electromagnetic solenoids for the assurance/improvement of the reliability of the plunger movement mechanism.

There was a problem of excessive downtime for an automatic internal grinding machine in a bearing manufacturing plant (NRB Bearings Ltd, India). The machine is used for internal grinding of the outer rings of the bearing. The research was carried out to analyze the downtime, find out the main cause and locate the critical components based on their frequency of failure, develop models to predict the reliability of the system and the expected costs associated with the current unreliable components, explore the design options available and estimate the cost benefit by considering the design change.

One year’s data from the production report were collected and analyzed to carry out a Pareto analysis of the causes behind failures. The expected number of failures of the most critical component (the plunger movement mechanism) was calculated based on a renewal integral model. A system approach was used to identify the root cause and find out alternative technical solutions to improve the reliability of the system. An overall annual cost assessment of the plunger movement mechanism was carried out, considering the component cost, replacement cost, cost incurred due to the loss in production and the annual rework and reject cost. A framework was developed for evaluation of the failure modes and improvement of the reliability by appropriate design modifications, and the expected overall annual cost was calculated for the newly implemented best design option (i.e. a pneumatic system). Cost-benefit analysis helped to access the effectiveness of the new design. An estimate could then be established for the annual loss the company could have had if the design change based on the reliability analysis had not been recommended.

On substitution of values in the cost model for the pneumatic cylinder arrangement, the expected overall cost of failure due to the pneumatic cylinder arrangement per year is INR 25,578. Comparing the overall cost before and after the design change, it is evident that the design option is far better than its predecessor. Therefore, by looking into design change options for the critical component the company saved INR (1,467,925 - 25,578) = INR 1,442,347 annually, which is approximately equal to US$ 33,100. The reliability and cost-benefit analysis helped the company to reduce the cost due to the unreliable components.

5.5. Paper V: Inspection Frequency Optimization Model for Degrading Flowlines on an Offshore Platform

Many offshore oil and gas installations in the North Sea are approaching the end of their designed lifetimes. Technological improvements and higher oil prices have developed favorable conditions for more oil recovery from these existing installations. However, in most cases, an extended oil production period does not justify investment in new installations. Therefore cost-effective maintenance of the existing platform infrastructure is becoming very important.

The paper is based on developing a model for optimization of the inspection frequency by analyzing the reliability of components having similar degradation behavior. A case study on an offshore oil and gas platform in the North Sea has been performed to optimize the flowline inspection frequency. Transformed flowline degradation data have been used to validate the model owing to the confidentiality of the data. Matlab software has been used to reduce the complexity in solving the model.

Flowlines are one of the most critical piping components on the production facility and demand a major share of the maintenance time to assure their reliability. The use of reliability analysis to optimize inspection intervals for flowlines is not common in the oil and gas sector, largely because it requires specialist knowledge. However, simple maintenance optimization models can be developed to provide engineering solutions to real industrial problems, although some sophistication will always be there when dealing with complex systems.

The model is based on the simple concept of minimization of the total maintenance cost of the component using optimization technique. An objective function is formulated for the total maintenance cost, subjected to various constraints. In this technique, the objective function is iterated for various feasible solutions of the preventive maintenance time in order to determine the optimum solution. The Matlab codes required to generate optimal solutions are given in Appendix A in the thesis.

The model has been validated by a case study performed on flowlines installed on the top side of an offshore oil and gas platform in the North Sea. Reliability analysis has been carried out to arrive at the best inspection frequency for the flowline segments under study.

The model can be used effectively by inspection and maintenance personnel in the industry to estimate the number of inspections/optimum preventive maintenance time required for a degrading component at any age or interval in its lifecycle, which will help in decision making when planning future inspection and maintenance intervals for different components.

Chapter 6

6. DISCUSSION AND CONCLUSIONS

This chapter summarizes the findings of the thesis. The findings are related to the stated research questions. Some aspects of the findings are discussed. Furthermore, the conclusions and the contributions of the research are discussed. Finally, some suggestions for further research are also presented.

6.1. Discussion

The study emphasizes the need to carry out reliability analysis and cost modeling in order to assure or improve the performance of systems/components. Paper I gives an overview of the reliability-based analysis procedure. Figure 6.1 describes the suggested concept of a reliability-based analysis procedure.

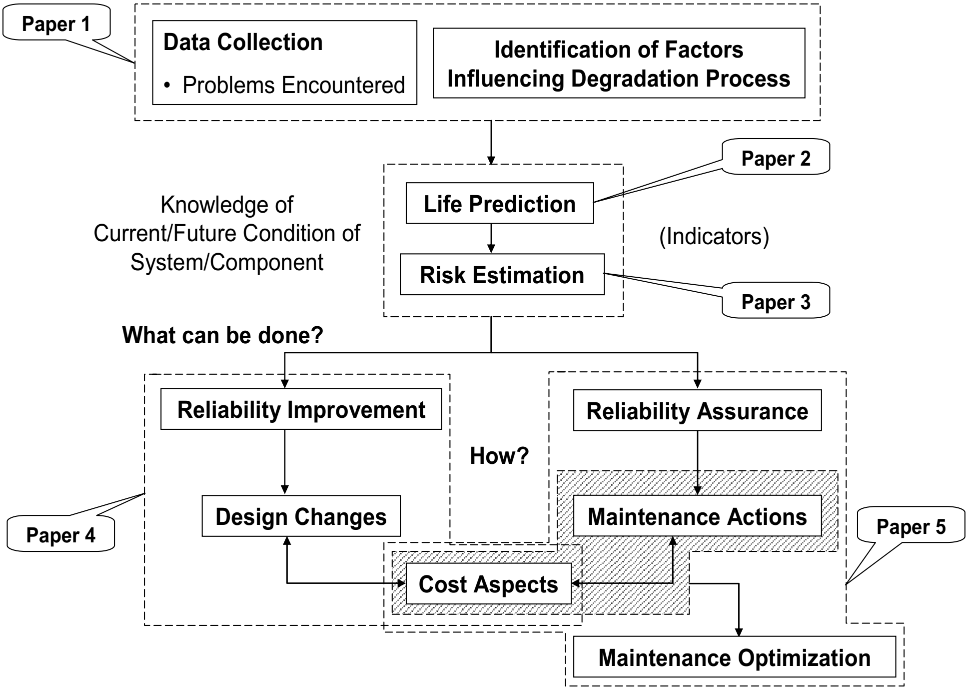

Figure 6.1: An approach to reliability-based analysis of degrading systems

The initial steps of the procedure (as discussed in Chapter 5 and Paper I) are collection and classification of the degradation and failure data depending on the conditions under which the failure occurred and the factors which played a dominant role in causing that failure. The factors influencing the degradation of both rails and pipeline structures are identified and discussed in Chapter 3. The problems encountered in the process of data collection and classification has been discussed (see Paper I). After the data have been classified (for example, according to the classification framework developed for the rail failure data in Paper II), they have to be analyzed for life prediction and risk estimation of systems/components. The first step during the data analysis is the trend and correlation test, which should be performed so that the assumption of independent and identical distribution is not contradicted for the data sets being analyzed. It is also very important to distinguish between repairable and non-repairable systems/components when carrying out reliability analysis. Often the same reliability analysis procedures are performed on both repairable and non-repairable systems, which may lead to an incorrect model assumption. The effects of a wrong failure distribution assumption are discussed in Section 6.2.1.

A case study on rail life prediction and risk estimation has been developed and the reliability-based analysis procedure has been described in detail in Paper II and III. By analyzing the degradation and failure data, knowledge of the current and future technical condition of the system/component is obtained. However, the question arises of what should be done in order to assure/improve the performance of the system. A reliable system can assure/improve the system performance. Paper IV describes a case study in a manufacturing company demonstrating the assurance or improvement of the reliability of a system through alternative designs of the components which are more susceptible to failures based on failure & repair data and reliability & cost-benefit analysis.

However, many times it is not possible to implement design changes due to system complexities, the designed life of the assets and cost considerations, especially in the case of infrastructural components. In such situations operational reliability can be assured through effective maintenance actions. By developing maintenance optimization models, optimized values of different maintenance criteria can be quantitatively assessed. A maintenance optimization model can be defined as a mathematical model in which both costs and benefits of maintenance are quantified and an optimum balance between both is obtained (Dekker, 1996). An optimization model for inspection frequency has been developed in Paper V which demonstrates the optimum inspection frequency required to assure component reliability and safety at a minimum maintenance cost. A case study of an offshore oil and gas infrastructure has been developed to validate the model.

6.2. Optimization Model for Inspection Frequency

The optimization model is developed to minimize the total maintenance cost of the component. In the model, the objective function is iterated for various feasible solutions for the preventive maintenance time to determine the optimum inspection frequency at a minimum cost.

An objective function for the total maintenance cost is developed which is the sum of the total preventive, corrective and fixed maintenance cost, as shown in Eq. (6.1).

Total maintenance cost of the component = [Total preventive maintenance cost + Total corrective maintenance cost + Total fixed maintenance cost] × $1/(1+i)^t$

$$C^{Total}(t) = \left[\left\{C^{PM} \cdot Mh^{PM} \cdot p(t)\right\} + \left\{C^{CM} \cdot Mh^{CM} \cdot \lambda(t) \cdot t\right\} + \left\{C^{FX} \cdot Mh^{FX} \cdot t\right\}\right] \times \frac{1}{(1+i)^t} \tag{6.1}$$

where,

$C^{Total}(t)$	Total maintenance cost of the component at time *t*
C^{PM}	Preventive maintenance cost of the component
Mh^{PM}	Preventive maintenance time (*man hours*) for the component at time *t*
$p(t)$	Failure probability of component at time *t*
C^{CM}	Corrective maintenance cost of the component
Mh^{CM}	Corrective maintenance time (*man hours*) for the component at time *t*
$\lambda(t)$	Failure rate of the component at time *t*
t	Age of the component
C^{FX}	Fixed maintenance cost of the component
Mh^{FX}	Fixed maintenance time (*man hours*) for the component at time *t*
i	Discount rate

***The unit of all cost elements is given in Norwegian Kroner (NOK) per hour*

The probability of failure $p(t)$ and the failure rate $\lambda(t)$ of the component depend on the degradation behavior of the component group. Each component group follows an appropriate failure probability distribution. It may not be appropriate to use the classical statistical distribution models if the failure data are not independent and identically distributed (i.i.d.).

6.2.1. Effect of Assuming Wrong Distribution for Representing Failures in the Model

The choice of an appropriate reliability-based prediction model is essential for achieving the correct and most probable results (Kumar and Klefsjö, 1992). A trend and serial correlation test should be performed for chronologically ordered failure data so that the assumption of independent and identical distribution (i.i.d.) is not contradicted. If the i.i.d. assumption is contradicted, non-stationary models such as non-homogeneous Poisson process (NHPP) must be fitted, for example the power law process (see for details Ascher and Feingold, 1984; Ascher and Hansen, 1998; Kumar and Klefsjö, 1992; see also Figure 3, Paper III). It is also important to distinguish between repairable and non-repairable systems/components when carrying out reliability analysis. A repairable system, as the name implies, is a system which can be restored to an operating condition in the event of a failure. The restoration involves any manual or automated action that falls short of replacing the entire system (Trindade and Nathan, 2008). A non-repairable system, on the other hand, is regarded as one which is replaced completely by a new one after failure. Many times the same reliability analysis procedures are performed on both repairable and non-repairable systems. Non-repairable failure data are independent and identically distributed. However, this assumption may not be true in many cases for repairable systems' failure data and may lead to incorrect conclusions being drawn from the analysis (Kumar, 1996). Furthermore, the assumption of the component state remaining in an *as-bad-as-old* condition or improving to an *as-good-as-new* condition should be based on the practical and realistic condition of the component after every repair. When making such assumptions, due consideration should be given to the time taken for maintenance and repair actions in comparison with the whole life time of the component (see, for details, Rigdon and Basu, 2000). The issue is further described in Appended Paper III with the help of a case study on the railway infrastructure.

The effects of the wrong failure distribution being used are described with an example based on actual failure data. Trend and serial correlation tests were performed and the failure data were found to be independent and identically distributed. The details of the test procedure can be found in Papers II, III and V. A comparison is made between the probability density functions of the best-fitting distribution (3-parameter Weibull distribution) and the second best-fitting distribution (lognormal distribution). The best-fit test was carried out using ReliaSoft's Weibull++6 software (ReliaSoft, 2003). Figure 6.2 shows the plots of both distributions. The figure also shows the areas overestimated and underestimated by the lognormal distribution in comparison with the area covered by the 3-parameter Weibull distribution. The overestimated areas imply that, if the lognormal distribution is used instead of the 3-parameter Weibull distribution, over-maintenance will be performed proportional to the overestimated area, which will result in an increase in the maintenance cost. The underestimated area implies negligence of maintenance, which increases the risk of failures.

Furthermore, the probability density function of the 3-parameter Weibull distribution was compared with that of the 2-parameter Weibull distribution and the negative exponential distribution which were the fifth and sixth best-fitting distributions, as shown in Figures 6.3 and 6.4 respectively. A trend showing an increase in the overestimated and underestimated areas was observed. This implies that the further we recede from the best-fitting distribution, the greater will be the risk of failure and an increase in the maintenance cost. Thus it is concluded that an inappropriate model assumption may lead to completely wrong conclusions.

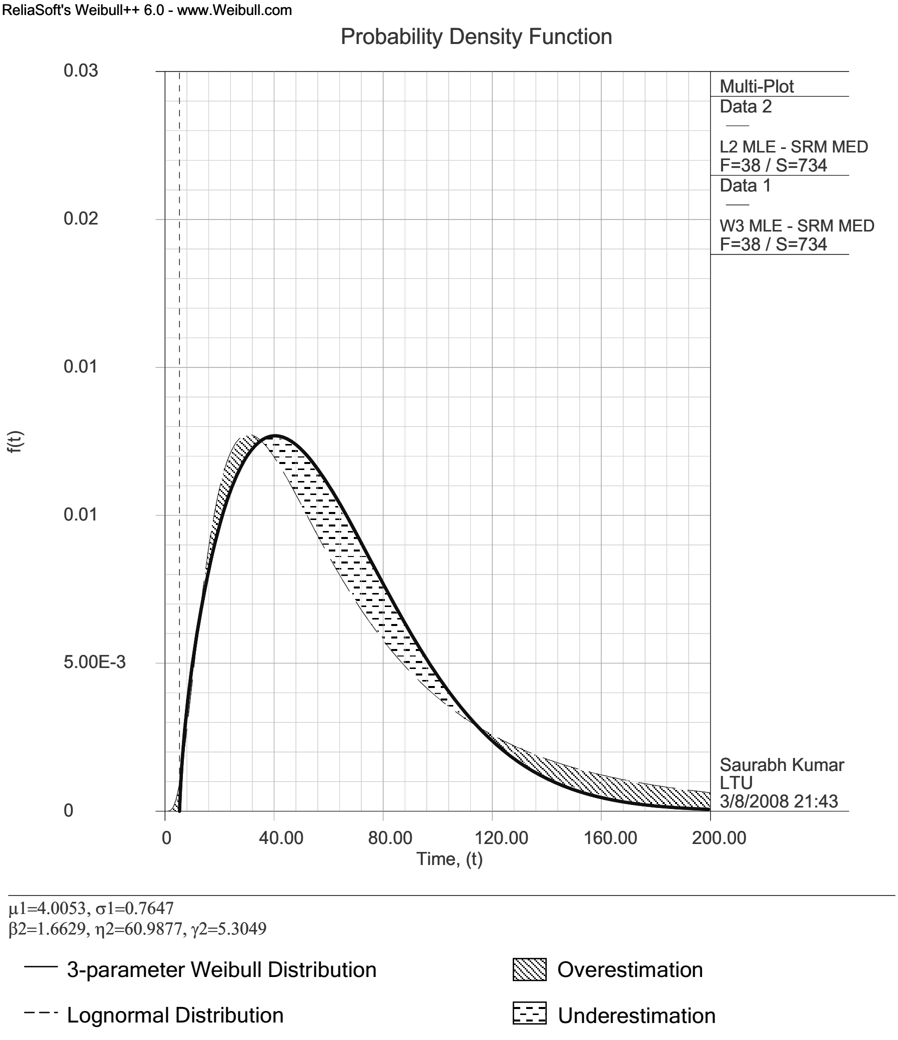

Figure 6.2: Comparison between probability distribution functions of 3-parameter Weibull distribution and lognormal distribution for the same data set

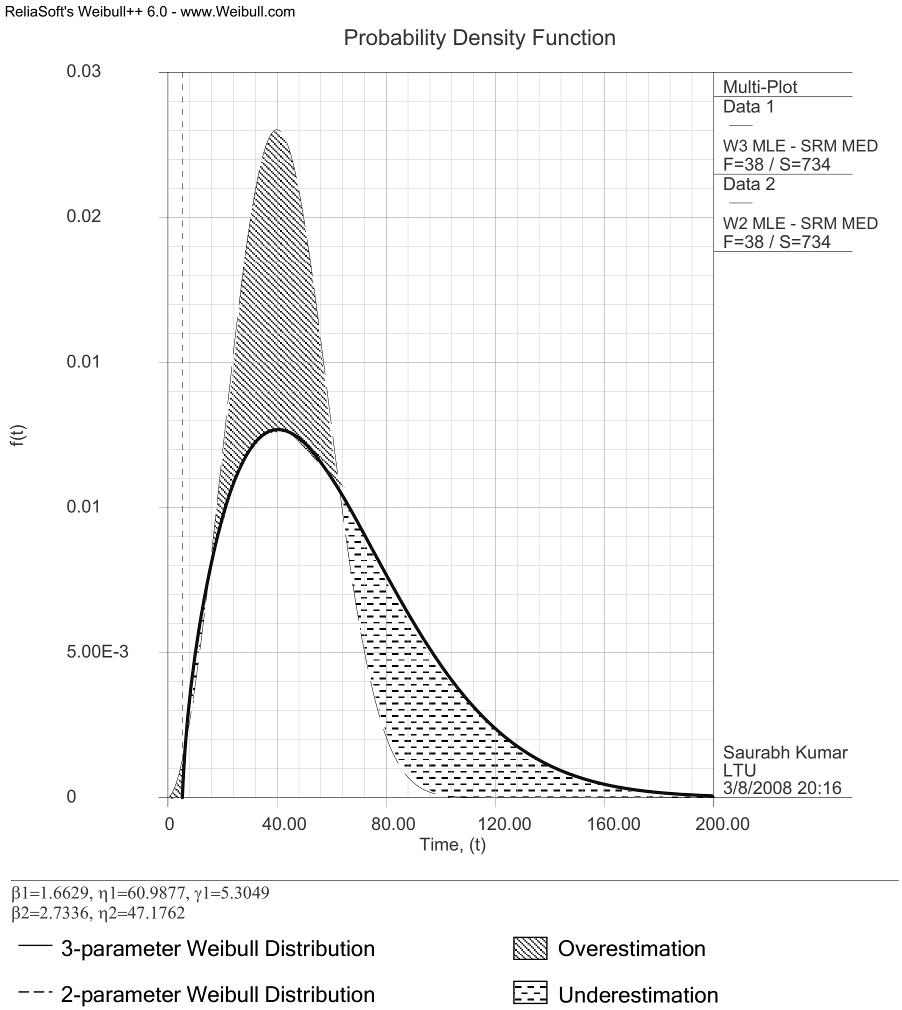

Figure 6.3: Comparison between probability distribution functions of 3-parameter Weibull distribution and 2-parameter Weibull distribution for the same data set

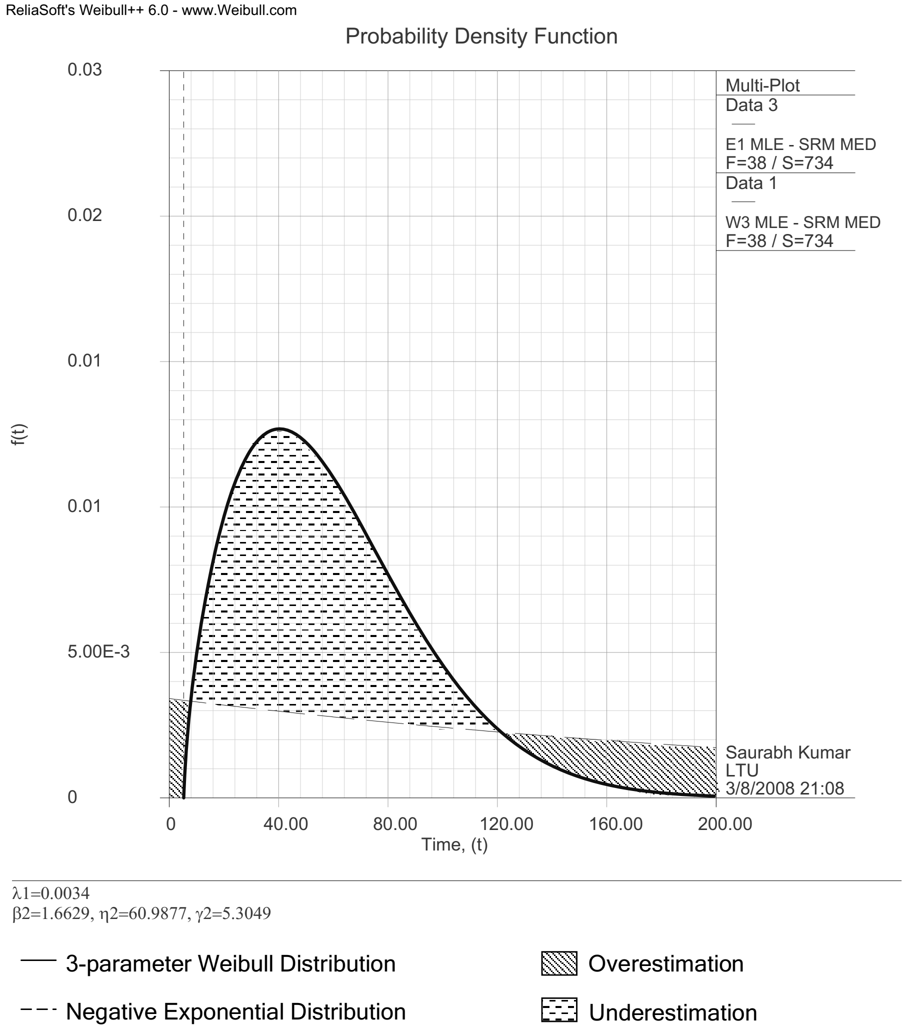

Figure 6.4: Comparison between probability distribution functions of 3-parameter Weibull distribution and negative exponential distribution for the same data set

6.3. Conclusions

Knowledge of the technical condition of systems/components is vital for making effective decisions regarding maintenance actions or alternative design options in the operation and maintenance phase to assure or improve their performance. Reliability analysis helps in identification of the technical condition of the system/component. Cost modeling provides a basis for maintenance optimization or alternative design selection considering the safety issues as well. The thesis has dealt with three different case studies, related to railway infrastructure, offshore oil & gas platform infrastructure and a bearing manufacturing company describing case-specific approaches based on reliability analysis and cost modeling.

In relation to the first research objective and the first research question of the thesis, the factors influencing rail and flowline degradation have been identified in Paper I and described in Chapter 3. Thereafter, a rail failure data classification framework was developed in Paper II based on the different factors influencing the rail degradation process. Therefore, the second research objective has been fulfilled by developing this classification framework. This framework with suitable modifications can be equally useful for failure data classification in other industries. Reliability analysis was then performed using the rail failure data classified according to the developed framework to predict the present condition and the remaining useful life of the components (see Paper II).

Risk assessment of rail defects can provide cost-effective options for the infrastructure managers for scheduling inspection, grinding, lubrication and replacement intervals. Risk assessment of the rail defects not only requires the failure probability, but also the severity or the consequence of the failure. The third research question (i.e., How can integration of reliability analysis based on failure data and expert judgment be used to estimate the system risk?) has been discussed in Paper III and the integration of reliability analysis and expert judgment has been described using field failure data for the estimation of system risk. A methodology for rail defect prioritization and risk assessment to support the decision-making process during the effective scheduling of the inspection and grinding frequency, based on the type of defect and its risk of occurring and developing into a rail break, has been developed in Paper III.

In Paper IV, root cause analysis of a system helped in finding out a defective component which was the cause of excessive downtime of the system, leading to production loss and quality problems. The application of reliability theories and the development of cost-benefit models for various alternative maintenance and design options lead to improvement of the system reliability. The approach combined reliability and cost analysis and technological decisions based on design changes to improve the performance of the system analyzed in the case study. This has partially answered the second research question (i.e. How can the performance of a degrading system be improved/assured using reliability analysis techniques?).

Many times it is not possible to implement design changes due to complexities and cost considerations, for example in the case of oil platforms or railway infrastructures, etc. In such situations operational reliability is assured through effective maintenance actions. This has been demonstrated in Papers II, III, and V with the case studies answering the second research question fully.

An optimization model for the inspection frequency/preventive maintenance time has also been developed and validated by a case study of an offshore oil and gas platform in Paper V fulfilling the third objective of the research and answering the fourth research question. The model can be used effectively by inspection and maintenance personnel in the industry to estimate the number of inspections/optimum preventive maintenance time required for a degrading component at any age or interval in its lifecycle, which will help in decision making when planning future inspection and maintenance intervals for different components. The developed model can be applied to other industries with suitable modifications.

6.4. Research Contribution

The research contributions, in short, can be described as:

- A detailed study of factors influencing the degradation process is presented (see Chapter 3 and Paper I).
- Development of a framework for classification of rail degradation and failure data and prediction of the remaining useful life of the system/component using reliability analysis techniques (Paper II).
- Development of a methodology for rail defect prioritization and risk estimation to support the decision-making process (Paper III).
- Demonstrating an improvement in system reliability through design change alternatives in the operational phase (Paper IV).
- Development of an optimization model for the inspection frequency/preventive maintenance time for effective decision-making (Paper V). The new concept of the virtual failure state is suggested in Chapter 3 and used in optimization model analysis.

6.5. Scope for Further Research

In this study, a number of factors influencing the degradation process have been identified. However, some of them could not be included in the classification framework, as relevant data and information regarding these factors were not available in the databases, because it is not easy to measure and record some of these factors. For collecting relevant information and data, adequate measurement tools and techniques need to be developed. Further research is needed to understand the combined effect of the influencing factors on the degradation process of the systems or components.

The inspection frequency optimization model has been developed for single components in this study. There is also scope for developing a multi-component optimization model for offshore oil and gas platform infrastructure. To achieve this, the relationship between the degradation behaviors of different component groups needs to be established.

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APPENDIX A

Matlab Code

```
%   OBJECTIVE FUNCTION FILE

% Failure probablity of the component = P
% P = 1-(exp(-((t/eta)^beta)))
% Manhours required for preventive maintenance of the component = Mh
% Manhours required for corrective maintenance of the component = Mh(CM)
% Manhours required for fixed maintenance of the component = Mh(FX)= 1 Hour
% (Considering a component consists a minimum of two maintenance points)

% Age of the component in years = t
% Discount Rate = i = 0.06

% Constraint on manhour required for maintenance of the component = Mh > 0
% Constraint on preventive maintenance cost component = C_PM > 0
% Constraint on corrective maintenance cost component = C_CM > 0

% (OBJECTIVE FUNCTION) f = [C_pm * Mh * P] +
% [C_cm * Mh(CM) * lamda(t)* % t] +
% [C_fx * Mh(FX) * t];

% ALL COSTS ARE IN NOK

% Preventive maintenance cost = C_pm
% C_pm = 0.3*C_R_PM + 0.1*C_Sc_PM + 0.6*C_I_PM

% Preventive maintenance (Replacement) cost = C_R_PM
% Preventive maintenance (Scaffolding) cost = C_Sc_PM
% Preventive maintenance (Inspection) cost = C_I_PM
% C_R_PM = (Fabrication Cost= Material Cost+Logistics Cost)+(Labour
%          Cost(Welding)+Testing Cost)+ Downtime Cost

% C_pm = 0.3*(15000+600+100000) + 0.1*500 + 0.6*500

% Corrective maintenance cost = C_cm
% C_cm = C_R_CM = Corrective maintenance (Replacement) cost
%               =(Fabrication Cost= Material Cost+Logistics Cost)+(Labour
%                 Cost(Welding)+Testing Cost)+ Downtime Cost
%               = 20000+700+100000

% Mh(CM) = 9.5577*(Mh^(-0.5391))
% Failure rate at time t= lamda(t)= (beta*(t^(beta-1))/(eta^beta)

% Fixed maintenance cost = C_fx

% C_fx = 0.3*C_R_FX + 0.1*C_Sc_FX + 0.6*C_I_FX

% Fixed maintenance (Replacement) cost = C_R_FX
% C_R_FX = (Fabrication Cost= Material Cost+Logistics Cost)+(Labour
%    Cost(Welding)+Testing Cost)+ Downtime Cost

% C_fx = 0.3*(15000+600+100000) + (0.1+0.6)*500
% Fixed maintenance (Scaffolding) cost = C_Sc_FX
% Fixed maintenance (Inspection) cost = C_I_FX
```

```
function f = objfun(Mh)

global t;

        eta = 24.28;
        beta = 4.13;
        i= 0.06;
        P= 1-(exp(-((t/eta)^beta)));

 f= ((Mh*(0.3*(15000+600+100000) + 0.1*500 + 0.6*500)*P)+...
    ((20000+700+100000)*(9.5577*(Mh^(-0.5391)))*((beta*(t^(beta-...
    1)))/(eta^beta))*t)+...
    (1*(0.3*(15000+600+100000)+ 0.7*500)*t))/((1+i)^t);

return;

%          CONSTRAINTS FILE

function [c, ceq] = confun(Mh)

global t;

    eta = 24.28;
    beta = 4.13;
    i= 0.06;
    P= 1-(exp(-((t/eta)^beta)));


        C_PM = (Mh*(0.3*(15000+600+100000) + 0.1*500 +
0.6*500)*P)/((1+i)^t);
       C_CM = ((20000+700+100000)*(9.5577*(Mh^(-0.5391)))*((beta*(t^(beta-
       ... 1)))/(eta^beta))*t)/((1+i)^t);



 c = [
        -Mh;
        -C_PM;
        -C_CM;

                ];
    ceq = [];

return;

%          MAIN RUN FILE

clear all;
clc;
    disMa1 = [];
    disMa2 = [];
    disMa3 = [];
    disMa4 = [];

Mh0=[1];

global t;
options = optimset('LargeScale','off');
```

```
fValtemp = -1;
for index= 1:1:100
        t= index;

        [Mh, fval] = fmincon(@objfun,Mh0,[],[],[],[],[],[],@confun,options)

        if fValtemp > fval
                  break;
            else
                  fValtemp = fval;
        end;

        eta = 24.28;
        beta = 4.13;
        P= 1-(exp(-((t/eta)^beta)));

        disMa1(index)= t;
        disMa2(index)= P;
        disMa3(index)= Mh;
        disMa4(index)= fval;

 end;

clc;

for index= 1:length(disMa1)
        display(sprintf('%0.0f %20.5f %20.5f %20.2f'...
,disMa1(index),disMa2(index),disMa3(index),disMa4(index)));
end;

% For display of plots

figure(1);
subplot(3,1,2);
plot(disMa1,disMa3)
hold all
    title('Variation of Optimal Maintenance Time with Component Age')
    ylabel('Optimal Maint Time - Manhours (Hrs)')
    xlabel('Age(Yrs)')

subplot(3,1,3);
plot(disMa1,disMa4)
hold all
    title('Variation of Minimum Total Maintenance Cost with Age')
    ylabel('Total Cost(NOK)')
    xlabel('Age(Yrs)')

subplot(3,1,1);
plot(disMa1,disMa2)
hold all
    title('Change in Probability with Age')
    ylabel('Probability of Failure')
    xlabel('Age(Yrs)')
```

```
%          CODES FOR PLOTTING COST CURVES AGAINST MANHOURS

clear all;
       j=1;
            t=23;
            eta = 24.28;
            beta = 4.13;
            i = 0.06;
            P= 1-(exp(-((t/eta)^beta)));

for Mh=5:0.5:50


        C_PM = (Mh*(0.3*(15000+600+100000) + 0.1*500 +
0.6*500)*P)/((1+i)^t);
        C_CM = ((20000+700+100000)*(9.5577*(Mh^(-0.5391)))*((beta*(t^(beta-
        ... 1)))/(eta^beta))*t)/((1+i)^t);
        C_FX = ((1*(0.3*(15000+600+100000)+ 0.7*500))*t)/((1+i)^t);

        C_TOTAL = C_PM + C_CM + C_FX;

        display(sprintf('%15.2f %15.2f %15.2f %15.2f %15.2f', Mh, C_PM,...
        C_CM, C_FX, C_TOTAL));

            MhMax1(j)= Mh;
            MhMax2(j)= C_PM;
            MhMax3(j)= C_CM;
            MhMax4(j)= C_FX;
            MhMax5(j)= C_TOTAL;

            j = j+1;

end

% Plotting the graph of Variation of Maintenance Costs with Maintenance
% Time (Hrs);

    figure(2);
    plot(MhMax1,MhMax2);
    hold all;

    plot(MhMax1,MhMax3);
    hold all;

    plot(MhMax1,MhMax4);
    hold all;

    plot(MhMax1,MhMax5);
    hold all;

    title('Variation of Maintenance Costs with Maintenance Time (Hrs)');
    ylabel('Cost(NOK)');
    xlabel('Maintenance Time(Hrs)');
    legend('Preventive Maint Cost','Corrective Maint Cost',...
                   'Fixed Maint Cost','Total Maint Cost')
```

APPENDED PAPERS

Paper I

A holistic procedure for rail maintenance in Sweden

Kumar, S., Espling, U. and Kumar, U. (2007). A holistic procedure for rail maintenance in Sweden. *Accepted for publication in Journal of Rail and Rapid Transit: Proceedings of the Institution of Mechanical Engineers, Part F.*

A Holistic Procedure for Rail Maintenance in Sweden

S Kumar[1]**, U Espling**[2]**, and U Kumar**[1]

[1] Division of Operation and Maintenance Engineering, Luleå Railway Research Center, Luleå University of Technology, Sweden

[2] Expert Support Unit, Banverket (Swedish National Rail Administration), Sweden

Abstract

The paper discusses a procedure for systematic and holistic (considering most of the factors influencing the rail degradation process) analysis and prediction of rail failures so that rail maintenance can be performed effectively. The current rail maintenance and reporting procedure followed by Banverket (Swedish National Rail Administration) for the Swedish Iron Ore Line is also described. The necessary data required to perform analysis and prediction of failures are discussed along with the improvement areas in Banverket's database management system.

This paper will help the infrastructure managers to better understand the existing rail maintenance procedure, and the improvements which can be incorporated in the existing procedure to make it more effective.

Keywords: Rail degradation, failure, influencing factors, rail maintenance procedure, data reporting, vehicle track interaction, rail defects

1. Introduction

Railways are one of the prime modes of transportation in many countries and as they are closely associated with the passenger and freight transportation, they own high risk in terms of loss of human life and damage/destruction of the assets, even though their probability of occurrence is very low. New technologies and stringent safety standards are constantly being introduced, but accidents still occur **[1, 2]**. The Hatfield derailment (UK) in October 2000 killed four and injured 34 people. The damages in terms of the consequential costs to Railtrack Company (acquired by Network Rail since 2002) were about £733 million **[3]**. The derailment happened because a rail, in which there were multiple cracks and fractures due to RCF (rolling contact fatigue), fragmented when a high speed train passed over it **[4]**.

The German ICE train derailment at Eschede on 3rd June 1998 took more than one hundred lives. The accident was caused by a fatigue fracture which started on the underside of the rim of a wheel separated from the disc connecting it to its axle by rubber pads. The derailment caused one of the carriages to swing out of line and to strike a support of the bridge, prompting its collapse **[2]**. There will always be some risk associated with the derailments and collisions, but it can be reduced by elimination of the root causes by means of effective maintenance procedures and models.

By the beginning of 1990s, many researchers and rail players felt the need for developing models and strategies for rail infrastructure maintenance. REPOMAN (Rail Expert Planning, Organization and Maintenance) and TRACS (Total Right-of-Way Analysis and Costing System) were developed in the early 1990s **[5-7]**. REPOMAN was based on maintenance planning while TRACS was based on the track degradation analysis and life-cycle costing.

Rail players in collaboration with academic/research institutions became actively involved in the development of the rail infrastructure maintenance strategies, which further produced useful track maintenance models like ECOTRACK **[8]**, ITDM, developed at Queensland University of Technology, Australia **[9, 10]** and DECOTRACK, developed jointly by Damill AB, Banverket and JVTC (Järnvägstekniskt Centrum) at Luleå University of Technology **[11]**. During this time, TTCI (Transportation Technology Center, Inc.), a subsidiary of AAR (Association of American Railroads), also developed InteRRIS (Integrated Railway Remote Information Service), a comprehensive, detector-based, internet-communicated vehicle-rail condition and performance monitoring system. InteRRIS acts as a data-warehouse for automatically storing and analyzing vehicle performance data.

Most of the above mentioned models provide efficient and innovative data reporting systems; some of them also analyse these data, however, many of the factors which influence the rail degradation process have not been considered. There is a need for describing an efficient and effective rail maintenance procedure considering these factors which influence the rail degradation process.

The outline of this paper is as follows: Section 1 describes the need for a holistic rail maintenance procedure and the state of the art. Section 2 describes the rail degradation and defect formation process. Failures due to vehicle-track interaction have also been mentioned in this section. Section 3 describes the current maintenance trend in Banverket. The rail maintenance procedure followed at Banverket's Iron Ore line is described in Section 4. Section 5 describes the steps required to develop an effective rail maintenance procedure. Contribution of this paper is discussed in the concluding section.

2 Degradations due to Vehicle-Track Interaction

Maintenance of rolling stock not only increases their life but also reduces rail degradation. As the wheels are in direct contact with the rails, degradation on the wheel surface and profile will effect degradation on the rails. Bogie condition will also influence rail degradation. Figure 1 shows the different kinds of degradation /failures taking place on both vehicle and track due to their interaction. Some of the degradations, defects or failures (e.g., hunting movement) having influence/being influenced by other failures are also shown in Figure 1.

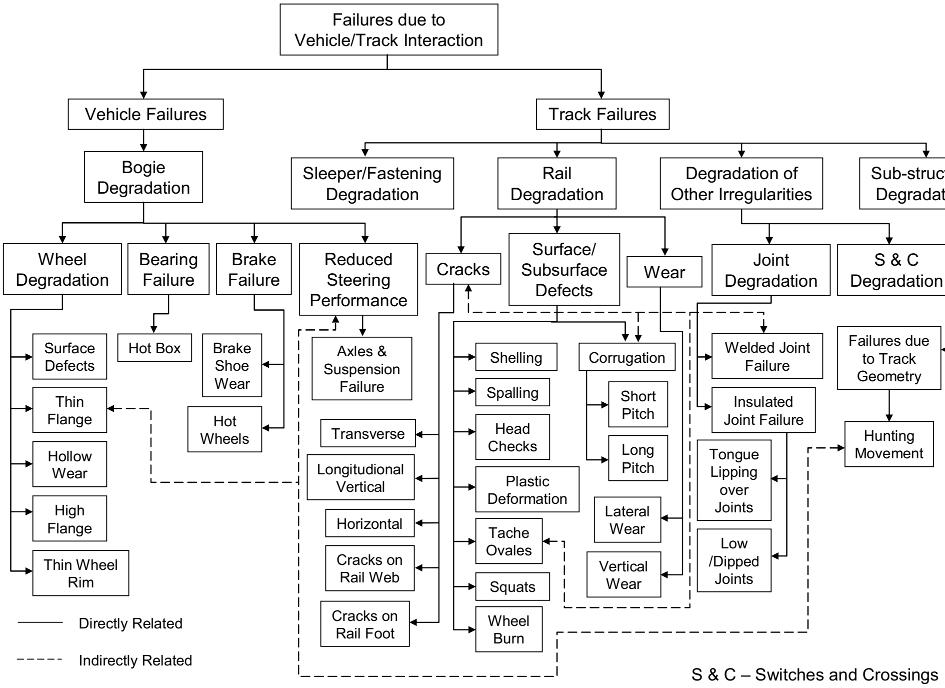

Figure 1. Failures occurring due to vehicle-track interaction (Adapted from **[12, 13]***)*

A track consists of different components, i.e., rails, switches, fasteners, sleepers, tie plates, ballast and subgrade **[14]**. Degradation of each of these components together constitutes the track degradation. Many track degradation models have been developed as mentioned above, but still there is a need to develop different component level degradation models so that detailed analysis is carried out at the component level, which together will lead to the development of an overall track degradation model (Figure 2). This model will help in framing out an effective track maintenance procedure. The track degradation model should be in-line with the track maintenance objectives.

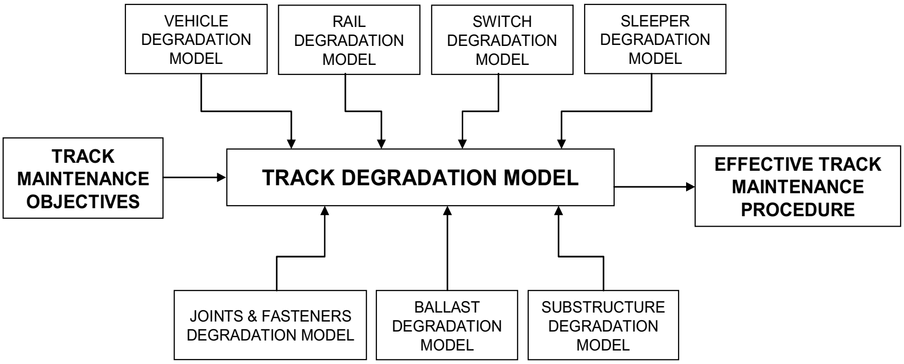

Figure 2. Need for an overall track degradation model to develop an effective track maintenance procedure

Bad wheel-rail interface is a cost driver and a lot of research is being done in this area **[15]**. Rails, among all the components of the track structure, are subjected to highest stress levels because rails are in direct contact with the wheels. The stress level between wheel and rail is in the order of 30 kN/cm^2, which is two orders smaller between rail and sleeper and reduces to around 30 N/cm^2 between sleeper and ballast. Finally the stress between ballast and substructure is only around 5 N/cm^2 **[14]**. The scope of the paper is limited to rail degradation and maintenance activities. Description of a detailed and holistic approach for developing each of the track component degradation models is beyond the scope of this paper.

2.1 Rail Degradation

Wear and rolling contact fatigue in rails are significant problems for the railway industry **[16]**. They are major contributors to rail deterioration depending on the different factors influencing the condition of the rail during its life cycle **[17]**. The rail head is worn away by wheels on its surface and deteriorates due to abrasive contact with the base plate or sleeper on its underside. Corrosion leads to loss of rail material and the surface crack reduces the fatigue resistance of the rail. Increased speed, higher axle loads, increased traffic and freight lead to the surface-initiated cracks on the rail **[18]**.

Rail break is the last phase of the crack development process. As the crack continues to increase in length as well as depth, stress concentration also increases and finally rail break occurs. However, this does not happen in all cases. Sometimes spalling takes place and a portion of rail material comes out as the crack develops. The end result of a crack is governed by its development path. It is very difficult to predict the crack development path as it depends on several factors. Some of the cracks disappear early on in their development as a result of wear and tear, while most of them are removed by grinding operations. Not all cracks pose a derailment risk, but they are major contributors to rail degradation. A rail break might also be caused due to manufacturing defects, such as formation of blowholes, but they are usually detected by NDT (non-destructive testing) inspection techniques. Detail fractures (a type of rail break) account for about 75 percent of the rail defects in continuously welded rail track in North America **[19]**.

2.2 Rail Defect Formation

The failure rate of the system depends on the condition of the system, which depends on the system being subjected to different kinds to stresses due to fatigue, lateral forces, axle loads, traffic density, etc., any of which causes degradation. Therefore, the system may not fail fully, but can degrade, and there may exist several states of degradation under which the efficiency of the system may decrease **[20]**. In some cases, if the degradation level exceeds a particular limit (for example, a rail defect propagates to form a rail break), the system may not operate successfully; this may be considered as a system failure. Failure is the termination of the ability of an item to perform a required function **[21]**. Rail break is a rail defect that can be considered as the last but definite failure state. A rail break may be defined as any rail which has separated into two or more pieces, or a rail from which a piece of metal becomes detached, causing a gap of more than 50 mm in length and more than 10mm in depth in the running surface **[22]**.

2.3 Rail Defect Classification

Due to the economic pressure there is a world-wide trend to increase axle loads, traffic density and speed to reduce operating costs and increase the efficiency of railways. This has lead to an increased rate of rail defect formation. Rail defects occur due to a number of causes, which have been used as a basis for rail defect classification by many researchers.

Olofsson and Nilsson (2002) **[23],** classified rail defects which occur due to RCF into surface-initiated and subsurface-initiated defects. Surface-initiated defects are formed mostly due to an increase in traffic density and axle load (e.g., head checks and squats). On the other hand, subsurface defects are often caused by metallurgical faults (e.g., shelling, tache ovale and longitudinal vertical crack).

Cannon *et al.*, (2003) **[24]**, divided rail defects into three broad groups:

- Defects originating from rail manufacture (e.g., tache ovale)
- Defects originating from damage caused by inappropriate handling, installation and use (e.g., the wheel burn defect, which is caused by spinning wheels)
- Defects caused by the exhaustion of the rail steel's inherent resistance to fatigue damage. Many forms of RCF-initiated defects are within this group (e.g., head checking and squats)

whereas Marais and Mistry (2003) **[25],** classified rail defects into two groups:

- Defects related to the rail joints (e.g., flash butt weld defects, thermit weld defects) and,
- Defects related to rail quality (e.g., horizontal head cracks, tache ovale)

Many infrastructure managers follow the UIC rail defect classification standard. According to the standard, broken, cracked and damaged rails are given a code that may comprise up to four digits. The first digit indicates the situation under which the defect occurred, the second and third digit indicates the defect location and pattern respectively, while the fourth digit indicates additional characteristics and differentiations, if any (see for details **[22]**). Standardized information in the form of rail defect code becomes particularly useful while carrying out data reporting, interpretation and analysis. Scope of misinterpretation of the information intended to be conveyed is considerably reduced by the use of defect codes to clearly explain defect characteristics.

3. Current Maintenance Trend at Banverket

The Railway operation in Europe has traditionally been integrated as a single entity looking into both traffic and infrastructure. During the last 20 years, deregulation and demands on increasing the effectiveness and efficiency has segregated the railways into traffic operators (TOC) and infrastructure managers (track owners) in some countries. It has also become common to outsource the maintenance activities concerning both the rolling stock and the infrastructure. Historically, maintenance in the railway sector has been based on time, tonnage accumulation or operated train kilometers (predetermined maintenance). The current trend within the European Railway sector is to move towards condition based maintenance. In Sweden this process started in mid 1990s.

The life-cycle of an infrastructure facility in Banverket is divided into four stages: operation, maintenance, upgradation and decommissioning (Figure 3) **[26]**. According to the Swedish standard **[27]**, the maintenance process is divided into preventive maintenance and corrective maintenance. Preventive maintenance is subdivided into condition-based and predetermined maintenance. The corrective maintenance approach is reactive in nature, whereas preventive maintenance is a form of proactive maintenance activity **[28]**.

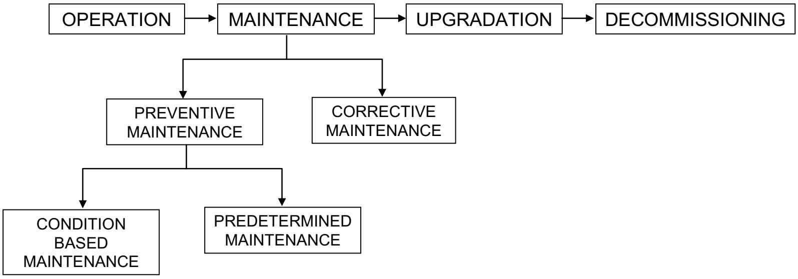

Figure 3. Maintenance definition followed by Banverket (Adopted from **[26, 27, 29 and 30]***)*

The current maintenance strategy in Banverket is to minimise the corrective maintenance and as far as preventive maintenance is concerned, predetermined maintenance should, to the extent possible, be changed to condition-based maintenance **[26]**. Banverket's strategy leads to its overall aim of rail maintenance, which is to provide a rail that meets functional demands for frequency of train service and loading capacity, travelling time, comfort, reliability (accessibility and punctuality), safety and environmental impact; and all these requirements are to be fulfilled as cost efficiently as possible **[31]**.

4. The Swedish Iron Ore Line

The iron ore line (Malmbanan) runs from Narvik in Norway, situated on the coast of the Norwegian Sea, to Luleå in Sweden, which is situated on the coast of the Gulf of Bothnia, spanning around 500 kilometers (Figure 4). The northern branch (Kiruna – Narvik) handles 15 millions net tonnes of ore which is 27 millions gross tons, while the southern branch (Luleå – Boden – Gällivare) handles 7 millions net tonnes of ore which is 18 millions gross tonnes **[32]**.

Figure 4. The iron ore line from Luleå to Narvik

The infrastructure managers, Banverket in Sweden and Jernbaneverket in Norway maintain the iron ore line. The line, running north of the Arctic Circle, is characterized by diverse geographical terrain requiring some small radius curves and steep gradients. The line is subjected to harsh climatic conditions such as snowstorms and temperatures close to -40° Celsius in winters and +25° Celsius in summers. Rail temperature variations over the four seasons are therefore very large. An effect of this is large tensile stresses during winter time, which increase the risk of crack propagation and, at worst, rail breakage.

Work on upgrading Swedish part of the iron ore line is under way, mainly comprising of increasing the number of wagons from 52 to 68, the train length from 470 meters to 750 meters and the train weight from 5200 to 8160 tonnes **[32]**. The line allows mix traffic and has been recently upgraded from 25 to 30 tonnes.

4.1 The Rail Maintenance Procedure followed at Banverket's Iron Ore Line

Banverket uses different guidelines for monitoring track and track components. They specify the minimum requirements for the infrastructure maintainer. Monitoring and maintenance include the functions of inspection and testing; assessment of inspection and test results, and the execution of preventive or corrective actions. The objectives are to inspect the critical elements of the track to determine its condition; record defects which might affect, or have the potential to affect the capability of the track to safely perform its required function; carry out assessments to determine the capacity of the track and finally, take actions where the track is unable to carry out the required function safely. Figure 5 shows the track failure data reporting procedure.

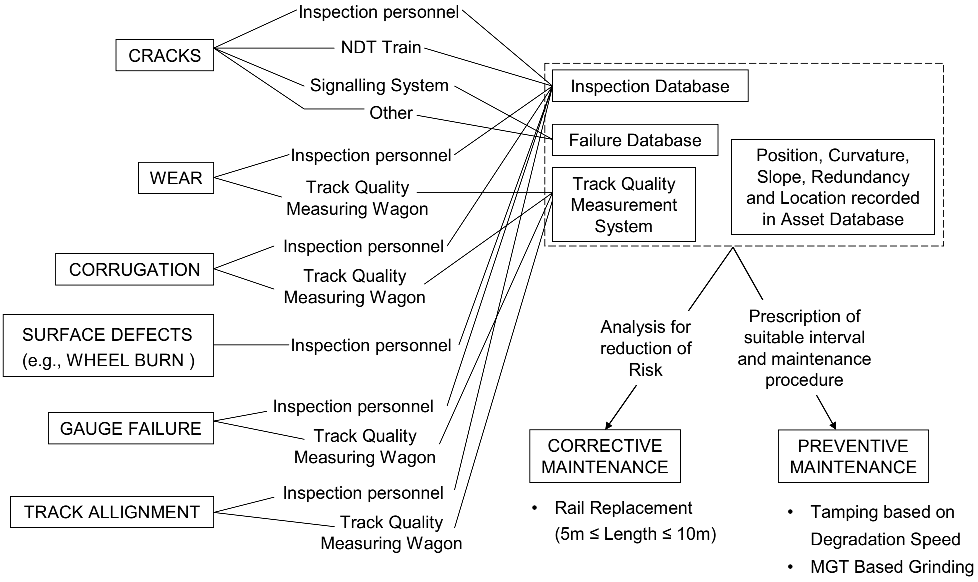

Figure 5. Track data reporting and analysis procedure followed in Banverket (Adapted from **[13]***)*

The rail maintenance procedure used at Banverket is shown in Figure 6. Banverket currently uses ultrasonic trains (also known as NDT cars), hand-held ultrasonic devices and visual inspection to inspect the rails to identify the possible internal defects (see **[17]** for details). To estimate the potential risk, each rail failure detected by the ultrasonic train is verified by hand-held ultrasonic equipment and recorded on the spot by an inspector in the form of a report. Severe defects which the inspectors thinks are of high priority are immediately recommended for corrective maintenance **[29]**. Visual inspection is carried out separately by rail inspectors according to an inspection plan (known as planned visual inspection), recorded in a report and stored in a database. Visual inspection may also be carried out in an unplanned manner by the inspector to check the track condition in between planned inspection intervals. Finally, track inspectors are obligated to report if they detect any deviation from normal rail condition, as they perform their daily maintenance work along the track. These reports are also stored in a database.

The signalling system, with its traffic control safety mechanism, detects any deviation that can be linked to a rail failure. However, signalling system is not used as a maintenance planning/inspection tool; it is a safety system for operating trains. If the signalling system detects any deviation from the norm, traffic control reports this to the maintenance contractor. The contractor then performs an inspection or repair if necessary, and reports the action to a database.

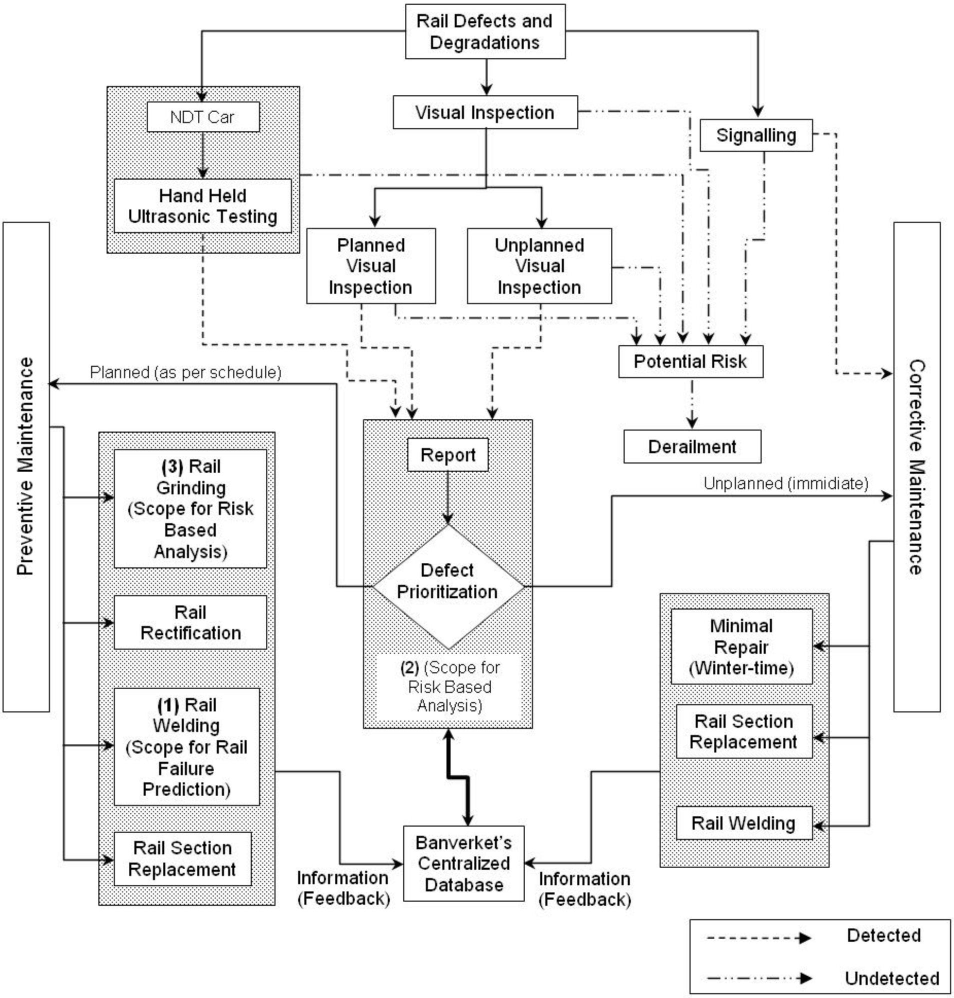

Figure 6. Banverket's rail maintenance procedure

All data recorded from the different systems are further analyzed by an expert. Historical data and information stored in a centralized database is also used to correlate failure patterns. Finally, a decision is made to prioritize these defects. Priority of defects is based on several factors, such as track geometry, traffic type, traffic density, axle load, age of rails, defect history, rail material, curvature, yearly and total accumulated MGT. The consequential costs and risks associated with a particular defect are also taken into consideration, if derailment occurs due to that defect.

Low-priority defects are then recommended for preventive maintenance in the form of e.g. grinding, minimal repair, rail welding or rail section rectification / replacement. The kind of preventive maintenance adopted for a particular kind of defect depends on its need and severity. High-priority defects are immediately recommended for corrective maintenance which may be in the form of minimal repairs (mostly carried out during the winter), rail section replacement and/or welding. Immediate maintenance is a procedure whereby emergency measures are either carried out immediately or traffic restrictions are imposed **[29]**. Minimal repairs as a form of corrective maintenance are temporary repairs carried out during the winter. Usually if a high priority defect/rail break occurs in winter, the segment containing the defect is replaced with a new rail segment. Welding of the rail segments is generally avoided in winter because it becomes very difficult to maintain uniform and correct welding temperatures, which may otherwise effect on weld quality. Therefore, the rail segments are temporarily attached by fishplates (known as minimal repair) which are later on replaced by welding in summer. The defects detected by signalling are generally severe, often in the form of rail breaks or rail breaks in a developing stage and need immediate attention, thus corrective maintenance is carried out to counter these defects **[17]**.

Figure 6 also illustrates those areas in Banverket's rail maintenance procedure where there is scope for risk-based analysis.

(1) Rail failure prediction can help the maintenance expert to make better decisions as regards recommending a defect for preventive or corrective maintenance by assessing the risk of each defect.
(2) A limit for permissible risk can be standardized for defects falling under different specifications. If the risk associated with a particular type of defect is more than the maximum permissible limit, the defect will be recommended for immediate, corrective maintenance and vice versa. This requires the development of an effective track maintenance procedure.
(3) Similarly, rail failure prediction and risk estimation will help in deciding on cost-effective grinding intervals. Rail failure prediction will also help in cost-effective welding procedures.

Defects left undetected by the above mentioned inspection tools build up operational risk in rails, some of which may eventually be detected through derailments. However, the percentage of defects leading to derailments is very small as shown in Figure 7.

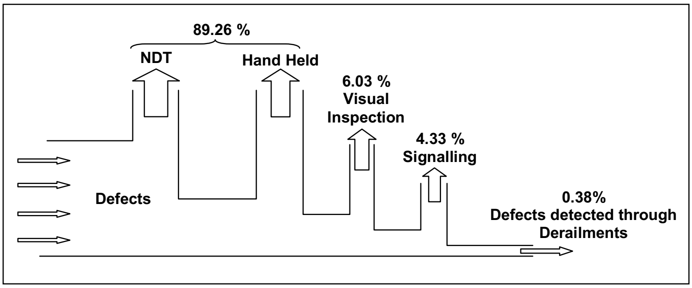

Figure 7. Percentage of potential rail breaks detected by the use of different inspection tools **[17]**

The figure gives an idea of the percentage of defects detected through various inspection tools used on the Swedish iron ore line. The figures are based on the inspection data collected from section 111, Malmbanan between the years 1997 and 2005 **[33]**.

5. The proposed procedure

In order to predict rail failures considering most of the factors influencing rail degradation, it becomes essential to develop a well defined procedure. The procedure should be explained to the contractor so that he/she knows what to collect/record and the reason behind it. The initial step of the procedure should be to identify the different factors influencing the rail degradation process. After these factors have been identified, the rail failure data needs to be collected and categorized depending on the conditions under which the failure occurred and the factors which played a dominant role to cause that failure. If there is a deficiency of field data, modelling of the actual conditions followed by simulation can be done to generate data. Once appreciable sample size of data under a particular category is available, trend test should be carried out followed by failure prediction using the most suitable failure distribution. Thereafter, based on analysis and interpretation of the results, maintenance budget is allocated during the decision making process, the aim of which is to develop an effective rail maintenance procedure. The following sub-sections have dealt with the steps described above.

5.1 Identification of factors influencing rail degradation

The identified factors responsible for rail degradation have been described by Ishikawa diagram in Figure 8 (see for details **[17]**).

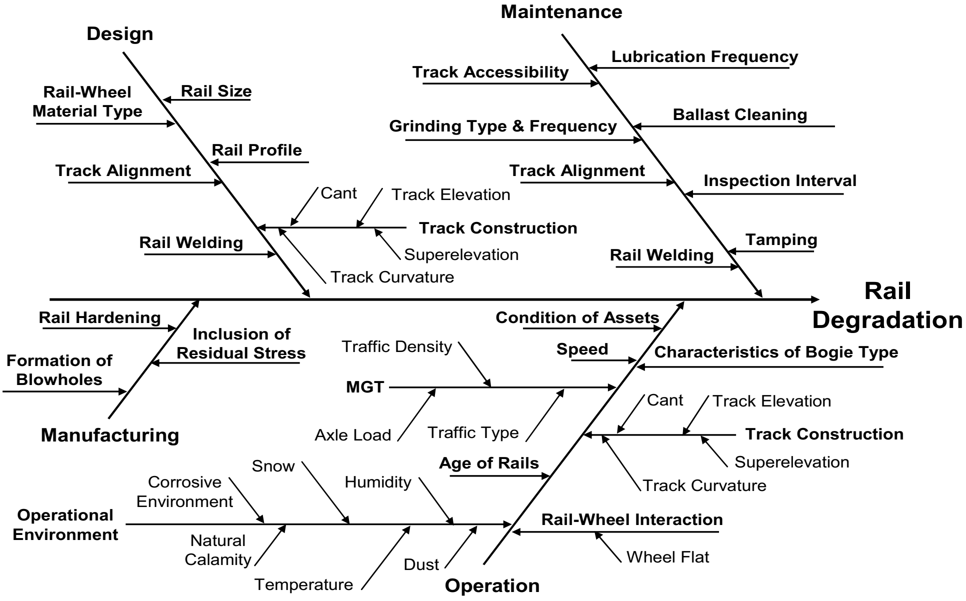

Figure 8. Ishikawa diagram (cause and effect diagram) for the factors influencing rail degradation

Four broad classification areas denoting the different phases (design, manufacturing, operation and maintenance) of rail life have been identified while constructing the Ishikawa diagram. During the design stage, selection of rail/wheel material type, rail size and rail profile depends on the required operating conditions such as axle load, speed, traffic type, traffic density, etc. Similarly, track is constructed according to the requirements of track geometry (elevation and curvature). Better track design will lead to less degradation and longer rail life. Defects may be generated during rail manufacturing. Other manufacturing aspects along with many of operational and maintenance factors will also influence the rail degradation.

5.2 Data Collection

The track inspectors should be very careful while reporting the information into the databases. Often confusing data/remarks in the databases lead to misinterpretations. In order to get a holistic picture of where the failures are located and what are the dominant factors causing failures, more structured databases are required having the complete information. For this, the infrastructure managers should know the parameters which are required to be measured; often this is not the case. Different databases should be linked with each other so that more detailed information is available in less time.

While reporting a defect, the type of defect along with the conditions under which the defect occurred should also be reported. Often, analysis of track failure data requires long spread sheets to correlate the factors responsible for the failure. In Banverket, corrective maintenance data is reported in a paper reporting sheet but often not reported completely in the databases, which makes it difficult to trace back while doing analysis. For example, a rail break is reported in the failure system and the required action has also been performed, but the exact location of the rail break is not reported in the database; a segment of rail has been replaced but not reported back in the asset management system. Thus it remains unclear whether left/right or high/low (in case of curves) rail was replaced.

Parameters such as traffic type, speed, tonnage, wheel condition, etc., should also be reported. One of the problems associated with tonnage can be overloading of the wagons by customers. For example, when a weight-in-motion system was installed in ProRail, it revealed that 20% more tonnage was carried by the infrastructure than was previously assumed **[34]**.

5.3 Data classification

Rail break data can be classified according to all the factors identified in Figure 8. The different levels of the classification framework will be governed by the dominance of the factors influencing rail degradation under a particular condition and the availability of data under that classification. This indicates that the classification framework for the Swedish iron ore line will be different from that of the Australian or American heavy haul lines, for example.

Data availability plays a crucial role in the development of a classification framework. It is important to have a good record of data measuring the effect of various factors influencing rail degradation as shown in Figure 9. If the required data is not available or is difficult to measure, then modelling and thereafter simulation of the actual conditions under which degradation is taking, place should be done. Figure 9 describes the improvement areas in Banverket's database management system, especially when track inspection, maintenance, reporting and classification activities are outsourced.

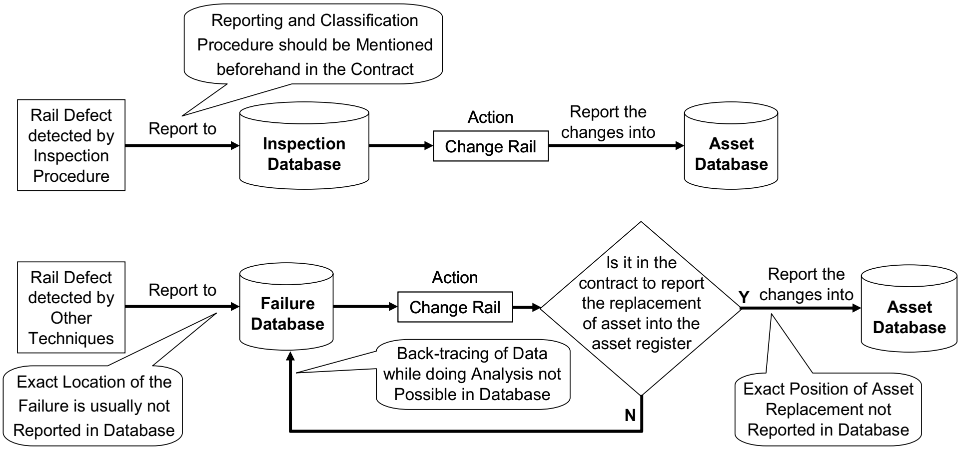

Figure 9. Scope for improvements in the data reporting and classification system

5.4 Analysis and Prediction of Rail Failures

After data collection and classification according to the different factors influencing the rail degradation process (Figure 8), data should be analyzed to predict rail failures. But before analysing the data sets or choosing an appropriate model for each of them, one must proceed for serial correlation and trend test. If failure data are independent and identically distributed (i.i.d.), they do not indicate any correlation and trend. The test for independence can be done by plotting ith time to failure against the (i-1)th time to failure, where, i=1,2,3,…,n and checking if there is any correlation among the plots. The test for identical distribution can be done by plotting cumulative number of failure against cumulative time to failure. If the plotted points lie on a straight line, there is no trend in the failure data and vice-versa.

If no evidence of trend is found in failure data, then stationary models such as Homogeneous Poisson Process (HPP) or classical distributions can be used for data analysis (e.g., Exponential, Weibull, Normal and Lognormal distribution). A goodness-of-fit test is used thereafter, to determine an appropriate distribution. If evidence of trend is concluded, a non-stationary model such as Non-homogeneous Poisson Process (NHPP) must be fitted (e.g., Power law process) **[35]**.

For example, Figures 10 and 11 shows the plots for serial correlation and trend test of the failure data for defect type 211 respectively. The description of the defects and their corresponding defect codes (according to UIC standard) considered to exemplify the trending and analysis procedure is given in Table A, Appendix. Real data of the frequently occurring defects on the rail section under study (section 111, of the iron ore line, see Figure 4) from the year 1997 to 2005, were taken (see for details, **[36]**). In this paper, the different defect types assigned by defect codes are considered as failure states. As ageing in rails takes place due to tonnage accumulation on the track resulting from traffic movement, rail defect data analysis is based on MGT of traffic flow. As per Banverket's inspection and failure databases, rail replacements and ageing is estimated by assuming 25 MGT per year of traffic flow on the Swedish iron ore line. The age of rail segments having a rail defect is calculated by multiplying the annual MGT of traffic flow with the difference between the year the rail segment was inspected for a rail defect and the year it was last replaced.

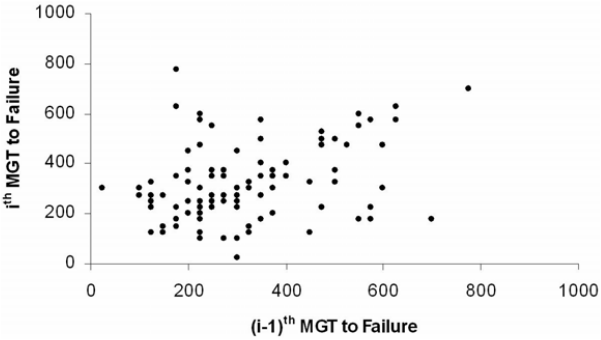

Figure 10. Test for serial correlation of defect type 211

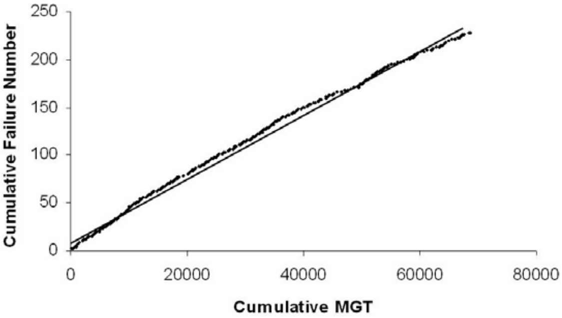

Figure 11. Trend test for defect type 211

It is evident from the two plots (Figures 10 and 11) that the failure data are independent and identically distributed (i.i.d.). Similar results were obtained when this test was further carried out for the other defect types **[36]**. The best-fit test was carried out using ReliaSoft's Weibull++6 software **[37]**. For most of the defect types (defect code 211, 411, 421 and 2321 see Table A in Appendix), 2-parameter Weibull distribution was the best fitting distribution where as 3-parameter Weibull distribution was the best fitting distribution for defect types having defect codes 135 and 235. The analysis was done using maximum likelihood estimation. The probability of occurrence of failures at different intervals of time (i.e., at different tonnage accumulation) for the failure data sets of each of the considered defect types is calculated. Figure 12 shows the probability of occurrence of failure for each of the defect types considered at different time intervals. For prediction of the risk involved with each defect type, their severity and probability of detection should also be known. This has been discussed in detail by one of the authors in a submitted paper **[36].**

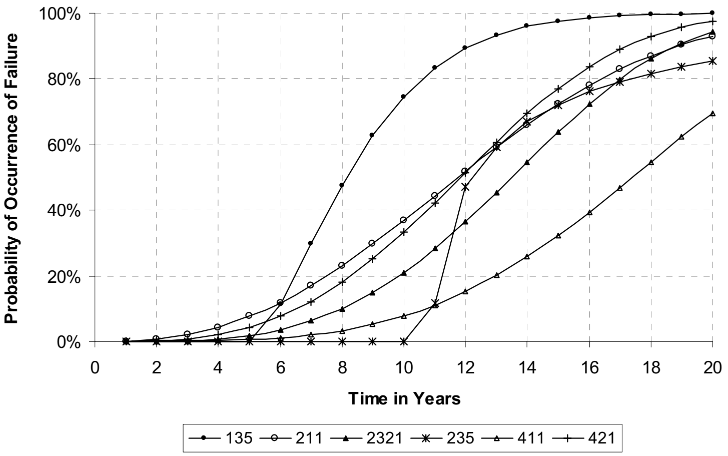

Figure 12: Probability of failure for different defect types at different time intervals

The failure behaviour of different defect types also depends on a number of factors influencing the degradation rate as shown in Figure 8. Some of the factors play a more dominating role on the failure behaviour of a particular defect type compared to others. Figure 13 shows an approach to predict rail breaks.

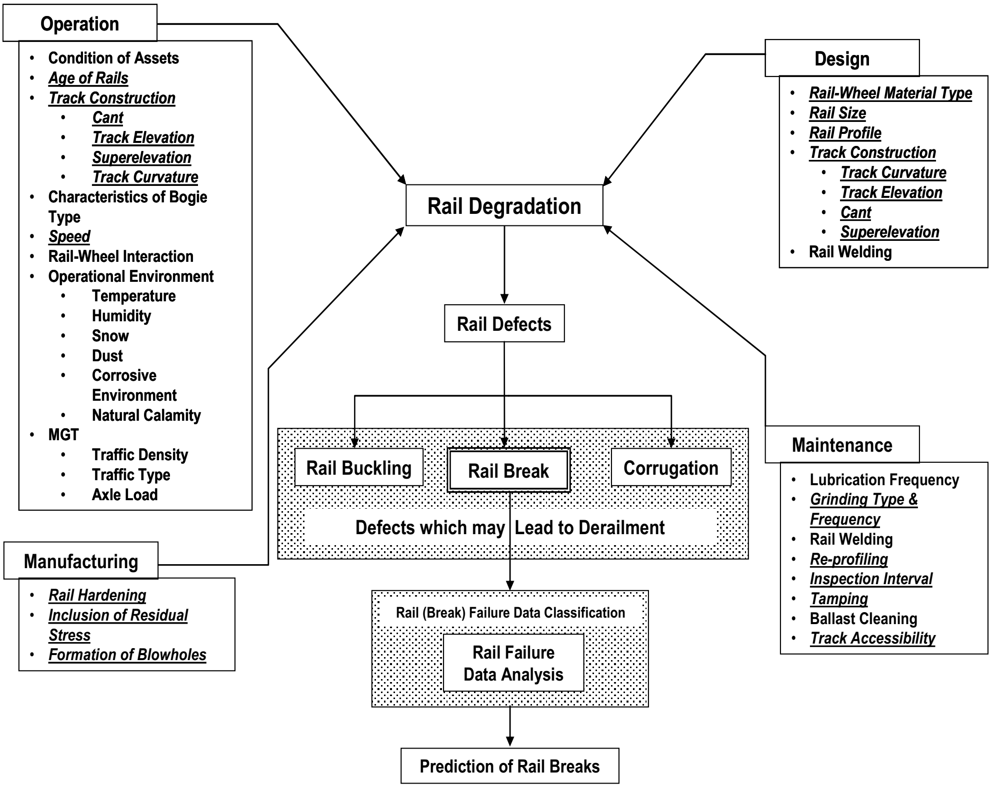

Figure 13. An approach for rail break prediction

The different factors which are being monitored and recorded by Banverket have been underlined. Appropriate measuring techniques need to be designed or incorporated to measure and record other factors in order to get more precise analysis results and failure predictions. Furthermore, development of a priority list of different factors affecting the rail degradation process is currently under study at the Luleå railway research center within the scope of 'the maintenance thresh hold limit project' (http://jvtc.project.ltu.se/).

5.5 Maintenance Decision Making Process

Rail players have well-defined business objectives based on stakeholders' demands which in turn create a foundation for the track maintenance objectives. Rail maintenance objectives can be considered as a part of the track maintenance objectives. Track reliability, availability and reduced risk of derailments can be achieved by reducing the rate of rail degradation (rail maintenance objective) which requires a well-structured and effective rail maintenance procedure (Figure 14).

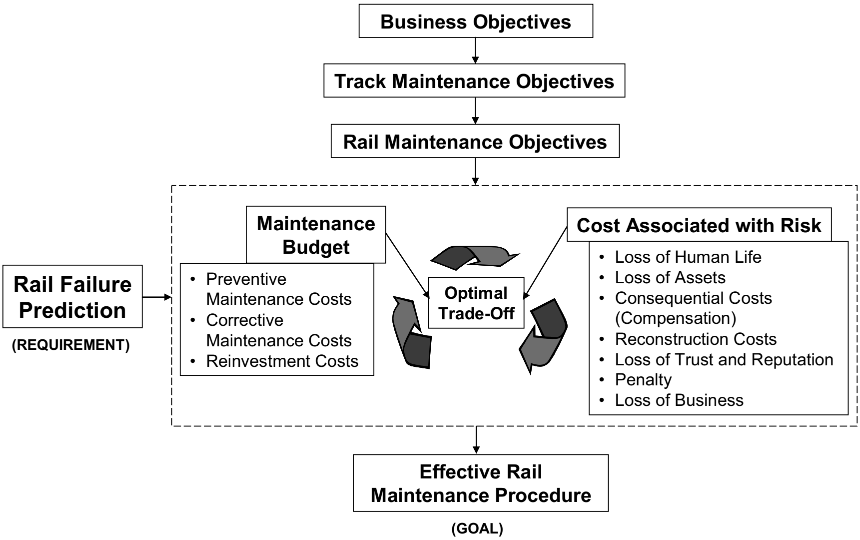

Figure 14. Process of developing an effective rail maintenance procedure

Prediction of the failure rate for a rail section helps in proper scheduling of maintenance activities (inspection, grinding, rectification/replacement and/or welding) in an optimal way. Predicting the failure of a degrading rail section will facilitate risk estimation as shown in Figure 14. Therefore, rail failure rate prediction is a requirement for the development of an effective rail maintenance procedure.

There are many examples showing the effect of rail maintenance in terms of reduction in the failure/accident rates or increment in rail life (see, **[38, 39]**). Some of the research studies carried out at Luleå railway research center has also shown that effective grinding and lubrication can increase rail life (see **[16, 40]**). Effective implementation of track maintenance and renewal activities by MRS Logistica, Brazil has reduced the accidents per train per million kilometers from 60.2 in 1996 to 7.0 in 2006; more specifically effective rail grinding and lubrication has increased the rail life from 750 MGT in 2002 to 1500 MGT in 2006 **[41]**. The annual grinding campaigns on Malmbanan have also improved the rail life and quality of the track significantly. For example, in the nineties about 10 km track needed to be changed annually on the northern branch of Malmbanan. During the last years the respective amount has been only 400 rail meters **[32]**.

Generally, a trade-off is made between maintenance budget and the cost associated with the risk involved with rail degradation. It is a cyclic process and continues until an effective rail maintenance procedure is finally developed.

If a maintenance procedure is not well-structured and effective, proper maintenance action may not be taken within the required time or a defect may be left uninspected, as a result, rail degradations and defects may develop into rail breaks. A rail break can cause derailments which may have catastrophic consequences.

In order to avoid the consequences and the probability of derailment, stringent safety standards have to be followed, which require massive rail maintenance investments. The investment limit depends on the availability of funds and the level of risk acceptable under the given operating conditions. An effective maintenance procedure should be able to strike the optimum balance between the cost associated with risk and the required maintenance budget.

6. Conclusion

Effective rail maintenance can be achieved through a well defined holistic (considering many of the factors which influence rail degradation process) maintenance procedure. This paper describes a procedure to collect and record useful data and classify them based on the identified factors influencing rail degradation and further analyse the data and predict the failure rate so that rail maintenance can be performed effectively. Data gives valuable information which delivers knowledge. The infrastructure managers and contractors should know what to collect/record and why it is important. Knowledge of the rail degradation and defect formation process can help the infrastructure managers to understand the kind of information required under specific conditions. The cost implications during the development of an effective rail maintenance procedure are described during the maintenance decision making process.

The paper also describes the current maintenance trend at Banverket. A case study of Banverket's rail maintenance procedure for its Iron Ore Line is presented. The paper also discusses the improvement areas in Banverket's database management system. Implementation of the suggestions and the described procedure can considerably improve rail failure data analysis and prediction.

APPENDIX

Table A: UIC rail defect code and its description **[22]**

UIC Defect Code	Description
Defect Code 135	Star cracking of fishbolt holes; this defect consists of progressive cracks that radiate from the fishbolt hole. They are mostly located near the rail ends.
Defect Code 211	Progressive transverse cracking (kidney-shaped fatigue crack); this defect develops from a defect inside the rail head, from an internal horizontal crack or deep shelling of the gauge corner.
Defect Code 2321	Horizontal cracking at the web-head fillet radius; This crack initially develops in the rail web, parallel to the web-head fillet radius and may curve either upwards or downwards as it progresses.
Defect Code 235	Cracking around the holes other than fishbolt holes; this defect has the same appearance as that of defect code 135, but they occur away from the rail ends.
Defect Code 421	Transverse cracking of the profile; this is a welding and resurfacing defect occurring in/near the thermit welding.
Defect Code 411	Transverse cracking of the profile; it's a resurfacing defect occurring in electric flash-butt welding. The crack develops in the weld cross-section either from an internal defect of the head in the weld or from a defect located in the foot of the rail.

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Paper II

Parameter estimation for rail degradation model

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Parameter Estimation for Rail Degradation Model

G. CHATTOPADHYAY[1], S. KUMAR[2 *]

[1] *PELM Centre, Central Queensland University, Faculty of Science,*
Engineering and Health
Bryan Jordan Drive, Gladstone, QLD, 4680, AUSTRALIA

[2,]*Division of Operations and Maintenance Engineering, Luleå University of Technology,*
SE-971 87 LULEÅ, SWEDEN

Abstract : Wear and fatigue in rails are major contributors of rail degradation depending on operational conditions, track, characteristics of bogie type, Million Gross Tonnes (MGT), curvature, traffic type and environmental conditions. Estimation of parameter for failure models is necessary for accurate prediction of expected number of rail defects over a period of time based on MGT of traffic and operating conditions for developing cost effective maintenance strategies. This paper focuses on collection and analysis of field data over a period of time for estimation of parameter for modelling rail life.

Key Words: *parameter estimation, rail degradation, rail break, curve radius, Weibull distribution*

1. Introduction

Wear and fatigue in rails are major contributors of rail degradation depending on operational conditions of the track, characteristics of bogie type, MGT, curvature, traffic type and environmental conditions. Other factors include grinding frequency, lubrication frequency and climatic conditions. Most of the rail players collect huge data while carrying out inspection and maintenance procedures. Utilisation of these data for analysis to get meaningful information is a tedious job. At present, the data is interpreted through experience of the technical people based on the non destructive testing (NDT) and visual checks [1]. The skill level of inspectors is important for estimation of criticality of the problem and appropriate maintenance decisions.

The rail inspection costs alone (assuming annual vehicle ultrasonic inspections followed by manual verification of detected defects) are estimated at about €70 million per year for a 0.5 million kilometer track system in European Union [2]. Rail players are looking for cost and risk reduction by modeling of inspection, grinding and maintenance intervals [3]. Estimation of parameter for failure models is necessary for accurate prediction of expected number of rail defects over a period of time based on MGT of traffic, operating conditions and maintenance strategies.

This paper focuses on collection of field data for various rail defects including rail breaks. Parameters of the failure models are estimated using real life data. Numerical examples are used for illustrations. Outline of this paper as follows: In

Section 1, need for modelling and estimation of parameters is explained. Section 2 deals with factors affecting rail degradation and provides a framework for analysis and estimation of parameters for failure model. Contribution of this paper with scope for future work is discussed in the concluding section.

2. Failure Modelling

Modelling is done by applying stochastic approach. This is known as a parametric model and defined by probability distributions.

2.1. Factors Influencing Rail Degradation

Rail-wheel interaction is a very complex phenomenon. Repetitive wheel loads on rail results in development of rolling contact fatigue (RCF). Wear in rail occurs due to interaction of rail and wheel and is dominant on curves where maximum rail wheel shearing occurs. Relative slippage between wheel and rail and the stress development between contact points play a major role in increasing wear. Jendel, [4] defined the concept of mild and severe wear. Mild wear takes place slowly but severe wear is often much faster, similar to adhesive wear. Severe wear is predominant in curves and dry conditions [5]. Lubrication helps to reduce rail gauge face wear and reduces energy or fuel consumption along with noise reduction. Rail surface grinding removes metal from the rail head to control RCF defects and rail wear. In 1980s rail grinding was mainly focused on corrugation removal with 15% of Canadian Pacific Railway's (CPR) grinding budget devoted to treatment of RCF compared to 60% on control of corrugation. In the late 1990s, grinding became a treatment of RCF of rails on some European railways. It is now widely followed in Europe. The annual grinding budget in North America for larger railways is about US $500 per kilometer of track, this means that on a system with 20,000 kms of track, the grinding budget is about US $10 million [2]. Mechanical properties in pearlitic rail steel structure are governed by the distance between cementite(Fe3C) layers and the grain size. These are controlled by cooling rate of the steel. The yield point and the tensile strength are inversely proportional to the distance between cementite layers and grain size. There are different types of heat treated, alloyed or plain carbon steel rails being used around the world. Apart from the usual manufacturing process of the rails, the tensile strength and toughness are increased by heat treatment. Heat treatment is usually done to rail head, turnouts and at the ends of non-welded rails to address to the issue of maximum stress concentration [6]. Rail degradation is more prevalent on steeper curves. A classification of data is carried out based on curve radius, climate, rail type, rail size, rail-wheel material type and high rail or low rail for estimation of parameter for failure model.

3. Data Collection and Analysis for Parameter Estimation

Field data was collected and analysed according to factors as classified in Figure 1.

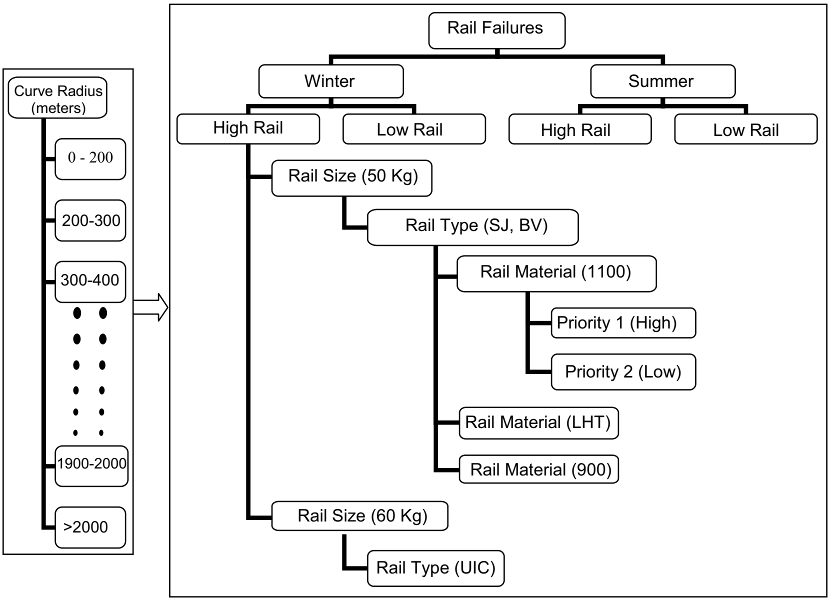


Figure 1: Rail Failure data Classification

Data collected from Swedish National Rail Administration (Banverket) is classified in Tables 1 to 4 in line with proposed framework [7].

Table 1: Winter Data (High Rail)

	Kgs	**50**		
	Rail Type	**SJ , BV**		
	Steel Grade	**1100**	**LHT**	**900**
	Priority	**High**	**High**	**High**
Curve Radius (Meters)	0-200			
	200-300	500, 500		
	300-400			
	400-500			
	500-600	400, 250, 325, 575, 400, 350		
	600-700			
	700-800	325, 250		
	800-900			
	900-1000			725, 750
	1000-1100			
	1100-1200			
	1200-1300			
	1300-1400			
	1400-1500	275		
	1500-1600			
	1600-1700			
	1700-1800			
	1800-1900			
	1900-2000			
	>2000			

Table 2: Winter Data (Low Rail)

	Kgs	**50**			**60**	
	Rail Type	**SJ,BV**			**UIC**	
	Steel Grade	**1100**	**LHT**	**900**	**1100**	**LHT**
	Priority	**High**	**High**	**High**	**High**	**High**
Curve Radius (Meters)	0-200					
	200-300					
	300-400					
	400-500					
	500-600	325, 350, 275, 125, 50, 400, 225				600
	600-700	375, 300				
	700-800	325				
	800-900	250				
	900-1000	275				
	1000-1100					
	1100-1200					
	1200-1300					
	1300-1400					
	1400-1500					
	1500-1600					
	1600-1700					
	1700-1800					
	1800-1900					
	1900-2000					
	>2000					

Table 3: Summer Data (High Rail)

	Kgs	**50**		
	Rail Type	**SJ,BV**		
	Steel Grade	**1100**	**LHT**	**900**
	Priority	**High**	**High**	**High**
Curve Radius (Meters)	0-200			
	200-300			
	300-400			
	400-500			
	500-600	275		
	600-700	300		
	700-800	375		
	800-900			
	900-1000			
	1000-1100			
	1100-1200			
	1200-1300			
	1300-1400			
	1400-1500	350		
	1500-1600			
	1600-1700			
	1700-1800			
	1800-1900			
	1900-2000			
	>2000			

Table 4: Summer Data (Low Rail)

	Kgs	**50**		
	Rail Type	**SJ,BV**		
	Steel Grade	**1100**	**LHT**	**900**
	Priority	**High**	**High**	**High**
Curve Radius (Meters)	0-200			
	200-300			
	300-400			
	400-500			
	500-600			
	600-700			
	700-800			
	800-900			
	900-1000			
	1000-1100	325, 400		
	1100-1200			
	1200-1300			
	1300-1400			
	1400-1500			
	1500-1600			
	1600-1700			
	1700-1800			
	1800-1900			
	1900-2000			
	>2000			

The values entered in the cells of these tables are the total MGT of the rail segments in which rail break occurred. Many cells in the tables have been left empty because either the rail break data associated with these cells were not found or the rail breakage never occurred under these specific classifications.

Following assumptions were made due to unavailability of complete data. These are:

- winter months are November to May and summer months are June to October.
- rail sizes were limited to50 Kg and 60 Kg
- two different sources SJ and BV adhere to the same specifications for same rail size
- rail break data not specified with exact curve radius were assumed to from a steeper curve radius of the range mentioned in the report where more than one curve radius exists in that range. For example, 302 meters was considered to be in the lower curve radius range that is 200-300 and not 300-400.
- annual traffic is 25 MGT

Due to inadequacy of rail break data for other ranges of curve radius, only one curve radius (500-600 metres) has been analysed and compared for high and low rail; the other factors influencing rail degradation being the same for both the data sets (see Tables 1 and 2). Before analysing these two data sets or choosing an appropriate model for each of them, one must proceed for trend test of chronologically ordered failure data sets. If no evidence of trend in failure data is found, then the data set could be assumed to be identically distributed. Thereafter, test for serial correlation can be done for verifying their independence. If failure data are independent and identically distributed (i.i.d.), their failure rate is observed. If failure data are having constant failure rate, Homogeneous Poisson Process (HPP) (for example, Exponential distribution) can be used for data analysis, otherwise classical models such as Weibull, Normal, or Lognormal distribution, etc. can be used [8]. If evidence of trend is concluded, a non-stationary model such as Non-homogeneous Poisson Process (NHPP) must be fitted (for example, Power law process) [9].

The test for identical distribution was done by plotting cumulative number of failure against cumulative failure MGT (cumulative million gross tonnes which has been calculated and replaced with cumulative time to failure). If the plotted points lie on a straight line, this implies that there is no trend in the failure data. Figure 2 and 3 shows the plot for identical distribution of the selected data set for high and low rail respectively. In both of these graphs, the plotted points lie on a straight line. This confirms the assumption that both the data sets are identically distributed.

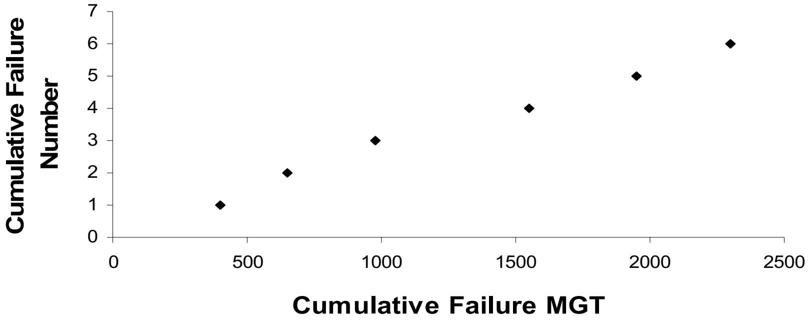


Figure 2: Data Sample 1 (High Rail Failure Data) - Test for identical distribution

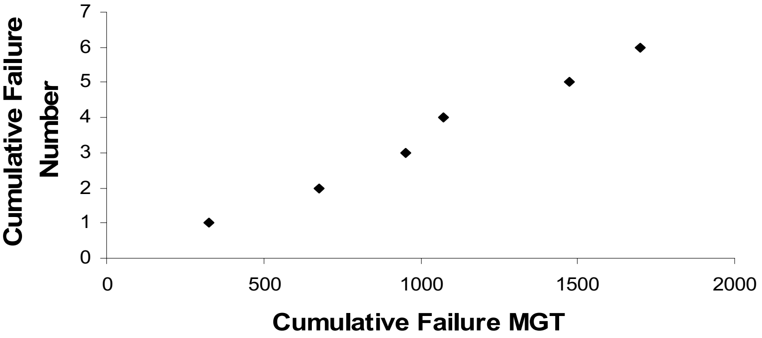


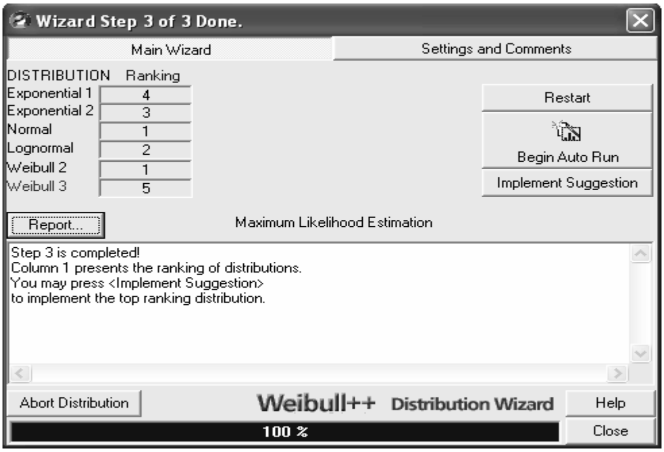
Figure 3: Data Sample 2 (Low Rail Failure Data) - Test for identical distribution

The test for independence can be done by plotting i^{th} time to failure against the $(i-1)^{th}$ time to failure, where, i=1,2,3,…,n and checking if there is any correlation among the plots. In the present case, the two sets of data could not be tested for independence as their sample size is too small to indicate any correlation among the plots. It is thus assumed that a rail break occurring in one segment of rail does not affect the occurrence of other rail breaks in the same or other rail segments. In other words, it is assumed that failure data are independent of each other.

Further, paired comparison test was carried out for the two data sets using Statgraphics software. This test was conducted to check if it is scientifically appropriate to compare the two data sets under similar operating conditions. The test is based on accepting or rejecting null hypothesis which states that the difference between the means of the two sample sets is equal to zero (H_o: $\mu 1 - \mu 2 = 0$). Since the P-value (P-Value = 0.248) for this test is greater than 0.05 significance level, we cannot reject the null hypothesis at the 95 percent confidence level. Thus it is concluded that the two sample sets can be compared at 95 percent confidence level (see [7] for details).

Once the trend test and the paired comparison test were done, an analysis of failure data for best fit distribution was carried out using Weibull++6 (Reliasoft, 2006) software as shown in Figure 4. 2-parameter Weibull distribution and normal distribution were the best fitted distributions. Weibull distribution has been used to analyse the data and predict the rail failure rate as it has the ability to provide reasonably accurate failure analysis and prediction with small sample size [10]. Another important reason to use this distribution is because Weibull distribution is often used to represent the problems related to mechanical component aging, wear and degradation. Further, Weibull distribution has no specific characteristic shape and depending upon the values of the parameters in its reliability functions, it can adapt shape of many distributions [11]. Great adaptability of Weibull distribution results in accurate failure analysis and prediction.

Winter, high and low rails, 50kg, 1100 steel type, high priority data for curve radius between 500 to 600 meters are analysed using 2-parameter Weibull distribution. Maximum likelihood estimation has been used to analyze and predict rail breaks.



DISTRIBUTION	Ranking
Exponential 1	4
Exponential 2	3
Normal	1
Lognormal	2
Weibull 2	1
Weibull 3	5

Maximum Likelihood Estimation

Step 3 is completed!
Column 1 presents the ranking of distributions.
You may press <Implement Suggestion>
to implement the top ranking distribution.

Figure 4: Best fitting distribution test by Weibull++6 Software

3.1. Parametric Model

Rail breaks are modelled as a point process with an intensity function $\Lambda(m)$ where m represents Millions of Gross Tonnes (MGT) and $\Lambda(m)$ is an increasing function of m indicating that the number of failures in a statistical sense increases with MGT. That means older rails with higher cumulative MGT passed through the section is expected to have more probability of initiating defects and if undetected then through further passing of traffic can lead to rail rail breaks. Chattopadhyay *et. al.,* [3] proposed the number of failures for an accumulated MGT, m, as a random variable and modelled using Weibull distribution.

Let cumulative MGT of rail, m, be known and $F_n(m)$ and $f(m)$ denote the cumulative rail failure distribution and density function respectively, modelled as Weibull distribution given by:

$$F_n(m) = 1 - \exp(-(\lambda m)^{\beta}) \tag{1}$$

And

$$f(m) = \lambda\beta(\lambda m)^{\beta-1}\exp(-(\lambda m)^{\beta}) \tag{2}$$

with the parameters β (known as shape parameter of the distribution) > 1 and

λ (known as inverse of characteristic function for the distribution)> 0

β greater than 1 indicates an increasing failure rate of the item under study and ageing is predominant in failure mechanism.

Rail track is normally made operational through repair or replacement of the failed segment and no action is taken with regards to the remaining length of the whole track. Since the length of failed segment replaced at each failure is very small relative to the whole track, the rectification action can be viewed as having negligible impact on the failure rate of the track as a whole, [12].

Failure data are analysed for estimating the probability of detecting defect with potential for failure before next inspection. Defect developed later in between inspections or undetected during inspection can result in rail breaks. Some rail breaks are detected by signalling system. Some of undetected breaks are detected by visual checks. Balance of undetected rail breaks can result in derailment [13].

Probability of Rail break in between inspection depends on probability that detectable defect present at the time of inspection is undetected and/or the developed defect grows into critical level resulting rail failure/ break before next inspection. Some of the other important factors which may affect rail degradation are curve radius, weather, rail type, rail size, rail-wheel material type and high rail or low rail. Classification of data, based on these factors is done in order to perform analysis considering the above mentioned classification.

3.2. Results and Discussions

The results of the analysis are shown in Figures 5, and 6. A software program (Weibull 6++) was used for the analysis of rail break data. Rail break data have been plotted at a 95-percent confidence interval.

From the values of β and η obtained, the mean time to failure can be calculated, where,

$$MTTF \quad = \eta \Gamma \left(\frac{1}{\beta} + 1 \right) = 422.103 \Gamma \left(\frac{1}{3.995} + 1 \right)$$

$$\approx 382 \text{ MGT}$$

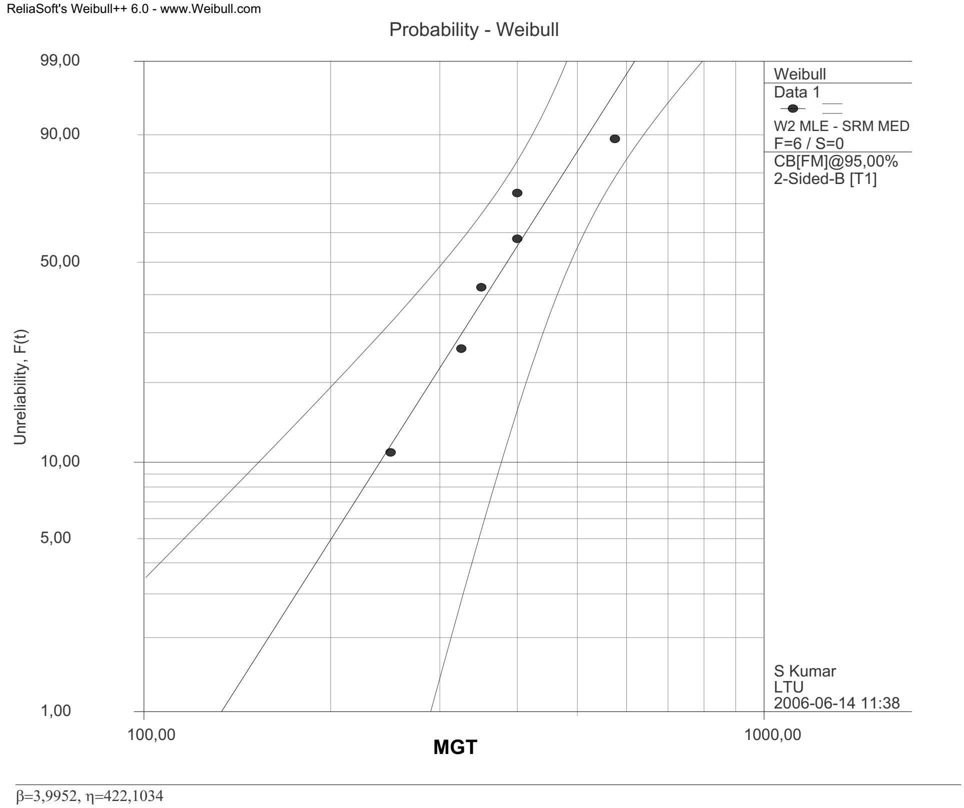


Figure 5: Winter, high rail, 50kg, 1100 steel type, SJ and BV rail type rail break data for curve radius 500-600 metres

This means that, based on the data used for analysis, the predicted mean rail life is 382 MGT in high rail segments having a curve radius of 500-600 metres, rail size of 50 kg, rail type SJ or BV, and rail steel type 1100 under the assumed winter conditions.

Figure 6 shows the Weibull plot for low rail, winter rail break data on 1100 steel type, 50kg rail size having the same curve radius of 500-600 meters.

The mean time to failure ($\beta = 3.759$ and $\eta = 314.705$) $= 314.705\,\Gamma\left(\frac{1}{3.759}+1\right)$

$$\approx 284 \text{ MGT}$$

This means that based on the data used for analysis, the predicted mean rail life is 284 MGT in low rail segments having a curve radius of 500-600 metres, rail size of 50 kg, rail type SJ or BV, and rail steel type 1100 under the assumed winter conditions.

Further, if we compare the values of shape parameter β and scale parameter η in Figure 5 and 6 and their respective Mean Time to Failure (MTTF), results show that low rail is more prone to failures compared to high rail under the same conditions and factors influencing rail break data.

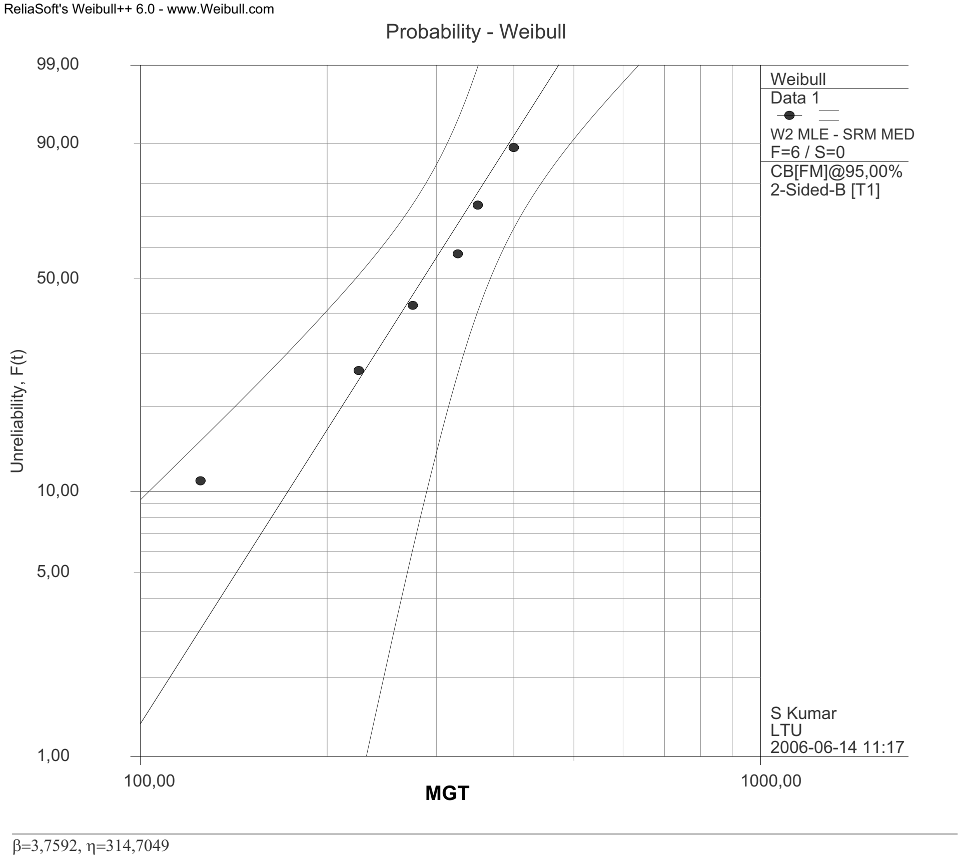


Figure 6: Winter, low rail, 50kg, 1100 steel type, SJ and BV rail type rail break data for curve radius 500-600 metres

A possible explanation in our opinion can be speeds maintained lower than the prescribed speed limits of trains passing through the curve segments with a curve radius of 500-600 metres as the track will be having the required superelevation. Moreover, the track section considered for the study has mixed traffic, with different vehicle speeds, thus the superelevation designed for curve radius 500 to 600 metres may be a compromise to balance freight as well as passenger traffic, loads and speeds. Analysis of the rail break data for different curve radii and under similar stated conditions will give a relationship between the curve radius and rail failure rate in high and low rails. More rail break data in each cell will give more accurate predictions.

Estimated parameters could be useful for planning inspection, grinding, rectification and replacement budgets and planning maintenance actions based on the need in various segments in the network.

4. Conclusions

Estimation of parameter for failure models is necessary for accurate prediction of expected number of rail defects over a period of time based on MGT of traffic and operating conditions for developing cost effective maintenance strategies. This paper is based on collection and analysis of field data over a period of time for estimation of parameter for models predicting rail life.

This paper has developed a framework for classification of data. It has also shown how to get information from incomplete data. There is huge scope for future work in this area for developing decision models related to inspection, rail grinding and rail rectification and replacement decisions.

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Dr. Gopinath Chattopadhyay has been working as Associate Professor of Asset Management in the Faculty of Science, Engineering and Health in Central Queensland University in Australia since 2007. He has worked in Queensland University of Technology as Lecturer and Senior Lecturer from 1996 to 2007. Dr. Chattopadhyay has published more than 110 high quality papers in international journals and conferences. He was President of Australian Society of Operations Research and Vice President of Maintenance Engineering Society of Australia. His research interests are Stochastic and economic modelling of failure, Asset management, Reliability analysis, Rail risk analysis, Warranty policies, Operations research and optimal decision making, Benchmarking and performance measurement in rail grinding and rail curve lubrication. He has research projects under cooperative research centers for Integrated Engineering Asset Management and Railway Technologies in Australia in the area of asset management and rail risk modelling.

Saurabh Kumar graduated in Mechanical Engineering and received his M.Tech. degree in Maintenance Engineering and Tribology in 2004 from Indian School of Mines, Dhanbad, India. He is currently pursuing PhD in Division of Operation and Maintenance Engineering at Luleå University of Technology, Sweden. His research interests are reliability modelling and prediction, risk based decision making, cost modelling and estimation, and maintenance engineering.

Paper III

Rail defect prioritization and risk assessment using a hybrid approach

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Rail Defect Prioritization and Risk Assessment Using a Hybrid Approach

S. Kumar[1], S. Gupta[2], B. Ghodrati[1]

[1] Division of Operation and Maintenance Engineering, Luleå Railway Research Centre,
Luleå University of Technology, Sweden
[2] Institute of Technology, Banaras Hindu University, India

Abstract

Increasing demands on passenger and freight transportation have increased the axle loads and traffic density, which has caused rail defects to appear in a greater variety and with a greater frequency. Many of these rail defects, if left undetected, can develop into rail breaks, which may lead to train derailments. In order to reduce the number of such catastrophic events, huge investments are made to inspect and maintain the rails. Proper maintenance planning and risk assessment are required to reduce the maintenance cost of rails. Frequent rail inspection intervals and rectifications (rail maintenance actions) require huge investments.

In this paper, we develop a methodology for rail defect prioritization and risk assessment to support the decision-making process during the effective scheduling of the inspection and grinding frequency, based on the type of defect and its risk of occurring and developing into a rail break. The methodology will help in reducing the overall rail maintenance cost, as it helps in making effective decisions related to inspection frequency (i.e. resource allocation according to the need). The methodology is presented with the aid of a case study from the Swedish National Rail Administration (Banverket). As both a quantitative and a qualitative analysis technique has been used in this paper, the methodology developed is considered as a hybrid approach.

Keywords: Rail Breaks, Fault Tree Analysis, Rail Defect Code, Weibull Distribution, Rail Defect Prioritization, Pairwise Comparison, Priority Matrix, Risk Assessment

1. Introduction

An increase in the axle load and the train traffic density has caused rail defects to appear in a greater variety and with a greater frequency than in the past. Many of these rail defects can develop into rail breaks if left undetected. Rail breaks are one of the major causes of train derailments among technical failures [1, 2]. Derailments can lead to catastrophic consequences which may be in the form of loss of human lives, assets, company trust and reputation, as well as fines, compensation, reconstruction costs and traffic delay [3]. The Hatfield derailment (UK) in October 2000 killed 4 and injured 34 people. The damages in terms of consequential costs to the Railtrack Company (acquired by Network Rail in 2002) were about £733 million [4]. According to a report on the Hatfield crash by the Office of Rail Regulation [5], the derailment happened because a rail in which there were multiple cracks and fractures, due to rolling contact fatigue (RCF), fragmented when a high-speed train passed over it.

In order to reduce the number of such catastrophic events, huge investments are made to inspect and maintain the rails. The rail inspection costs alone (assuming annual ultrasonic vehicle-based inspections, followed by manual verification of the detected defects) are estimated at about €70 million per year for a 0.5 million kilometer track system in the European Union [3]. The presence of defects in the rail further increases the maintenance costs exponentially. Proper maintenance planning (such as effective grinding and lubrication frequencies) and risk assessment are required to reduce the huge maintenance investments being made in rails. A great deal of research has been performed on the modeling and analysis of different types of rail defects with the aim to reduce their occurrence [2, 6-9]. This has helped, to some extent, reduce the replacement and rectification cost of the rails. However, there has not been a great deal of research performed to reduce the inspection cost, which still remains unchanged. Therefore, to reduce the inspection costs, rail defect prioritization and risk assessment are required for the effective scheduling of the inspection frequency based on the type of defect and its risk of occurring and developing into a rail break. One benefit from optimizing the inspection frequency is that the resources can be allocated according to the need [10]. Furthermore, a rail section replacement or remedial strategy (optimum intervals for grinding campaigns) can also be developed for different types of defects, based on their risk of developing into a rail break.

This paper presents a methodology for rail defect prioritization and risk assessment with the aid of a case study from the Swedish National Rail Administration (Banverket). Data related to the defect type, the age of the rail and the inspection frequency have been extracted from Banverket's inspection reports. Qualitative assessment of the severity of different types of defects is performed according to their likeliness to develop into a rail break, based on expert judgment using the paired comparison technique. This technique is used for estimation of severity, because the severity of a defect depends on a number of influencing factors, the data for which will not be practically available. As both a quantitative and a qualitative analysis technique has been used in this paper, the developed methodology is considered as a hybrid approach.

1.1 Rail Defect Code

The possible causes of rail defect initiation and propagation include rolling contact fatigue (RCF), shear stress, wear, ratcheting and weld problems, which depend upon the different factors influencing the rail degradation process [11]. These causes initiate a variety of defects in rails, such as surface/subsurface cracks, head checks, squats, spalling, shelling, etc. As these defects are considered as part of an ongoing degradation process, their probability of occurrence can be modeled if their state of degradation can be clearly defined. The UIC rail defect classification standard [12] defines the different types of rail defects into different degradation states based on their location and propagation characteristics, and assigns them a defect code. In this paper, the different defect types assigned by defect codes are considered as failure states.

Many infrastructure managers follow the UIC rail defect classification standard, as it helps them to understand and analyze the rail defects better [13]. Standardized information in the form of a rail defect code becomes particularly useful while carrying out data reporting, interpretation and analysis. The scope for misinterpreting the information intended to be conveyed is considerably reduced by the use of defect codes to explain clearly the defect characteristics.

2. Risk Assessment

Risk assessment of rail defects can provide cost effective options for the infrastructure managers for scheduling inspection, grinding, lubrication and replacement intervals. Risk assessment of rail defects requires not only the failure probability, but also the severity or the consequence of the failure [14, 15]. In this paper, the risk of the occurrence of a rail defect and its development into a rail break is calculated as the product of the probability of occurrence of failure and the severity of the defect.

Risk analysis is a technique of identifying, characterizing, quantifying and estimating the hazards and consequences [16]. There are several methodologies and techniques available that can help a maintenance team to identify and estimate the level of risk, for example Failure Mode and Effects (Criticality) Analysis (FMEA/FMECA), Fault Tree Analysis (FTA), Event

Tree Analysis (ETA), Preliminary Hazard Analysis (PHA), Hazard and Operability Study (HAZOP), etc. In this paper, FTA is used to identify logically the possible causes of a train accident. The fault tree analysis method has been evolving for the past four decades and is probably the most widely used method for the prediction of system failure. FTA is concerned with the identification and analysis of conditions and factors which cause or contribute to the occurrence of a defined undesirable event, usually one which significantly affects system performance, economy, safety or other required characteristics. FTA is often applied to the safety analysis of systems [17]. FTA is a technique that can be used to predict the expected probability of the failure/hazardous outcome of a system in the absence of actual experience of failure. FTA is an example of a deductive analysis approach. It is a graphical approach which starts with a failure and branches out showing the possible causes [18].

Figure 1 shows the fault tree of a train accident. The top event of the fault tree is the train accident, which is caused either by a derailment or a collision (undesired events). The middle events, such as technical failure, track failure, etc., are the intermediate events, which connect the bottom events to the top events. The bottom events are the basic events, which consist of different rail defects and the important factors influencing these defects. There are several other conditions under which a train accident can happen, but they are not looked into, as they are beyond the scope of this paper. The rail defects are shown according to their UIC code in Figure 1.

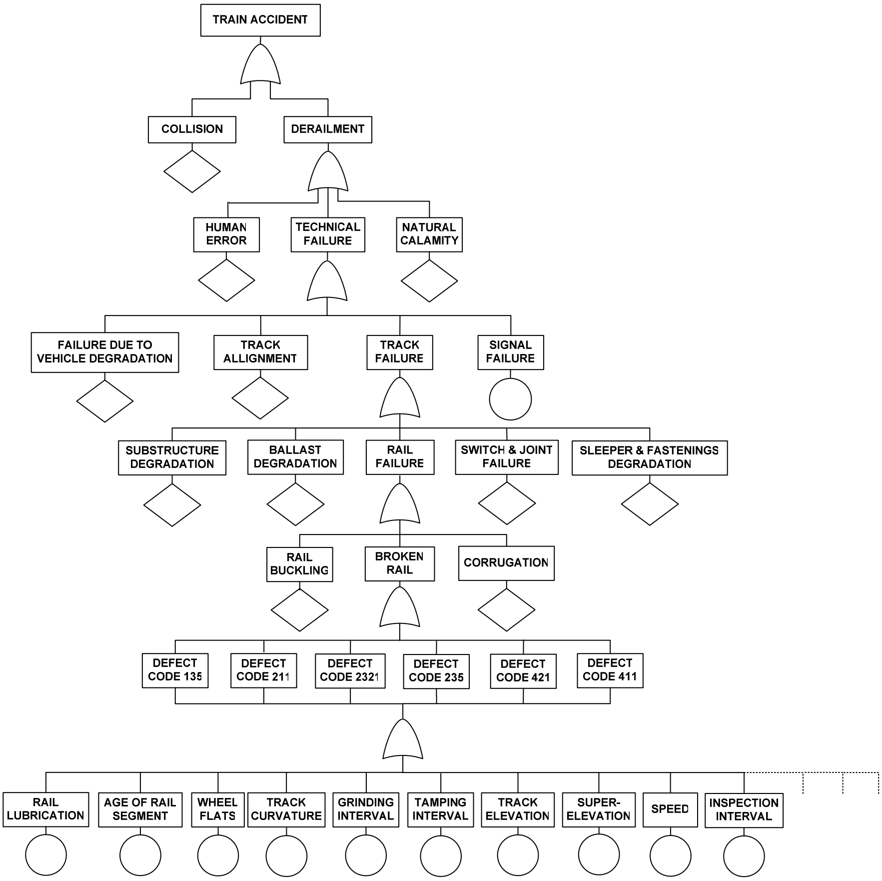

Figure 1: Fault tree of a train accident

3. Methodology and Model Development

In order to calculate the risk of the occurrence of a rail defect and its development into a rail break, the probability of the occurrence of failure and the severity of each of the six defect types need to be calculated. The first part (i.e. the probability of the occurrence of failure) is calculated from the data extracted from Banverket's ultrasonic car inspection reports, hand-held ultrasonic equipment inspection reports and visual inspection reports on section 111 (the Iron-ore Line from Kiruna to Riksgränsen in Sweden). The line allows a 30-tonne axle load with mixed traffic.

The data were entered into an Excel spread sheet after their extraction from the inspection reports. Inspection data were then classified according to the defect type, defect location, date of inspection of that defect and year in which the rail segment on which the defect occurred was earlier replaced. As ageing in rails takes place due to tonnage accumulation on the track resulting from traffic movement, rail defect data analysis is based on Million Gross Tonnes (MGT) of traffic flow. Rail segments are used as per the database of rail replacements and ageing is estimated by assuming 25 MGT per year of traffic flow [11]. The age of the rail segments having a rail defect is calculated by multiplying the annual MGT of traffic flow by the difference between the year in which the rail segment was inspected for a rail defect and the year when it was last replaced.

During the entire operational life of a rail segment, several maintenance and repair actions are repeatedly taken, such as welding, grinding, lubrication, etc., so that the rail segment does not deteriorate at an accelerated rate. Therefore, a rail segment is considered as a repairable system. It is assumed that the maintenance and repair actions keep the rail system in an *as-bad-as-old* condition, which means that the failure rate of a rail segment neither accelerates nor decelerates, but progresses at the same rate as the rate before the maintenance and repair actions were taken, as shown in Figure 2 (a). The time taken to repair a rail segment is considered negligible when considering the whole life of that rail segment (see for details, [19]).

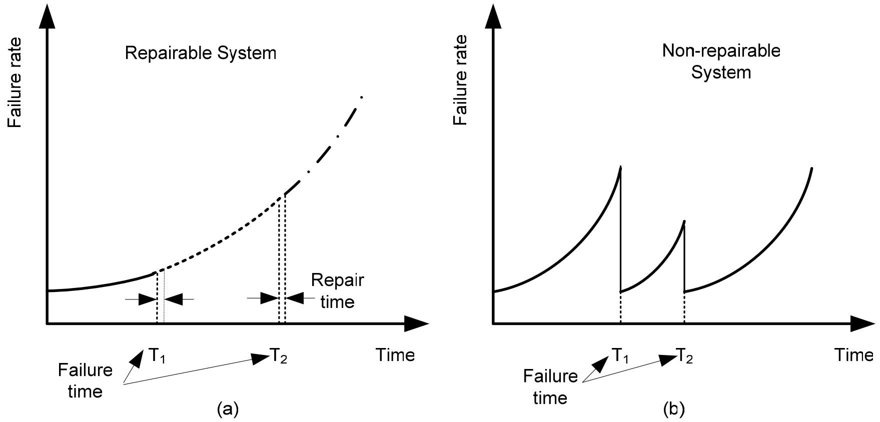

Figure 2: Plot of failure rate vs time for repairable and non-repairable system (adapted from [20])

However, in the case of a non-repairable system, failures and hence replacements over time occur according to a renewal process, since each failed item is replaced by a new one as shown in Figure 2 (b).

3.1. Trend Analysis

Before analyzing the data sets (classified according to different defect types) or choosing an appropriate failure distribution model for each of them, one must proceed with a trend test. Figure 3 illustrates a flow chart explaining the order in which the field failure data should be analyzed instead of fitting a reliability model based on distribution analysis from the very beginning [21].

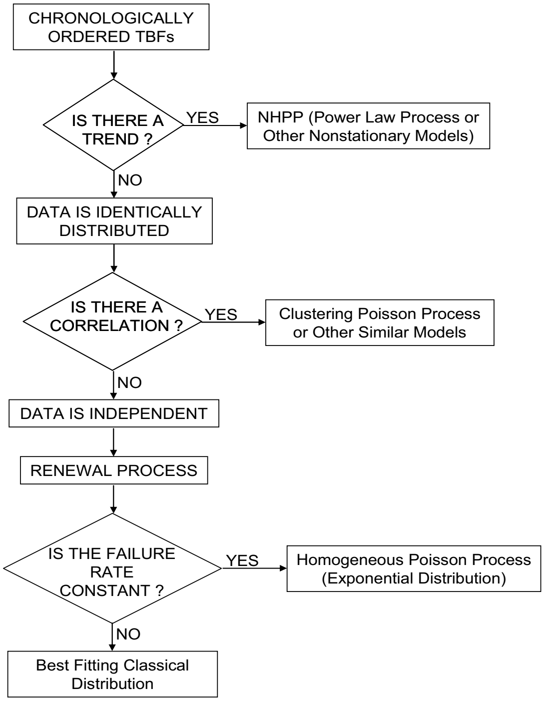

Figure 3: The steps in field failure data analysis before fitting distribution models (adapted from [22])

The trend test was carried out for chronologically ordered failure data by plotting the cumulative number of failures against the cumulative failure MGT. If the plotted points lie on a straight line, this implies that there is no trend in the failure data. However, if evidence of a trend is concluded, a non-stationary model such as the Non-homogeneous Poisson Process (NHPP) must be fitted (for example the Power Law Process) [23]. Figure 4 and 5 show the plot for the trend test of the failure data for defect types 211 and 411 respectively.

In both of these graphs, the plotted points lie on a straight line, which means that the data do not have any trend. Similar plots were observed for all the other defect types analyzed. This confirms that the data sets are identically distributed.

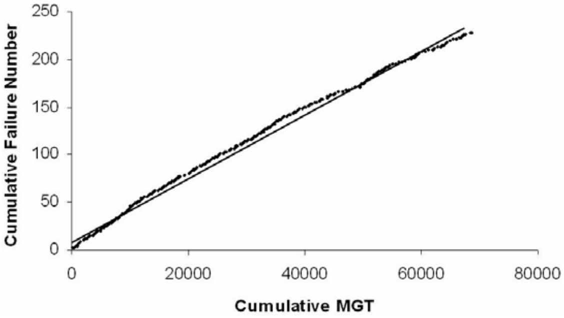

Figure 4: Trend test for defect type 211

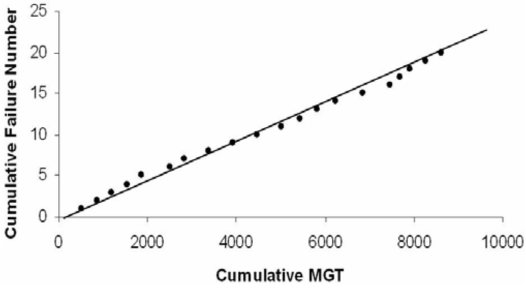

Figure 5: Trend test for defect type 411

Thereafter, a test for serial correlation can be performed graphically by plotting the ith time to failure against the (i-1)th time to failure, where i=1,2,3,…,n, and checking if there is any correlation among the plots. Figure 6 and 7 show the plot of serial correlation for defect types 211 and 411 respectively.

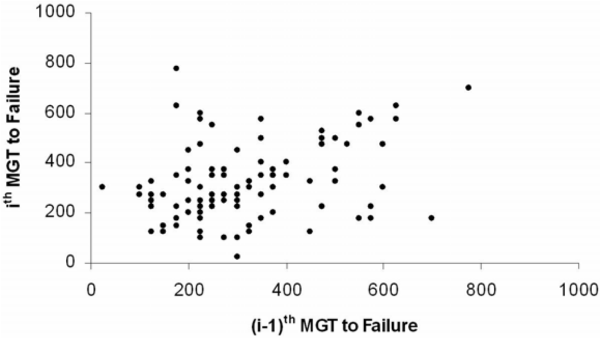

Figure 6: Test for serial correlation of defect type 211

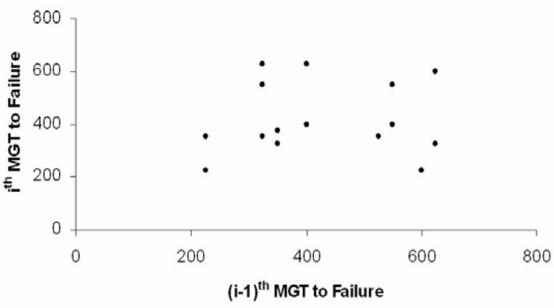

Figure 7: Test for serial correlation of defect type 411

It is evident from the two plots that the data are not correlated. Similar results were obtained when this test was further carried out for the remaining data sets. Therefore, according to Figure 3, a classical distribution which best fits the data sets will be the most appropriate failure model for the data sets in the present case. It may not be appropriate to use classical statistical techniques if the failure data are not independent and identically distributed [24].

3.2. Data Analysis Using the Best Fitting Failure Model

The best fit test was carried out using ReliaSoft's Weibull++6 software. For most of the defect types (defect code 211, 411, 421 and 2321), the 2-parameter Weibull distribution was the best fitting distribution, whereas the 3-parameter Weibull distribution was the best fitting distribution for defect types having defect codes 135 and 235. The analysis was performed using maximum likelihood estimation. Weibull distribution is often used to represent the problems related to mechanical component aging, wear and degradation [25]. Therefore, the data sets were analyzed using the above distributions with the aid of ReliaSoft's Weibull++6 software. Unreliability (i.e. the probability of the occurrence of failure) for the 3-parameter Weibull distribution is expressed as:

$$F(t) = 1 - e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \tag{1}$$

where β, η, γ are the shape, scale and location parameters respectively. In the case of the 2-parameter Weibull distribution the location parameter becomes zero.

The probability of the occurrence of failure at different intervals of time (i.e. at different tonnage accumulation) for the failure data sets of each of the defect types was calculated. Table 1 shows the probability of the occurrence of failure for each of the defect types at different time intervals.

Table 1: Probability of occurrence of failure for each defect type at different time intervals

		Defect Types (Code)					
		135	**211**	**2321**	**235**	**411**	**421**
Time in Years	**1**	0.0000	0.0013	0.0001	0.0000	0.0000	0.0003
	2	0.0000	0.0077	0.0007	0.0000	0.0002	0.0024
	3	0.0000	0.0215	0.0030	0.0000	0.0008	0.0087
	4	0.0000	0.0441	0.0085	0.0000	0.0023	0.0215
	5	0.0000	0.0763	0.0189	0.0000	0.0055	0.0434
	6	0.1146	0.1184	0.0363	0.0000	0.0111	0.0762
	7	0.2964	0.1699	0.0625	0.0000	0.0200	0.1216
	8	0.4747	0.2300	0.0994	0.0000	0.0334	0.1800
	9	0.6263	0.2969	0.1482	0.0000	0.0522	0.2510
	10	0.7449	0.3687	0.2093	0.0000	0.0776	0.3326
	11	0.8321	0.4433	0.2821	0.1158	0.1104	0.4219
	12	0.8930	0.5182	0.3650	0.4712	0.1512	0.5149
	13	0.9338	0.5912	0.4549	0.5935	0.2005	0.6069
	14	0.9602	0.6602	0.5477	0.6687	0.2580	0.6935
	15	0.9766	0.7236	0.6388	0.7215	0.3230	0.7709
	16	0.9866	0.7800	0.7237	0.7612	0.3941	0.8364
	17	0.9925	0.8290	0.7985	0.7923	0.4696	0.8888
	18	0.9959	0.8701	0.8605	0.8173	0.5469	0.9284
	19	0.9978	0.9038	0.9089	0.8380	0.6234	0.9564
	20	0.9989	0.9305	0.9441	0.8553	0.6964	0.9750

3.3. Assessment of Severity of Different Defect Types

The severity of a defect type depends on a large number of factors influencing the initiation and propagation of a defect (see Figure 1). It is difficult to calculate the severity of a defect quantitatively, because to do so one would have to know the extent of the effect (i.e. percentage of contribution) of each of these factors influencing a rail defect in quantitative terms. Many of these factors are subjective in nature and it is difficult to model their influencing function. However, it is easier to compare the relative importance between two factors, as is done in the pairwise comparison approach. Expert judgment was used as a qualitative assessment tool to find out the severity of different defect types which can develop into a rail break. The assessment by field experts was carried out based on a pairwise comparison technique. In the pairwise comparison technique, the ratio of priorities for each factor is established through paired comparison [26]. The experts judge the relative importance of two defect types, which ultimately forms the judgment matrix, which is based on the likeliness of the different defect types to develop into a rail break. The principal eigenvector of the comparison matrix standardizes so that it sums to unity and becomes the ratio measure of the relative importance of each defect type. It can measure the consistency in the experts' judgment also.

3.3.1. Pairwise Comparison Matrix

The pairwise comparison approach is based on the fundamental principle that it is more difficult to evaluate n elements (where $n > 2$) simultaneously than to compare two such elements at a time. In pairwise comparison, experts compare the importance of two factors on a relatively subjective scale. In this way a judgment matrix of importance is build up according to the relative importance given by the experts. Table 2 represents a pairwise comparison scale for the value rating of judgments and for deriving pairwise ratio scales. Table 2 also includes reciprocals, which are equally adopted for relative measurements or comparisons of factors. A total of $\frac{n(n-1)}{2}$ judgments are required for comparing n factors.

Table 2: AHP pairwise comparison scale

Value rating for judgment	**Verbal judgment**
1	Elements are equally preferred
3 or (1/3)	One is moderately preferred to the other
5 or (1/5)	One is strongly preferred to the other
7 or (1/7)	One is very strongly preferred to the other
9 or (1/9)	One is extremely preferred to the other
Note: (2, 4, 6, 8: intermediate judgmental values between adjacent scale values)	

3.3.2. Method of Collection of Judgments from Different Experts

A multiple choice questionnaire was prepared which consisted of 15 questions (a sample questionnaire is given in Appendix B) regarding the relative likeliness of one defect type, compared with another, to develop into a rail break. A pre-study was carried out by sending the questionnaire to three experts individually, to obtain some suggestions for improvement. Thereafter, a suitable team of experts working at different positions in Banverket were invited to assess the (improved) questionnaire. When selecting the experts more stress was placed on the experience of the candidate. Eight experts were selected for judging the questionnaire, of whom only five were consistent enough throughout their judgment. The short list of these five experts was based on their consistency ratio (CR), see below.

3.3.3. Measuring Inconsistency in Judgments

Human judgments are the basis of the pairwise comparison approach. Some degree of inconsistency may be introduced in pairwise comparisons as a result of a number of factors, for example a lack of adequate information, improper conceptualization, mental fatigue, etc. The difference $\lambda_{\max} - n$ (where $\lambda_{\max}$ is the largest eigenvalue and n is the number of comparisons) can be employed as a measure of inconsistency. However, instead of using this directly, Saaty (1987) defined a consistency index (CI) calculated as:

$$CI = \frac{\lambda_{\max} - n}{n-1} \qquad (2)$$

The closer this CI comes to zero, the better is the overall consistency in the judgments. The simulation of a large number of randomly generated pairwise comparisons for different sizes of matrices carried out by Saaty, with regard to calculations of the average CIs, resulted in what he defines as the random index (RI). The values of such standard CIs (or RIs) are presented in Table B, Appendix A [27]. The significance of the values of the RI is that the ratio of the CI for a particular set of judgments to the RI of the same size of matrix indicates a measure of the inconsistency ratio or consistency ratio (CR) for the matrix of judgments, i.e. a measure of inconsistency in judgments. A perfectly consistent judgment will yield a CI of zero; the CR will also be zero. Usually, a value of the CR between 0 and 0.10 (i.e. 10 per cent of what would be the outcome from random judgments) is acceptable [26]. The CR of the judgment matrices of all the experts was calculated. The final judgment matrixes of all the five experts are presented in Appendix C and the CR values of their judgment matrices are tabulated in Table 3.

Table 3: Final CR values of the judgment matrices

Expert	**CR Value**
1	0.0716
2	0.0347
3	0.0584
4	0.0716
5	0.0777
Overall	0.0100

3.3.4. Aggregating Judgments of Different Experts

Each expert's assessment generates a pairwise comparison matrix for the set of defect codes. As pointed out by [28], the same pairwise comparison for each expert can be aggregated into a group comparison by taking the geometric mean of all the comparisons. The geometric mean is the only averaging process that maintains the reciprocal relationship ($a_{ij}=1/a_{ji}$) in the aggregate matrix. The general formula for calculating a geometric mean group response is:

$$\text{Weighted mean value of } \left(\prod_{k=1}^{n} w_k \cdot a_{ij} \right)^{1 / \sum_{k=1}^{n} w_k} \tag{3}$$

where a_{ij} is each expert's paired comparison value,
n is the number of experts, and
w_k is the weight of the k^{th} expert.

In this study, we have assumed that all the experts have equal expertise and therefore $w_k = 1$ for all k. The priority vector of six defect codes is given in Table 4. These values denote the severity of each defect type according to their likeliness to develop into a rail break.

Table 4: Final priority value (severity) of defect codes

Defect Code	Severity
211	0.1858
411	0.1488
421	0.3083
2321	0.0874
235	0.0679
135	0.2018

4. Results and Discussions

After estimating the severity of different defect types, the risk of the occurrence of a rail defect and its development into a rail break, for different defect types, can be estimated as a product of the probability of the occurrence of a rail defect and the severity of that defect according to its likeliness to develop into a rail break. Table 5 shows the risk of the occurrence of a rail defect and its development into a rail break for different defect types at different intervals of time. This table is a result of multiplying the probability values in Table 1 by the estimated severity of different defect types (Table 4).

Table 5: Risk of occurrence of different types of rail defects and their development into a rail break at different time intervals

		Defect Types (Code)					
		135	**211**	**2321**	**235**	**411**	**421**
Time in Years	**1**	0.00000	0.00025	0.00000	0.00000	0.00000	0.00008
	2	0.00000	0.00144	0.00006	0.00000	0.00002	0.00073
	3	0.00000	0.00400	0.00026	0.00000	0.00011	0.00267
	4	0.00000	0.00819	0.00074	0.00000	0.00034	0.00664
	5	0.00000	0.01418	0.00165	0.00000	0.00081	0.01337
	6	0.02312	0.02200	0.00317	0.00000	0.00164	0.02351
	7	0.05982	0.03158	0.00547	0.00000	0.00298	0.03749
	8	0.09579	0.04272	0.00869	0.00000	0.00497	0.05551
	9	0.12640	0.05516	0.01295	0.00000	0.00777	0,.07738
	10	0.15033	0.06851	0.01829	0.00000	0.01155	0.10255
	11	0.16791	0.08237	0.02466	0.00787	0.01643	0.13009
	12	0.18020	0.09629	0.03190	0.03200	0.02250	0.15874
	13	0.18844	0.10985	0.03976	0.04030	0.02983	0.18711
	14	0.19376	0.12267	0.04787	0.04540	0.03839	0.21382
	15	0.19709	0.13444	0.05583	0.04899	0.04806	0.23768
	16	0.19910	0.14493	0.06325	0.05168	0.05865	0.25787
	17	0.20029	0.15402	0.06978	0.05380	0.06988	0.27403
	18	0.20097	0.16167	0.07521	0.05550	0.08138	0.28621
	19	0.20136	0.16792	0.07944	0.05690	0.09277	0.29485
	20	0.20157	0.17288	0.08251	0.05808	0.10362	0.30059

Figure 8 shows the plot of the risk of the occurrence of a defect type and its development into a rail break against time in years. It can be inferred from the plot that there is a very low risk of occurrence of the defect types which can develop into a rail break during the first five years after a new rail segment is put into use (assuming the annual tonnage to be 25 MGT on the track section under study). However, there is a slight risk that defects having defect codes 211 and 421 can occur and develop into a rail break during the first five years of a new rail segment in comparison with the other defect types analyzed.

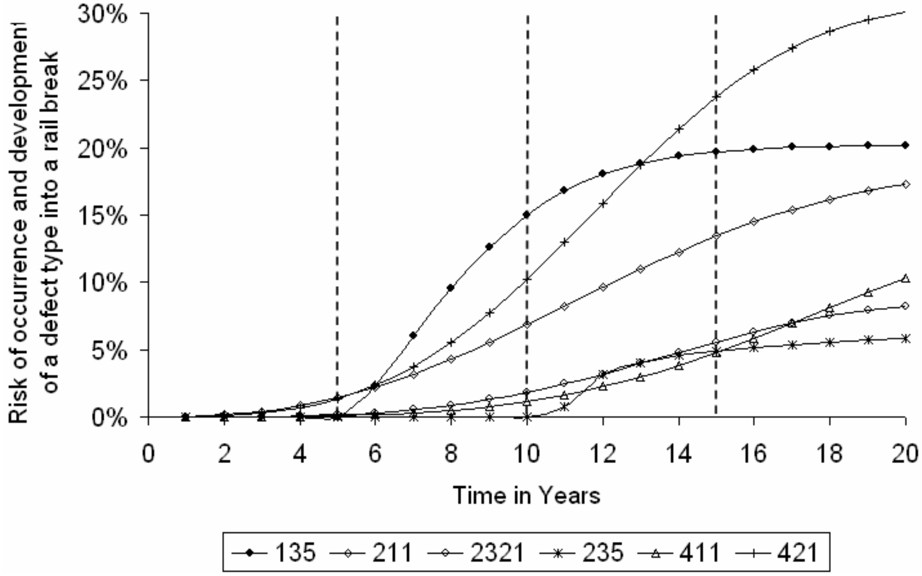

Figure 8: Plot of risk of a defect type developing into a rail break at different time intervals

There is a sudden increase in the risk of the occurrence of defect type 135 when the rail segment has an age of 5 to 10 years. Therefore, we can find a greater amount of star cracking of fishbolt holes lying near the rail ends when the age of the rail segment is between 5 and 10 years, and these defects have an increasing risk of developing into a rail break. There is also a gradual increase in the risk of occurrence and development of rail breaks for defect types 421 and 211 when the age of the rail segment is 5 years. This means that the inspectors should put more effort into inspecting the rail ends and thermit welds visually or increase the inspection frequency after the age of the rail segment has reached 5 years according to the curve of defect type 135 and 421. The ultrasonic car inspection frequency should also be increased when the rail segment has an age of 5 years, as defect type 211 (i.e. kidney-shaped fatigue cracks, a subsurface defect) is on the rise. Defect types 2321, 235 and 411 have a low risk of occurring and developing into a rail break when the age of the rail segment is between 5 and 10 years.

When the age of the rail segment is between 10 and 20 years, there is an increasingly high risk of the occurrence of defect type 421 and its development into a rail break. Therefore, thermit welds should be inspected regularly when the age of the rail segment has reached 10 years, and the inspection intervals should be gradually shortened as the age of the rail segment progresses. Defect type 135 shows a relatively constant risk after 10 years. Therefore, constant visual inspection intervals could be fixed for inspecting these defect types after the age of the rail segment has reached 10 years. There is an abrupt increase in the risk of the occurrence of defect type 235 and its development into a rail break when the age of the rail segment is between 10 and 12 years (Figure 8). This trend stabilizes later on as the age of the rail segment progresses. A possible recommendation for this trend can be to intensify slightly the visual inspections, looking into the holes on the rail segments other than the fishbolt holes when the age of the rail segment has reached 10 years. Electric flash-butt welds should be of low priority from an inspection point of view, as the defects originating in these welds (defect code 411) have a low risk in comparison with other defect types.

4.1. Algorithm of the Proposed Methodology for Risk Assessment of Different Defect Types

Step 1. Collect and classify data in relation to different types of rail defect
Step 2. Proceed for trend analysis
Step 3. Analyze the data for the best fitting distribution
Step 4. Calculate the probability of occurrence of failure for different intervals of time
Step 5. Prepare the questionnaires
Step 6. Make a list of experts to assess the questionnaire based on their experience and expertise
Step 7. Gather the experts' opinions of pairwise comparison regarding the likeliness of the defects to develop into rail breaks
Step 8. Verify the consistency in the experts' judgments through the consistency ratio
Step 9. Form the aggregated judgment matrix
Step 10. Rank and calculate the severity of different defect types
Step 11. Estimate the risk of the occurrence of a rail defect and its development into a rail break for different defect types as a product of the probability of occurrence of failure and the severity of the rail defect
Step 12. Discuss the results and possible suggestions to help in the decision-making process

5. Conclusions

A methodology has been developed for rail defect prioritization and risk assessment to support the decision-making process during the effective scheduling of the inspection and grinding frequency, based on the type of defect and its risk of occurring and developing into a rail break. The algorithm of the methodology is proposed in Section 4.1. A large number of inferences can be drawn from the risk plot (Figure 8) and inspection intervals can be scheduled according to the need. However, the minimal inspections required should always be performed, as the deductions of the paper are purely probabilistic in nature. The developed methodology will help in reducing the overall rail maintenance cost, as it helps in making effective decisions related to inspection intervals. The grinding campaigns can also be scheduled according to the inspection frequencies of different defect types. Furthermore, a more detailed analysis is required to look into the cost aspects of inspection and grinding intervals for making optimal decisions.

A scientific approach and logical reasoning have been applied for rail defect prioritization and risk assessment through performing a trend and serial correlation test, choosing the best fitting distribution, and pairwise comparison for estimation of the severity of different rail defect types.

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APPENDIX A

Table A: UIC defect code and its description [12]

UIC Defect Code	Description
Defect Code 135	Star cracking of fishbolt holes; this defect consists of progressive cracks that radiate from the fishbolt hole. They are mostly located near the rail ends.
Defect Code 211	Progressive transverse cracking (kidney-shaped fatigue crack); this defect develops from a defect inside the rail head, from an internal horizontal crack or deep shelling of the gauge corner.
Defect Code 2321	Horizontal cracking at the web-head fillet radius; this crack initially develops in the rail web, parallel to the web-head fillet radius and may curve either upwards or downwards as it progresses.
Defect Code 235	Cracking around the holes other than the fishbolt holes; this defect has the same appearance as that of defect code 135, but it occurs away from the rail ends.
Defect Code 421	Transverse cracking of the profile; this is a welding and resurfacing defect occurring in/near the thermit welding.
Defect Code 411	Transverse cracking of the profile; this is a resurfacing defect occurring in electric flash-butt welding. The crack develops in the weld cross-section either from an internal defect of the head in the weld or from a defect located in the foot of the rail.

Table B: RI of many randomly generated pairwise comparison matrices of size n (adopted from [27])

Size of matrix (n)	**Random index (RI)**
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

APPENDIX B

Defect code A is	Absolutely more likely	Strongly more likely	Moderately more likely	Slightly more likely	Equally likely	Slightly less likely	Moderately less likely	Strongly less likely	Absolutely less likely	than defect code B to develop into a rail break
	☐	☐	☐	☐	☐	☐	☐	☐	☐	
211	☐	☐	☐	☐	☐	☐	☐	☐	☐	411
211	☐	☐	☐	☐	☐	☐	☐	☐	☐	421
211	☐	☐	☐	☐	☐	☐	☐	☐	☐	2321
211	☐	☐	☐	☐	☐	☐	☐	☐	☐	235
211	☐	☐	☐	☐	☐	☐	☐	☐	☐	135
411	☐	☐	☐	☐	☐	☐	☐	☐	☐	421
411	☐	☐	☐	☐	☐	☐	☐	☐	☐	2321
411	☐	☐	☐	☐	☐	☐	☐	☐	☐	235
411	☐	☐	☐	☐	☐	☐	☐	☐	☐	135
421	☐	☐	☐	☐	☐	☐	☐	☐	☐	2321
421	☐	☐	☐	☐	☐	☐	☐	☐	☐	235
421	☐	☐	☐	☐	☐	☐	☐	☐	☐	135
2321	☐	☐	☐	☐	☐	☐	☐	☐	☐	235
2321	☐	☐	☐	☐	☐	☐	☐	☐	☐	135
235	☐	☐	☐	☐	☐	☐	☐	☐	☐	135

APPENDIX C

Judgment matrix of Expert:1

Defect Code	211	411	421	2321	235	135
211	1	1/3	1/7	3	1/3	1/5
411	3	1	1/5	7	1	1/3
421	7	5	1	9	5	3
2321	1/3	1/7	1/9	1	1/5	1/7
235	3	1	1/5	5	1	1/3
135	5	3	1/3	7	3	1

Judgment matrix of Expert:2

Defect Code	211	411	421	2321	235	135
211	1	1	1/7	1/6	3	1/2
411	1	1	1/7	1/6	3	1/2
421	7	7	1	3/2	9	5
2321	6	6	2/3	1	7	3
235	1/3	1/3	1/9	1/7	1	1/4
135	2	2	1/5	1/3	4	1

Judgment matrix of Expert:3

Defect Code	211	411	421	2321	235	135
211	1	5/2	1/2	9/2	8	6
411	2/5	1	2/7	3	7	9/2
421	2	7/2	1	6	9	7
2321	2/9	1/3	1/6	1	5	2
235	1/8	1/7	1/9	1/5	1	1/2
135	1/6	2/9	1/7	1/2	2	1

Judgment matrix of Expert:4

Defect Code	211	411	421	2321	235	135
211	1	3	1/3	7	1	1/5
411	1/3	1	1/5	3	1/3	1/7
421	3	5	1	7	3	1/3
2321	1/7	1/3	1/7	1	1/5	1/9
235	1	3	1/3	5	1	1/5
135	5	7	3	9	5	1

Judgment matrix of Expert:5

Defect Code	211	411	421	2321	235	135
211	1	3	9	7	9	5
411	1/3	1	7	5	7	3
421	1/9	1/7	1	1/3	1	1/5
2321	1/7	1/5	3	1	3	1/3
235	1/9	1/7	1	1/3	1	1/5
135	1/5	1/3	5	3	5	1

Overall aggregated judgment matrix

Defect Code	211	411	421	2321	235	135
211	1	3/2	1/2	23/9	7/3	1
411	2/3	1	2/5	11/5	13/6	4/5
421	2	22/9	1	20/7	29/7	3/2
2321	2/5	4/9	1/3	1	4/3	1/2
235	3/7	1/2	1/4	3/4	1	2/7
135	1 0/9	5/4	2/3	2	18/5	1

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Paper IV

Reliability improvement through alternative designs: a case study

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Short communication

Reliability improvement through alternative designs—A case study

Saurabh Kumar[a,*], Gopi Chattopadhyay[b], Uday Kumar[a]

[a]*Division of Operations and Maintenance Engineering, Luleå University of Technology, SE 97187 Luleå, Sweden*
[b]*Queensland University of Technology School of Engineering Systems, 2, George Street P.O. Box 2434, Brisbane QLD 4001, Australia*

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Abstract

In today's competitive world, reliability of equipment is extremely important to maintain quality and delivery deadlines. This is achieved by using proper maintenance and design changes for unreliable subsystems and components of a complex system. It is significant to develop a strategy for maintenance, replacement and design changes related to those subsystems and components. An analysis of down time along with causes is essential to identify the unreliable components and subsystems.

This paper presents an analysis of failure data of solenoid coils of automatic internal grinding machine used in a bearing manufacturing plant. It analyses various replacement and change of design options such as introduction of pneumatic system in place of electromagnetic solenoids for improvement of reliability of the plunger movement mechanism.

Keywords: Down time; Design changes; Reliability improvement; Cost estimation

1. Introduction and background

Reliability analysis is one of the main tools to ensure agreed delivery deadlines which in turn maintain certain intangible factors such as customer goodwill and company reputation [1]. Downtime often leads to both tangible and intangible losses. These losses may be due to some unreliable subsystems/components, thus an effective strategy for maintenance, replacement and design changes related to those subsystems and component needs to be framed out [2–4].

A system is constituted by a number of components and/or subsystems designed to achieve a common specific result with an acceptable level of reliability. The type of component failure and its frequency has a direct effect on the system's reliability. Thus it becomes very important to locate the critical components and analyse their reliability. Furthermore, in many situations it is easier and less expensive to test components/subsystems rather than entire system.

In the present case study, the problem is based on excessive downtime of automatic internal grinding machine of a bearing production plant (NRB Bearings Ltd, India). The machine is used for internal grinding of outer rings of the bearing. The general outline and the working principle are presumed to be self explanatory from Figs. 1 and 2.

Rejects, reworks and downtime leads to wastage and additional costs to the products, profit margin drops down and thus the product becomes less competitive in the market. Sometimes this leads to reduction in market share [5]. So the company has to reduce production forcibly (underutilization of plant capacity) which ultimately increases the cost of production. On the other hand, problems with quality also add cost, the effect of which is in-line with the loss in productivity. In addition to this, there is a probability of loosing customer goodwill.

This research was carried out to analyse downtime, find out main cause and locate the critical components/subsystems based on their frequency of failure, develop models to predict reliability of the system (see Ref. [6]) and expected costs associated with current unreliable subsystem and components, explore the design options available and estimate the cost benefit by considering the design change.

One-year data from production report is collected and analysed to carry out Pareto analysis of the causes behind failures. The expected number of failures of the most

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*Corresponding author. Tel.: +46 920 49 1272; fax: +46 920 49 1935.
E-mail address: saurabh.kumar@ltu.se (S. Kumar).

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Notations

$F(t)$	cumulative distribution function
$f(t)$	density function
t	time interval between failures
η	characteristic life or scale parameter
β	slope or shape parameter
n	expected no. of failures per year
C_c	cost of component
r	repair rate per hour
L_n	number of labours required
P_n	no. of products manufactured per hour
C_p	contributing cost per piece
MTTR	mean time to repair
TTR	time to repair
C_{rj} (Elec.Sol.)	total annual cost of rejections due to electromagnetic solenoid
C_{rw} (Elec.Sol.)	total annual cost of reworks due to electromagnetic solenoid
C_{rj} (Pneu.Cyl.)	the annual cost of rejections due to pneumatic cylinder arrangement
C_{rw} (Pneu.Cyl.)	total annual cost of reworks due to pneumatic cylinder arrangement
INR	Indian rupees

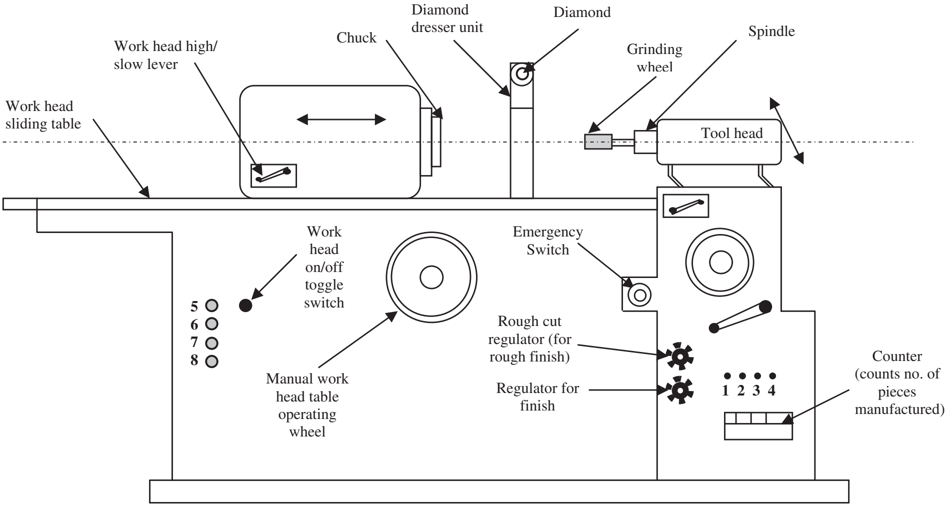

Fig. 1. Automatic internal grinding machine.

critical component (plunger movement mechanism) is calculated based on renewal integral model. a system approach is used to identify the root cause and find out alternative technical solutions to improve the reliability of the system. The overall annual cost assessment of the plunger movement mechanism is done, considering the component cost, replacement cost, cost incurred due to loss in production and annual rework and reject cost. A framework is developed for evaluation of failure modes and improvement of reliability by appropriate design modifications and the expected overall annual cost is calculated for the newly implemented best design option (i.e., pneumatic system). This cost benefit analysis helps to access the effectiveness of the new design for managerial decision. An estimate could then be established for the annual loss the company could have had if the design change based on the reliability analysis would not have been recommended.

2. Modelling and analysis of component reliability

Analysis of failure data (Appendix A: Table A1) of different machine component results in locating the weak component. Once weak components are located, corrective measures are taken to eliminate failures which results in improvement in reliability of the system. There exist many models discussed in the literature which deal with such problems (see Refs. [7–12]).

However, in our case, we focussed on reliability analysis to locate the weak components and find alternative design options by calculating failure expectancy, using renewal integral function (For details see Refs. [13–17]). The best possible design option under the given operating conditions is arrived at and validated using cost modelling and estimation. For this purpose some of the existing models were referred [17,18].

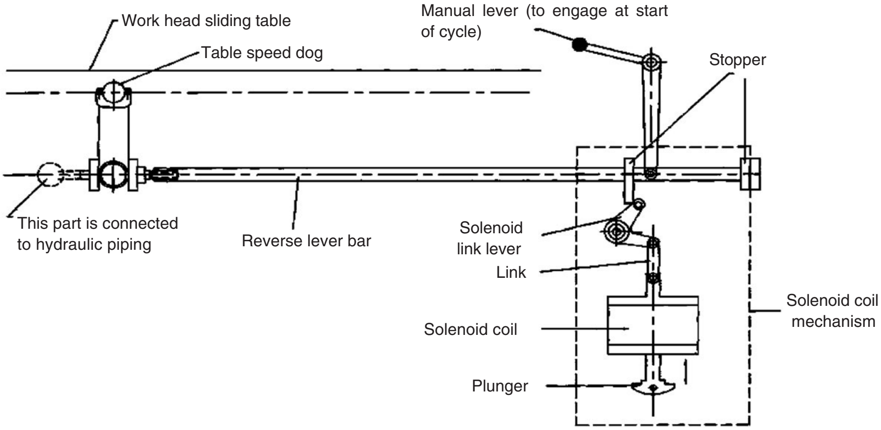

Fig. 2. Schematic diagram of the plunger movement mechanism.

Fig. 3 shows that solenoid coil burnout is the most frequent of all the failures. Thirty-nine percent of the total failures which occurred during a period of 1 year were due to solenoid coil burnout. The annual overall cost due to solenoid coil burnout was INR 24326.46 (Appendix A: Table A2) which is much higher than failures due to other components. On further assessment of other factors, a conclusion is drawn that electromagnetic solenoid is the most critical of all the components.

Thus, the plunger movement subsystem is focussed which comprises of solenoid, plunger, linkage mechanism, bearings and pins. These are treated as non-repairable items and replaced on failures [19]. This is modelled as renewal process.

Failures are modelled using distribution function [20]. Time is a random variable, (T_n), defining the total time to failure of the plunger movement mechanism [4].

$$P\{T_n \leqslant t\} = F^n(t) = F(t) \times F(t) \times \cdots \times F(t). \tag{1}$$

Eq. (1), when expressed in terms of counting process $N(t)$[1] implies that

$$\begin{aligned} P\{N(t)=n\} &= P\{N(t)\geqslant n\} - P\{N(t)\geqslant n+1\} \\ &= P\{T_n \leqslant t\} - P\{T_{n+1}\leqslant t\} = F^n(t) - F^{(n+1)}(t) \end{aligned} \tag{2}$$

the expected number of failures, over a period of time, t, is given by

$$M(t) = E[N(t)] = \sum_{n=0}^{\infty} nP\{N(t)=n\}.$$

Substituting Eq. (2) here

$$M(t) = \sum_{n=0}^{\infty} n\{F^n(t) - F^{(n+1)}(t)\} = \sum_{n=0}^{\infty} F^n(t) \tag{3}$$

or

$$M(s) = \sum_{n=0}^{\infty} \frac{\{f(s)\}^n}{s},$$

where $M(s)$ is the Laplace Transform of $M(t)$.

Taking Laplace transform

$$M(s) = \frac{1}{s}\frac{f(s)}{1-f(s)} \quad \text{or} \quad M(s)[1-f(s)] = F(s). \tag{4}$$

Taking inverse Laplace transform, we get

$$M(t) - M(t) \otimes f(t) = F(t),$$

where $\otimes$ is a convolution operation which could be expressed as

$$M(t) = F(t) + \int_0^t M(t-x)f(x)\,\mathrm{d}x, \tag{5}$$

where $M(.)$ is the renewal function associated with $F(.)$.

Table 1 gives a record of the failures which occurred due to electromagnetic solenoid. The yearly percentage failure time interval was calculated by dividing the time to failure with the total working hours in a year.

---

[1] A counting process $\{N(t),\ t\geqslant 0\}$ is an ordinary renewal process if the following hold:

- $N(0)=0$,
- Sum of n independent and identically distributed random variable

$$T_n = \sum_{i=1}^{n} X_i,\ n\geqslant 1 \quad \text{and} \quad T_0 = 0$$

- $N(t) = \sup\{n : T_n \leq t\}$

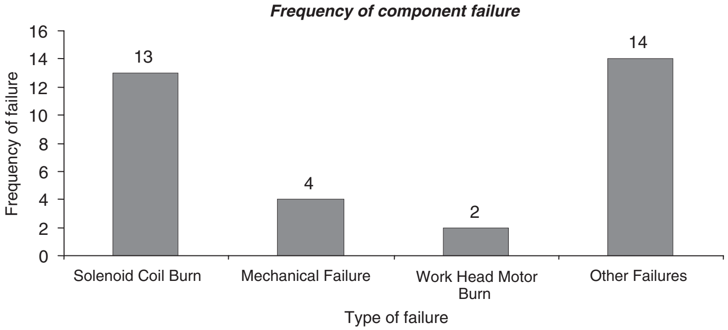

Fig. 3. Graph of frequency of component vs. failure type.

Table 1
Failures due to electromagnetic solenoid

Month of failure	Date of failure	Time to repair (h)	Time to failure (h)	Yearly % failure time interval	Quarterly % failure time interval
November 2003	1-11-2003	1.75	2.250	0.00053	0.002
November 2003	27-11-2003	2.00	345.994	0.08099	0.324
January 2004	22-01-2004	2.25	692.319	0.16206	0.648
February 2004	16-02-2004	1.75	303.578	0.07106	0.284
March 2004	23-03-2004	2.50	452.824	0.10600	0.424
April 2004	26-04-2004	2.00	401.658	0.09402	0.376
May 2004	20-05-2004	1.75	314.327	0.07358	0.294
June 2004	17-06-2004	2.25	340.743	0.07976	0.319
July 2004	26-07-2004	2.00	479.990	0.11236	0.449
August 2004	14-08-2004	2.25	232.497	0.05442	0.218
September 2004	18-09-2004	2.00	406.907	0.09525	0.381
October 2004	21-10-2004	2.00	420.909	0.09853	0.394
December 2004	1-12-2004	2.00	493.906	0.11562	0.462

$$
\begin{aligned}
\text{Where, Total working hour} \\
&= \text{Actual working hour in a day} \\
&\qquad \text{(considering the normal daily allowance)} \\
&\quad \times \text{No. of working days in a week} \\
&\quad \times \text{No. of weeks in a month} \\
&\quad \times \text{No. of months in a year.} \\
&= 14.833 \times 6 \times 4 \times 12 = 4271.904\,\text{h}.
\end{aligned}
$$

Analysis of quarterly failure time interval data was done to find out the best fitting distribution. ReliaSoft Weibull++6 software was used for analysis. The data was left censored as the exact failure time interval of the initial data was not available. Two parameter Weibull distribution [20] gave reasonably good results for this particular component data. The values of (slope or shape parameter) β and (characteristic life or scale parameter) η were found to be 4.1570 and 0.4172, respectively. (Appendix A: Fig. A1). This could be verified by tallying the mean time to failure (MTTF) [21] with the mean value of quarterly failure time interval obtained from Table 1, excluding the initial value. The time of failure which took place before the first recorded data is not exactly known. Thus, this value is excluded for the following calculation, as it is not the exact failure time interval. The mean value comes out to be 0.38.

$$
\begin{aligned}
\text{MTTF} &= \eta\Gamma\left(1+\frac{1}{\beta}\right) \\
&= 0.4172\Gamma\left(1+\frac{1}{4.1570}\right) \\
&= 0.38. \qquad (6)
\end{aligned}
$$

Owing to some of the limitations in the available renewal integral table [4], the data available in the percentage failure time interval for a quarter of a year was considered for analysis. The renewal function for a quarter of a year $M(t)$ was found out to be 3.9524 from the table [4]. Thus, the expected no. of failures in a year, $n = M(t)/\eta = 9.4736$.

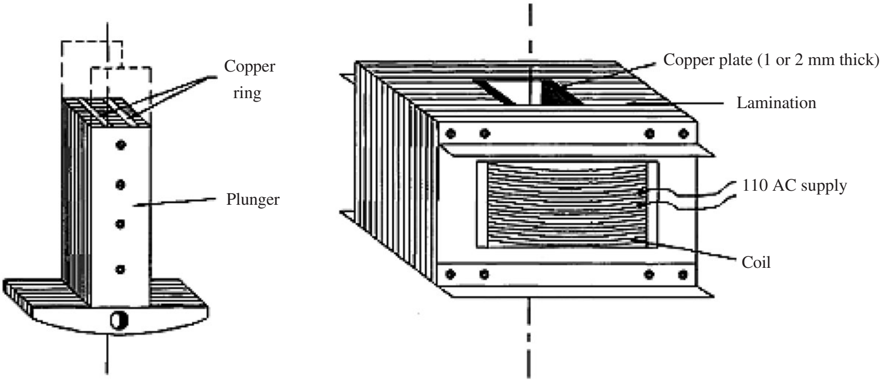

Fig. 4. Solenoid coil with plunger.

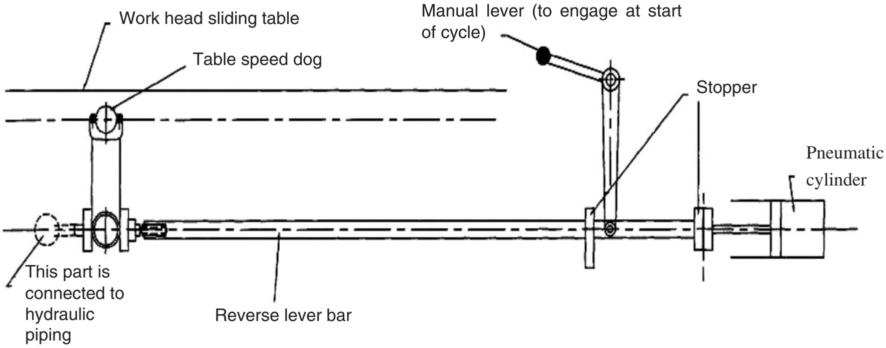

Fig. 5. Schematic diagram of the plunger movement mechanism with electromagnetic solenoid replaced by pneumatic cylinder.

Such a high frequency of coil burn could be attributed to factors such as increase in loads and fluctuations in voltage due to which the coil may have been overheated resulting in burnout furthermore the plunger was unable to maintain the required cycle time for the operation. It resulted in lower quality of finished products leading to more number of rejects.

A close observation revealed that there was a gap in between plunger and lamination. This gap between the surfaces lead to chattering (unwanted production of noise and heat) due to which the coil got burnt. Some remedial measures were taken to overcome this problem, like inserting copper plates of 1 mm thickness in between the plunger and lamination surfaces, as shown in Fig. 4. This would prevent the lateral deviation of the plunger inside the lamination slot. But still the reliability of this component could not be improved satisfactorily.

2.1. *Modelling of expected costs of critical subsystem/component*

The expected overall cost of failure due to Electromagnetic Solenoid per year

$$= n\{C_c + (\mathrm{MTTR} \times r \times L_n) + (\mathrm{MTTR} \times P_n \times C_p) + C_{rj}(\mathrm{Elec.Sol.}) + C_{rw}(\mathrm{Elec.Sol.})\}$$

where $C_c = 1100$ (in the present case); $\mathrm{MTTR} = 2.063$; $r = 65$; $L_n = 2$; $P_n = 36$; $C_p = 5.83$.

Total annual cost of rejection and reworks due to electromagnetic solenoids plays a very important role in cost estimation of the component. Due to the unavailability of data supplied, it is assumed that the average ratio of quality products to reworks and rejects remains the same throughout the year before and after installation of

Table 2
Number of quality products. rejects and reworks before and after installation of pneumatic cylinder

Month	No. of days	No. of quality products	No. of reworks	No. of rejects
Before installation of pneumatic cylinder				
October 2004	25	8584	1400	516
November 2004	26	9883	1520	543
After installation of pneumatic cylinder				
December 2004	25	14 653	587	0
January 2005	16	5040	368	0

pneumatic cylinder as depicted in Table 2.

$$\begin{aligned} C_{rj}\,(\text{Elec.Sol.}) &= \text{Average no. of Rejects due to Electromagnetic Solenoid} \\ &\quad \times \text{No. of Working Days} \times \text{Cost of rejection per piece} \\ &\quad \times \text{Percentage of Failure which occurred due to Electromagnetic Solenoid.} \\ &= \frac{516+543}{51} \times 300 \times 55 \times 0.39 = 133620.88. \end{aligned}$$

Similarly C_{rw} (Elec.Sol.) is calculated. The cost of rework per piece is 0.5 C_{p}.

Thus, C_{rw} (Elec.Sol.) = 19527.07.

By substituting the values in the cost model, the expected overall cost of failure due to electromagnetic solenoid per year comes out to be INR 1,467,925.98

2.2. *Reliability improvement through alternative design options*

Looking on to various design options available, any electrical actuating mechanism was ruled out because the electrical supply in the company was susceptible to voltage fluctuations. A hydraulic cylinder arrangement would not be suitable for high actuation speeds required. Thus, the option of a pneumatic cylinder arrangement was the most suitable, reliable and cost effective one (Fig. 5).

Expected failure costs:

The expected overall cost of failure due to pneumatic cylinder arrangement per year

$$\begin{aligned} &= C_{\text{c}} + (\text{TTR} \times r \times L_n) + (\text{TTR} \times P_n \times C_{\text{p}}) \\ &\quad + C_{\text{rj}}(\text{Pneu.Cyl.}) + C_{\text{rw}}(\text{Pneu.Cyl.}), \end{aligned}$$

where

$$C_{\text{c}} = 3000;\ \ \text{TTR} = 6.5;\ \ r = 65;$$
$$L_n = 2;\ \ P_n = 36;\ \ C_{\text{p}} = 5.83.$$

C_{rj} (Pneu.Cyl.) is zero as there were no rejects during the period of inspection. Thus it is assumed that the same trend would be maintained throughout the year.

Calculation of C_{rw} (Pneu.Cyl.) is similar to that of C_{rw} (Elec.Sol.)

Thus, C_{rw} (Pneu.Cyl.) = 20369.45.

On substitution of values in the cost model for pneumatic cylinder arrangement, the expected overall cost of failure due to pneumatic cylinder arrangement per year is INR 25,578.67. Comparing the overall cost before and after the design change, it is evident that the design option is far better than its predecessor. Thus, by looking into design change options for the critical components/subsystems the company is saving INR (1,467,925.98–25,578.67) = INR 1,442,347.31 annually which is approximately equal to US$ 33,101.87.

This case study has applied integrated approach to improve reliability through systematic analysis of failure data, maintenance strategies and cost-benefit models linked to design changes. This has changed the practise of the company from corrective maintenance to preventive maintenance. It has significantly improved their maintenance practise through continuous improvement and systematic design analysis approach implemented throughout the organisation to enhance plan reliability.

3. Conclusions

In this paper, analysis of down time and design of plunger movement mechanism of automatic internal grinding machine for bearing production plant is carried out. It helped to identify the root cause of excessive downtime leading to production loss and quality problems. This research has applied reliability theories and developed a cost-benefit model for various alternative maintenance and design options.

This research has improved the maintenance practise throughout the organisation. The integrated approach has combined reliability theories, economic analysis and technological decisions based on design changes of existing equipments. This technique can also be useful for design and development of new equipments.

There is a huge scope for future research in this area of reliability growth through similar approaches. Authors are currently working on some of the problems in Rail industries applying this integrated approach in inspection, maintenance and design decisions for enhancing rail reliability to reduce risk in rail operations. Results of these researches would be published in the future.

Acknowledgement

We are thankful to Mr. Kundan Kumar of NRB Bearings Ltd, India for providing us the data and much useful information for better analysis.

Appendix A

Tables A1 and A2 provides the original data and the overall cost of failure respectively. Fig. A1 shows the results of the analysis of quarterly failure time interval data.

Table A1
Original data

Month	Date	Reason for breakdown	TTR (h)	TTF (h)
November 2003	1-11-2003	Electrical breakdown (coil burnt)	1.75	2.25
	20-11-2003	Power failure	0.50	253.245
	27-11-2003	Solenoid coil burnt	2.00	92.749
December 2003	02-12-2003	Preventive maintenance	7.00	49.832
	11-12-2003	Oil leakage	2.00	118.665
January 2004	20-01-2004	Problem in solenoid coil	3.00	497.989
	22-01-2004	Solenoid coil burnt	2.25	25.833
	31-01-2004	Mechanical problem	0.50	109.248
February 2004	2-02-2004	Preventive maintenance	6.50	21.25
	12-02-2004	Chattering of plunger	2.50	139.581
	16-02-2004	Solenoid coil burnt	1.75	33.499
	29-02-2004	Reverse valve spring broken	2.00	170.58
March 2004	3-03-2004	Work head motor burnt (2 HP)	14.50	32.166
	23-03-2004	Solenoid coil burnt	2.50	250.078
April 2004	3-04-2004	Preventive maintenance	7.50	122.414
	25-04-2004	Feed motor gear box not working	2.50	287.744
	26-04-2004	Solenoid coil burnt	2.00	0.5
May 2004	12-05-2004	Replacement of work head bearing	3.50	215.912
	20-05-2004	Solenoid coil burnt	1.75	98.415
June 2004	2-06-2004	Preventive maintenance	7.00	154.663
	12-06-2004	Mechanical problem	2.25	119.165
	17-06-2004	Solenoid coil burnt	2.25	66.915
	29-06-2004	V-belt spindle damaged	15.00	145.747
July 2004	25-07-2004	Adjustment of dresser control valve	6.75	331.16
	26-07-2004	Solenoid coil burnt	2.00	3.083
August 2004	2-08-2004	Preventive maintenance	8.00	83.165
	8-08-2004	Air leakage from work head chuck	2.50	71.833
	14-08-2004	Solenoid coil burnt	2.25	77.499
September 2004	1-09-2004	Work head motor burnt	17.00	225.328
	16-09-2004	Worm gear teeth worn out	34.00	177.996
	18-09-2004	Solenoid coil burnt	2.00	3.583
October 2004	2-10-2004	Preventive maintenance	8.50	172.413
	12-10-2004	Spindle motor bearing failed	4.00	137.581
	16-10-2004	Mechanical problem	2.00	32.499
	21-10-2004	Solenoid coil burnt	2.00	78.416
November 2004	7-11-2004	Dresser unit damaged	8.50	196.995
	10-11-2004	Human unavailability	3.50	41.666
	14-11-2004	Alterations done in setting	4.50	37.333
	29-11-2004	Mechanical problem	2.50	198.746
December 2004	1-12-2004	Solenoid coil burnt	2.00	19.166
	2-12-2004	Preventive maintenance	7.00	12
	6-12-2004	Replacement of solenoid coil with pneumatic cylinder	6.50	39.583

Table A2
Overall cost of failure of different subsystems along with their frequency

Mode of failure	Cost of component (Rs)	Labour hours (h)	Total cost of repair/ replacement Component cost + labour cost@Rs 65 per h	Overall cost (Rs)	Frequency
Electrical breakdown (coil burnt)	1100.00	1.75	1327.50	18135.00	13
Power failure	0.00	0.50	65.00	65.00	1
Solenoid coil burnt	1100.00	2.00	1360.00		
Preventive maintenance	1100.00	7.00	2010.00	14395.00	7
Oil leakage	0.00	2.00	260.00	260.00	1
Problem in solenoid coil	0.00	3.00	390.00		
Solenoid coil burnt	1100.00	2.25	1392.50		
Mechanical problem	0.00	0.50	65.00	942.50	4
Preventive maintenance	1100.00	6.50	1945.00		
Chattering of plunger	0.00	2.50	325.00	325.00	1
Solenoid coil burnt	1100.00	1.75	1327.50		
Reverse valve spring broken	10.00	2.00	270.00	270.00	1
Work head motor burnt (2HP)	1000.00	14.50	2885.00	6095.00	2
Solenoid coil burnt	1100.00	2.50	1425.00		
Preventive maintenance	1100.00	7.50	2075.00		
Feed motor gear box not working	0.00	2.50	325.00	325.00	1
Solenoid Coil Burnt	1100.00	2.00	1360.00		
Replacement of work head bearing		3.50	455.00	455.00	1
Solenoid coil burnt	1100.00	1.75	1327.50		
Preventive maintenance	1100.00	7.00	2010.00		
Mechanical problem	0.00	2.25	292.50		
Solenoid coil burnt	1100.00	2.25	1392.50		
V-belt spindle damaged (bearings and pulley)	1400.00	15.00	3350.00	3350.00	1
Adjustment of dresser control valve	0.00	6.75	877.50	877.50	1
Solenoid coil burnt	1100.00	2.00	1360.00		
Preventive maintenance	1100.00	8.00	2140.00		
Air leakage from work head chuck	0.00	2.50	325.00	325.00	1
Solenoid coil burnt	1100.00	2.25	1392.50		
Work head motor burnt	1000.00	17.00	3210.00		
Worm gear teeth worn out	250.00	34.00	4670.00	4670.00	1
Solenoid coil burnt	1100.00	2.00	1360.00		
Preventive maintenance	1100.00	8.50	2205.00		
Spindle motor bearing failed	250.00	4.00	770.00	770.00	1
Mechanical problem	0.00	2.00	260.00		
Solenoid coil burnt	1100.00	2.00	1360.00		
Dresser unit damaged		8.50	1105.00	1105.00	1
Alterations done in setting	0.00	4.50	585.00	585.00	1
Mechanical problem	0.00	2.50	325.00		
Solenoid coil burnt	1100.00	2.00	1360.00		
Preventive maintenance	1100.00	7.00	2010.00		
Replacement of solenoid coil with pneumatic cylinder	3000.00	6.50	3845.00	3845.00	1

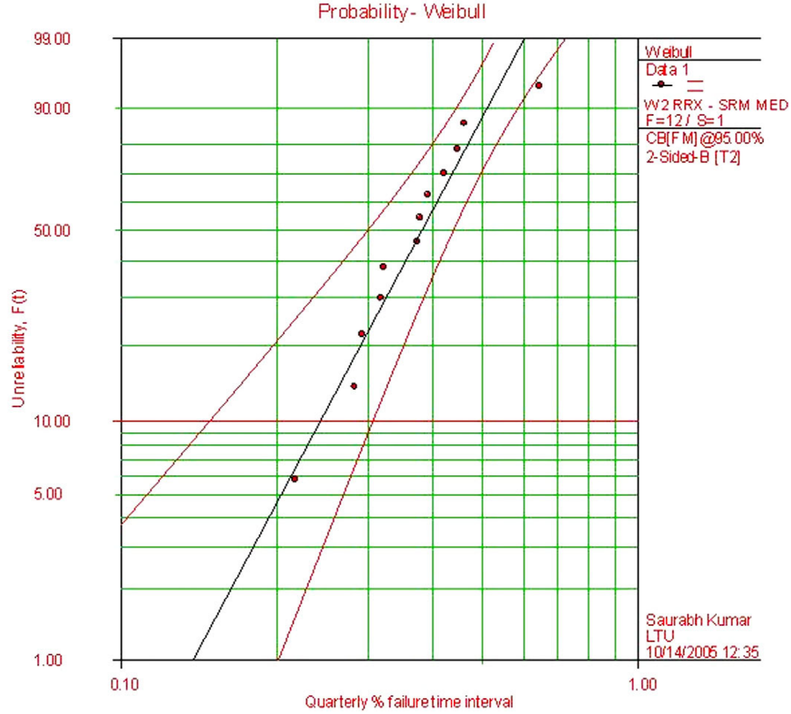

Fig. A1. Two parameter Weibull distribution with $\beta = 4.1570$ and $\eta = 0.4172$.

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Paper V

Inspection frequency optimization model for degrading flowlines on an offshore platform

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INSPECTION FREQUENCY OPTIMIZATION MODEL FOR DEGRADING FLOWLINES ON AN OFFSHORE PLATFORM

SAURABH KUMAR[1*], RAJIV DANDOTIYA[1], RAJESH KUMAR[2] and UDAY KUMAR[1]

[1]Division of Operation and Maintenance Engineering,
Luleå University of Technology, Luleå, SE-97187, Sweden
saurabh.kumar@ltu.se, rajiv.dandotiya@ltu.se, uday.kumar@ltu.se

[2]Aker Kvaerner, Stavanger, N-4003, Norway
rajesh.kumar@akerkvaerner.com

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Many offshore oil and gas installations in the North Sea are approaching the end of their designed lifetimes. Technological improvements and higher oil prices have developed favorable conditions for more oil recovery from these existing installations. However, in most cases, an extended oil production period does not justify investment in new installations. Therefore cost-effective maintenance of the existing platform infrastructure is becoming very important.

In this paper, an inspection frequency optimization model has been developed which can be used effectively by the inspection and maintenance personnel in the industry to estimate the number of inspections/optimum preventive maintenance time required for a degrading component at any age or interval in its lifecycle at a minimum total maintenance cost. The model can help in planning inspections and maintenance intervals for different components of the platform infrastructure. The model has been validated by a case study performed on flowlines installed on the top side of an offshore oil and gas platform in the North Sea. Reliability analysis has been carried out to arrive at the best inspection frequency for the flowline segments under study.

Keywords: Offshore oil and gas platforms; flowlines; inspection; degradation; virtual failure state; suspensions; cost; reliability analysis; component; preventive maintenance; corrective maintenance; model; optimization.

1. Introduction

Oil and gas platforms in the North Sea are facing aging problems as most of these installations have either reached or are about to reach their designed lifetime. New technologies and higher oil prices have, however, made it possible to produce more from the existing oil/gas reservoirs which were earlier thought to be unprofitable. Huge investments in new installations are not justified for extended production. Therefore, cost-effective maintenance and upgradation of the existing platform infrastructure is an economically sound alternative in the current scenario.

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[*] Corresponding author

On the other hand, the platform infrastructure faces adverse operational and environmental conditions, which causes degradation in the form of corrosion, erosion or stress generation. Therefore, these installations are always under the constant threat of leaks and failures which might have catastrophic consequences. To avoid such incidents, inspection, repair and replacement activities are carried out according to stringent health, safety and environmental (HSE) norms. The challenge is to perform cost-effective maintenance without compromising on risk and safety issues.

Inspection (in the operational phase) is a maintenance activity carried out at predetermined time intervals in order to reduce the probability of failure (or the performance degradation) of the system/component[3]. The inspection cost increases when the inspection interval is shortened (or the inspection frequency is increased), as inspection is one of the cost elements[12]. However, risk or loss caused by failure will increase when the inspection interval is lengthened[16,19]. Therefore, an appropriate setting of inspection schedules is important for reducing the maintenance cost. The optimum inspection frequency can be calculated using maintenance optimization models, because they are the only approach which combines reliability with economics in a quantitative way[9]. A wide range of maintenance optimization models have been developed and reviewed from time to time “see Refs. 5, 8-10, 15, 18, 23 and 24, for more details.” However, most of them have focused on mathematical analysis and techniques rather than solutions to real world problems and practical applicability[7,9].

The present work is based on developing a model for optimization of the inspection frequency by analyzing the reliability of components having similar degradation behavior. A case study on an offshore oil and gas platform in the North Sea has been performed to optimize the flowline inspection frequency. Transformed flowline degradation data have been used to validate the model owing to the confidentiality of the data. Matlab software has been used to reduce the complexity in solving the model. The presented model can be used effectively by the industry to estimate the optimum preventive maintenance time/number of inspections required for a degrading component at any age or interval in its lifecycle.

2. Flowline Degradation

Flowlines[a] are one of the most critical piping components on the production facility and demand a major share of the maintenance time to assure their reliability. The use of reliability analysis to optimize inspection intervals for flowline is not common in the oil and gas sector, largely because it requires specialist knowledge[13]. However, simple maintenance optimization models can be developed to provide engineering solutions to

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[a] Flowlines are the topside piping systems on the platform taking the well-stream from the well head to the production manifold.

real industrial problems, although some sophistication will always be there when dealing with complex systems[22].

Flowline degradation takes place mainly in the form of corrosion and erosion. The process is accelerated at points with higher stress levels and well-stream content (e.g., sand particle level), which causes localized degradation “see Ref. 13 for details”. The degradation process in the present case mostly results in non-uniform loss of material, which is precisely measured as the maximum reduction in the thickness level at a point using non-destructive testing (NDT) techniques.

There are a number of flowlines on the platform connected to different wells. Most of them are production lines from which a mixture mainly comprising oil, gas, water and sand particles comes out of the reservoirs; others are injection lines which are used to inject sea water, produced water and/or gas into the reservoir. The degradation behavior of the producers and injectors will be quite different from each other due to their flow content. We chose production line inspection data for analysis in our case study, because production lines are more critical from a risk point of view. In this study, it is assumed that all the production lines being considered are operating under similar environmental conditions and have the same material specification (carbon steel).

Flowlines consist of a number of components such as bends, flanges, reducers, etc. Similar components (for example bends) from all the flowlines can be grouped together based on their degradation behavior[13] to carry out component level reliability analysis “see also Ref. 17 for details”. Fig. 1 shows the degradation behavior of one of these component groups.

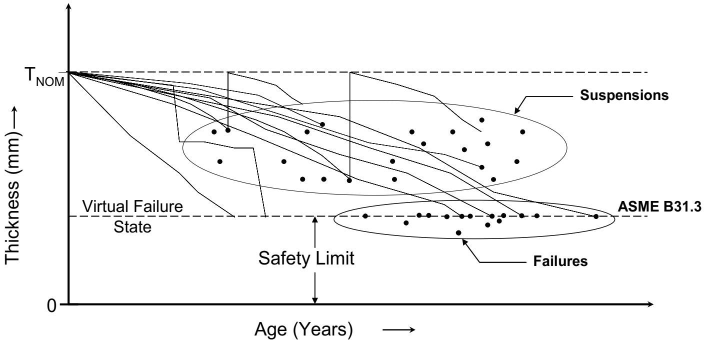

Fig. 1. Degradation behavior of a component group

When a new component is installed, it has its nominal thickness level, which continues to decrease due to the degradation and aging and finally reaches a safety limit specified by a standard (for example, ASME B31.3[2]). We call this limit a “virtual failure state” (as shown in Fig. 1), because the consequential damage due to a real failure in the form of leaks or cracks is extremely serious and unacceptable. The occurrence of a real failure may cause the loss of human life, damage to the marine environment, production loss and the loss of assets, etc. Therefore, replacement and repair actions are taken long before the real failure state is reached. In this paper, it is assumed that, when a component's wall thickness level has reached the virtual failure state, it is considered to have failed and some maintenance action in the form of replacement, repair, etc. needs to be taken.

Fig. 1 shows that some components fail long before the failure of most of the other components, or their failure rate is accelerated during a very short interval of time. This may be due to certain local reasons (e.g., a sudden increase in the sand particle level, etc.). These components are considered as outliers, as they do not show the general behavior of the group which is followed by most of the other components in that group. Some of the components which have degraded to a certain extent but have still not reached the virtual failure state are considered as suspensions. Some components are replaced before they reach the virtual failure state, due to a campaign/bulk replacement policy being followed by the company. An explanation for such an action may be based on the estimation that these components will enter the virtual failure state before the next block replacement is performed. A component may also be considered very critical based on its location, thus leading to its early replacement. These replaced components are also considered as suspensions.

2.1. *Trend Test*

According to their degradation behavior, each component group follows a failure probability distribution. However, before choosing an appropriate failure distribution model for a component group, a trend test was carried out for chronologically ordered failure data "see Ref. 1". In the present case, the failure data of the component group considered, were independent and identically distributed (i.i.d.). It may not be appropriate to use classical statistical techniques if the failure data are not independent and identically distributed[14]. Further investigations showed that their failure rate was not constant, and therefore the possibility of the distributions following homogeneous Poisson process (HPP) as the best fitting distribution for the considered failure data was ruled out. Finally, two-parameter Weibull distribution turned out to be the best fitting distribution among the classical distributions using ReliaSoft's Weibull++6 software for the best-fit test. Weibull distribution is often used to represent the problems related to mechanical component aging, wear and degradation[6]. The analysis was performed using maximum likelihood estimation. The values of the shape parameter β and the scale parameter η were found to be 4.13 and 24.28 respectively (based on transformed data).

3. Inspection Frequency Optimization Model

The model is based on a simple concept of minimization of the total maintenance cost of the component using optimization technique. An objective function is formulated for the total maintenance cost, subjected to various constraints. In this technique, the objective function is iterated for various feasible solutions of the preventive maintenance time in order to determine the optimum solution.

3.1. *Assumptions and limitations*

- Every inspection is perfect and reveals the true state of the component without error. This assumption is a basic assumption proposed by Barlow and Porschan in 1965 "Ref. 4" and has been assumed in many inspection models ever since "also see Ref. 24".
- In the model, the corrective maintenance time is expressed in terms of the preventive maintenance time. The relationship between the preventive and the corrective maintenance time is obtained from five years of preventive and corrective maintenance time data provided by the company for the component group considered. It is assumed that this relationship exists throughout the life cycle of the component. This assumption is made due to the unavailability of preventive and corrective maintenance time data for a larger number of years.
- It is assumed that each component in the group takes the same maintenance time, and therefore the preventive and corrective maintenance time for one component was calculated by dividing the total preventive and corrective maintenance time for the component group by the number of components in that group (see Table B, Appendix).
- In preventive maintenance, it is assumed that the replacement, repair and inspection activities are condition-based and fixed maintenance is stochastic in nature. In corrective maintenance, replacement is the only activity performed.
- Repair and inspection activities do not require production shutdown, while the replacement of a component requires production shutdown for the system being considered. Scaffolding is assumed to be the only repair activity in the present case. It is also assumed that a replacement action brings the component back to an *as good as new* condition.
- The model is only applicable to degrading components.

3.2. *Model Formulation*

An objective function for the total maintenance cost is developed which is the sum of the total preventive, corrective and fixed maintenance cost (Eq. (1)), (see for notations Table A, Appendix).

Total maintenance cost of the component = [Total preventive maintenance cost + Total corrective maintenance cost + Total fixed maintenance cost] × $1/(1+i)^t$

$$C^{Total}(t) = \left[\left\{C^{PM} \cdot Mh^{PM} \cdot p(t)\right\} + \left\{C^{CM} \cdot Mh^{CM} \cdot \lambda(t) \cdot t\right\} + \left\{C^{FX} \cdot Mh^{FX} \cdot t\right\}\right] \times \frac{1}{(1+i)^t} \qquad (1)$$

3.2.1. *Preventive maintenance hours (Mh^{PM})*

The preventive maintenance hours constitute a decision variable that will be determined at different values of the total maintenance cost of the component at a given time *t*.

Mh^{PM} corresponding to the minimum total maintenance cost will be the optimum Mh^{PM}. The main objective is to carry out the trade-off analysis between the preventive and the corrective maintenance cost that is controlled by the preventive and corrective maintenance hours.

$$Mh^{PM} = Mh^{PM}_{rep} + Mh^{PM}_{scaff} + Mh^{PM}_{insp} \tag{2}$$

where, $Mh^{PM}_{rep} = X_{rep} \cdot Mh^{PM}$; $Mh^{PM}_{scaff} = X_{scaff} \cdot Mh^{PM}$; $Mh^{PM}_{insp} = X_{insp} \cdot Mh^{PM}$

X_{rep}, X_{scaff} and X_{insp} represent the fraction of the total time allocated to replacement, scaffolding and inspection respectively. The value of the fraction coefficients has been provided by the company as follows: $X_{rep} = 0.3$; $X_{scaff} = 0.1$; $X_{insp} = 0.6$

3.2.2. *Corrective maintenance hours (Mh^{CM})*

In many maintenance models, a relationship between the inspection frequency and the failure rate is proposed instead of the preventive and corrective maintenance time "see Refs. 3, 11 and 20". However, inspections alone cannot reduce the failure rate if maintenance actions (repair and replacement) are not performed. Therefore, in our view,

$$Mh^{CM} = f(Mh^{PM}) \tag{3}$$

and can be expressed in the form, $Mh^{CM} = a \cdot \left(Mh^{PM}\right)^{-b}$ where a > 0 and b > 0 (4)

We propose the relationship in this form (Eq. (4)) because an increase in the preventive maintenance time causes a reduction in the probability of failure of the component, which decreases the corrective maintenance time[21]. Thus the corrective maintenance time is inversely proportional to the preventive maintenance time. Fig. 2 shows the plot of the preventive and corrective maintenance time data for one component (based on Table B, Appendix).

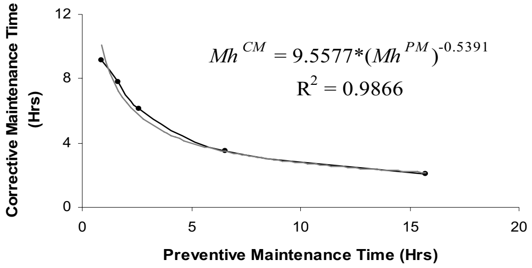

Fig. 2. Plot of corrective and preventive maintenance time

The value of parameters *a* and *b* is determined by performing regression analysis on the data.

$$Mh^{CM} = 9.5577 \cdot \left(Mh^{PM}\right)^{-0.5391} \tag{5}$$

The R-Squared statistic indicates that Eq. (5) as fitted explains 98.66% of the variability in Mh^{CM}.

3.2.3. *Fixed maintenance hours (Mh^{FX})*

The fixed maintenance hours for replacement, scaffolding and inspection are allocated in the same proportion as the preventive maintenance hours, as discussed in Section 3.2.1

$$Mh^{FX} = Mh_{rep}^{FX} + Mh_{scaff}^{FX} + Mh_{insp}^{FX} \tag{6}$$

3.2.4. *Preventive maintenance cost (C^{PM})*

The preventive maintenance cost of a component consists of the replacement cost, scaffolding cost and inspection cost in preventive maintenance. For the present case study, the total preventive maintenance cost is given by Eq. (8).

$$C^{PM} \cdot Mh^{PM} = C_{rep}^{PM} \cdot Mh_{rep}^{PM} + C_{scaff}^{PM} \cdot Mh_{scaff}^{PM} + C_{insp}^{PM} \cdot Mh_{insp}^{PM}$$

Using the relation given in Section 3.2.1

$$C^{PM} \cdot Mh^{PM} = \left(0.3 \cdot C_{rep}^{PM} + 0.1 \cdot C_{scaff}^{PM} + 0.6 \cdot C_{insp}^{PM}\right) \cdot Mh^{PM}$$

$$\Rightarrow C^{PM} = \left(0.3 \cdot C_{rep}^{PM} + 0.1 \cdot C_{scaff}^{PM} + 0.6 \cdot C_{insp}^{PM}\right) \tag{7}$$

where, C_{rep}^{PM} = [Labor Cost (Welding + Testing Cost) + Downtime Cost + Fabrication Cost (Material Cost + Logistics Cost)] $\Rightarrow C_{rep}^{PM} = C_{lab}^{PM} + C_{dt} + C_{fab}^{PM}$

$$C^{PM} = 0.3\left(C_{lab}^{PM} + C_{dt} + C_{fab}^{PM}\right) + 0.1\left(C_{scaff}^{PM}\right) + 0.6\left(C_{insp}^{PM}\right) \tag{8}$$

3.2.5. *Corrective maintenance cost (C^{CM})*

The corrective maintenance cost of a component is equal to the corrective replacement cost. We assume that corrective replacement is the only activity carried out in corrective maintenance. Thus, the corrective maintenance cost is given by Eq. (9).

C^{CM} = [Labor Cost (Welding + Testing Cost) + Downtime Cost + Fabrication Cost (Material Cost + Logistics Cost)]

$$C^{CM} = C_{lab}^{CM} + C_{dt} + C_{fab}^{CM} \tag{9}$$

3.2.6. *Fixed maintenance cost*

Time-based fixed replacement, repair and inspection actions are carried out by the company every year. Therefore, the fixed maintenance cost of the component comprises the replacement cost, scaffolding cost and inspection cost. The fixed maintenance cost for the component, is expressed by Eq. (10) similarly to the expression of the preventive maintenance cost by Eq. (7)

$$C^{FX} = 0.3 \cdot C_{rep}^{FX} + 0.1 \cdot C_{scaff}^{FX} + 0.6 \cdot C_{insp}^{FX} \tag{10}$$

where the replacement cost in fixed maintenance is given by Eq. (11)

C_{rep}^{FX} = [Labor Cost (Welding + Testing Cost) + Downtime Cost + Fabrication Cost (Material Cost + Logistics Cost)] $\Rightarrow C_{rep}^{FX} = C_{lab}^{FX} + C_{dt} + C_{fab}^{FX}$ (11)

3.2.7. *Failure rate $\lambda(t)$ and failure probability $p(t)$ for a two-parameter Weibull distribution*

$$\lambda(t) = \frac{\beta \cdot t^{(\beta-1)}}{\eta^{\beta}} \; ; \; p(t) = 1 - e^{-(t/\eta)^{\beta}}$$

3.2.8. *Discount rate (i)*

Investments made at different times have different economic values. To take these into account, all future costs are discounted to convert them to present values of cost. Therefore the total maintenance cost is multiplied by $1/(1+i)^t$.

3.2.9. *Constraints*

In the operation research modeling for the given case study, we have defined the constraints on man hours and the preventive and corrective maintenance costs. The man hours and the costs for maintenance cannot be negative.

$$Mh^{PM} \geq 0; \; C^{PM} \geq 0; \; C^{CM} \geq 0$$

4. Model Validation

Transformed degradation data and preventive, corrective and fixed maintenance cost data of flowlines on an offshore oil and gas platform in the North Sea have been used for model validation. The values of different cost and degradation parameters are given in Table A, Appendix. Matlab software is used to determine the optimum preventive maintenance hours required at any given age of the component. The results obtained by optimization of the objective function at regular intervals of time throughout the life cycle of the component are given in Table C, Appendix. Fig. 3 shows a plot of the optimum preventive maintenance hours required at different ages of the component. From Fig. 3, we know that a relationship exists between the optimum preventive maintenance hours Mh^{PM} and the time/age of the component (*t*), thus, $Mh^{PM}(t) = f(t)$.

After performing polynomial regression analysis (using Statgraphics software), a third order polynomial equation was best fitted to the curve in Fig. 3 with a P-value less than 0.01 and an R-Squared value of 99.98%, indicating that a statistically significant relationship in the form of Eq. (12) exists between Mh^{PM} and (t) at the 99% confidence level.

$$Mh^{PM}(t) = 0.0015 \cdot t^3 - 0.0396 \cdot t^2 + 0.3357 \cdot t + 15618 \qquad (12)$$

The optimum maintenance hours $Mh^{PM}(\Delta t)$ required for any given time interval $\Delta t = t_2 - t_1$ can be calculated by integrating Eq. (12).

$$Mh^{PM}(\Delta t) = \int_{t_1}^{t_2} Mh^{PM}(t).dt \qquad (13)$$

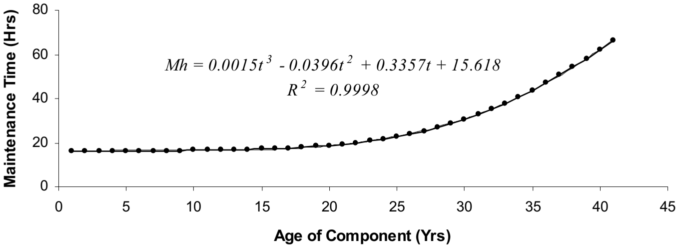

Fig. 3. Variation of optimum preventive maintenance hours with aging of the component

Fig. 4 shows the variation of the total minimum maintenance cost with the aging of the component, corresponding to the optimum preventive maintenance hours.

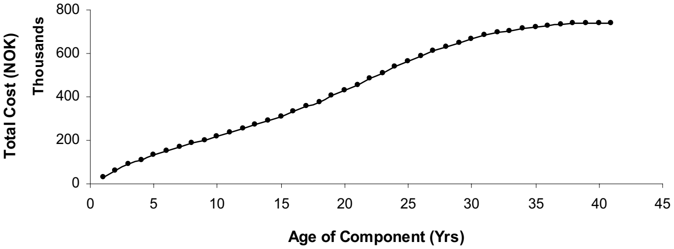

Fig. 4. Variation of total minimum maintenance cost with aging of the component

Table C, Appendix and Fig. 3 describes that, as the failure probability of the component increases due to aging, the corresponding optimum preventive maintenance time also increases, to counter the increasing chances of failures. Depending on the maintenance time required, the total maintenance cost also increases as the component ages and degrades (Fig. 4). This cost curve is the lowest possible total maintenance cost achieved in the corresponding years. Sixty percent of the optimum preventive maintenance time is devoted to preventive inspections as shown in Eq. (5). Assuming that every preventive inspection on an average requires the same time, we can estimate the inspection frequency required at any age of the component or between any age intervals. In the present case, 1.5 hours is considered (by the company) as the average inspection time of a single point on the component.

Fig. 5 shows the variation of the various costs with the preventive maintenance time, keeping the age of the component fixed. The corresponding data are given in Table D, Appendix.

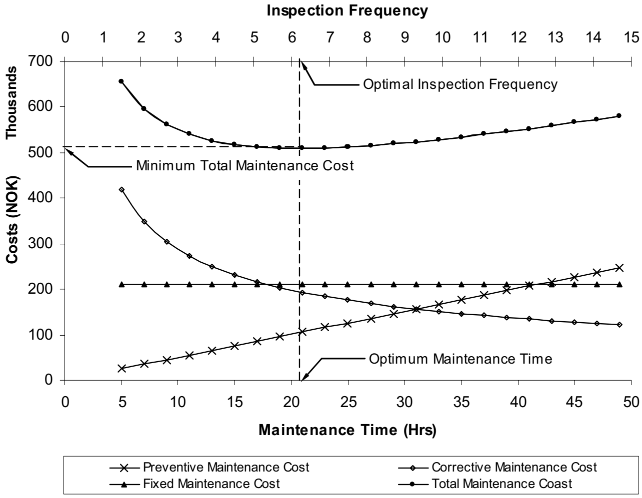

Fig. 5. Variation of various costs with preventive maintenance time

In the present case, the age of the component is fixed at 23 years. As is obvious, the preventive maintenance cost will increase if the preventive maintenance time is increased. However, this will result in a reduction of the occurrence of failures, leading to a reduction in the corrective maintenance cost. In addition, there will always be some fixed maintenance cost as shown in Fig. 5. Summing up all these costs will give the total maintenance cost curve. The preventive maintenance time corresponding to the minimum total maintenance cost will give the optimum preventive maintenance time. Fig. 5 also shows the corresponding optimum inspection frequency required, at the age of 23 years. If the required number of inspections is not an integer, the inspection frequency is rounded off to the nearest higher integer, as shown in Table D, Appendix.

5. Conclusions

An inspection frequency/preventive maintenance time optimization model has been developed and validated by a case study of an offshore oil and gas platform in the North

Sea. In the case study, flowline degradation and cost data have been transformed to maintain their confidentiality. The concept of a virtual failure state has been introduced to calculate the failure distribution of those highly critical components where the possibility of actual failure is rare and unacceptable. Matlab software has been used to reduce the complexity in solving the model.

The model can be used effectively by inspection and maintenance personnel in the industry to estimate the number of inspections/optimum preventive maintenance time required for a degrading component at any age or interval in its lifecycle, which will help in decision making when planning future inspection and maintenance intervals for different components.

There is a scope for developing a multi-component optimization model for offshore oil and gas platform infrastructure. To achieve this, the relationship between the degradation behaviors of different component groups needs to be found out.

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Appendix

Table A: Notations and values of the parameters described in the case study

t	Age of the component	C_{scaff}^{PM}	Preventive scaffolding cost = 500
$p(t)$	Failure probability of component at time *t*	C_{insp}^{PM}	Preventive inspection cost = 500
$\lambda(t)$	Failure rate of the component at time *t*	C_{lab}^{PM}	Labor cost for preventive maintenance = 600
η	Shape parameter of the component = 24.28	C_{dt}	Downtime cost = 100000
β	Scale parameter of the component = 4.13	C_{fab}^{PM}	Fabrication cost for preventive maintenance = 15000
i	Discount rate = 0.06	C_{rep}^{CM}	Corrective replacement cost
Mh^{PM}	Preventive maintenance time (*man hours*) for the component at time *t*	C_{lab}^{CM}	Labor cost for corrective maintenance = 700

Mh^{CM}	Corrective maintenance time (*man hours*) for the component at time *t*	C_{fab}^{CM}	Fabrication cost for corrective maintenance = 20000
Mh^{FX}	Fixed maintenance time (*man hours*) for the component = 1 Hour	C_{rep}^{FX}	Fixed replacement cost
$C^{Total}(t)$	Total maintenance cost of the component at time *t*	C_{Scaff}^{FX}	Fixed scaffolding cost = 500
C^{PM}	Preventive maintenance cost of the component	C_{Insp}^{FX}	Fixed inspection cost = 500
C^{CM}	Corrective maintenance cost of the component	C_{lab}^{FX}	Labor cost for fixed maintenance = 600
C^{FX}	Fixed maintenance cost of the component	C_{fab}^{FX}	Fabrication cost for fixed maintenance = 15000
C_{rep}^{PM}	Preventive replacement cost		

[b]The unit of all cost elements is given in Norwegian Kroner (NOK) per hour

Table B: Preventive and corrective maintenance time data for different years for the same component group (Transformed data)

	For Component Group		For Single Component	
Year	**PM(Hrs)**	**CM(Hrs)**	**PM(Hrs)**	**CM (Hrs)**
t1	50.96	511.84	0.91	9.14
t2	91.84	434.00	1.64	7.75
t3	145.60	343.84	2.60	6.14
t4	366.80	197.12	6.55	3.52
t5	882.00	115.36	15.75	2.06

[c] 56 components in this group

Table C: Results obtained by optimization of objective function at regular intervals of time throughout the life cycle of the component

Age (Yrs)	P(t)	Mh	Total Cost	Age (Yrs)	P(t)	Mh	Total Cost
1	0.00000	16.29	33050.09	23	0.55048	20.76	510139.98
3	0.00018	16.29	88478.50	25	0.67641	22.71	562043.82
5	0.00146	16.30	132664.52	27	0.78785	25.29	609324.05
7	0.00586	16.32	169439.73	29	0.87541	28.61	649706.83
9	0.01646	16.38	202561.92	31	0.93563	32.77	681962.56
11	0.03729	16.49	235388.84	33	0.97131	37.82	706048.15
13	0.07297	16.69	270619.12	35	0.98920	43.77	722838.13

15	0.12788	17.02	310084.98	37	0.99664	50.56	733587.10
17	0.20502	17.52	354595.49	39	0.99916	58.13	739433.68
19	0.30457	18.26	403850.42	41	0.99983	66.45	741181.94
21	0.42256	19.31	456463.22				

Table D: Data regarding various costs with variation of preventive maintenance time and corresponding inspection frequencies

Mh (PM)	**Cost (PM)**	**Cost (CM)**	**Cost (FX)**	**Cost TOTAL**	**Insp Time**	**Insp Freq**	**Insp Freq (Rounded)**
5.00	25241.58	418812.84	210927.44	654981.86	3.00	1.5	2
9.00	45434.85	305072.16	210927.44	561434.45	5.40	2.7	3
13.00	65628.12	250211.84	210927.44	526767.40	7.80	3.9	4
17.00	85821.39	216520.84	210927.44	513269.66	10.20	5.1	6
21.00	106014.65	193208.53	210927.44	510150.62	12.60	6.3	7
25.00	126207.92	175875.47	210927.44	513010.82	15.00	7.5	8
29.00	146401.19	162351.37	210927.44	519680.00	17.40	8.7	9
33.00	166594.46	151427.19	210927.44	528949.08	19.80	9.9	10
37.00	186787.72	142369.57	210927.44	540084.73	22.20	11.1	12
41.00	206980.99	134704.76	210927.44	552613.19	24.60	12.3	13
45.00	227174.26	128111.42	210927.44	566213.12	27.00	13.5	14
49.00	247367.53	122362.97	210927.44	580657.93	29.40	14.7	15

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About the Authors

Saurabh Kumar is a PhD student at the Division of Operation and Maintenance Engineering, Luleå University of Technology, Luleå, Sweden. His research interests are reliability analysis, maintenance engineering and cost modeling.

Rajiv Dandotiya is a PhD student at the Division of Operation and Maintenance Engineering, Luleå University of Technology, Luleå, Sweden. His research interests are cost modeling and optimization.

Rajesh Kumar obtained his PhD in industrial service management from University of Stavanger, Stavanger, Norway and presently working as a specialist engineer in maintenance in Aker Kvaerner, Norway. His research interests are operation and maintenance engineering related to oil and gas industry.

Uday Kumar is Professor and Head of the Division of Operation and Maintenance Engineering, Luleå University of Technology, Luleå, Sweden. His research interests are reliability analysis and maintenance engineering. He has authored, reviewed and edited a number of papers related to reliability and maintenance engineering.