



Salla Lind

Accident sources in industrial maintenance operations

| Proposals for identification, modelling and management of accident risks

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Proposals for identification, modelling and management of accident risks

Salla Lind

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VTT, Bergsmansvägen 3, PB 1000, 02044 VTT

tel. växel 020 722 111, fax 020 722 4374

VTT Technical Research Centre of Finland, Vuorimiehentie 3, P.O. Box 1000, FI-02044 VTT, Finland
phone internat. +358 20 722 111, fax + 358 20 722 4374

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“If there are two or more ways to do something and one of those results in a catastrophe, then someone will do it that way”

-Captain Murphy, 1949

Salla Lind. Accident sources in industrial maintenance operations. Proposals for identification, modelling and management of accident risks [Tapaturmat teollisuuden kunnossapitotöissä - Ehdotuksia tapaturmariskien tunnistamiseen, mallinnukseen ja hallintaan]. Espoo 2009. VTT Publications 710. 105 p. + app. 67 p.

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Abstract

Industrial maintenance operations involve specific safety risks for maintenance workers. Such risks arise, for example, from the need to work in close proximity to machinery and processes, the execution of tasks during various times of the day and the infrequency of certain tasks. Additional sources of risks include system design and working conditions that may not support safe and quick maintenance work. In maintenance, as in most kinds of work, variation in human performance, organizational issues, such as poor working instructions and inadequate supervision, can all increase the frequency and probability of risks.

This thesis considers accidents and accident prevention in industrial maintenance operations. The thesis explores potential and realized accident sources and offers proposals to manage the risks and prevent accidents in companies. The focus is from the maintenance workers' perspective. Three studies were carried out during 2002–2006 to discover the kinds of risks that are prevalent in maintenance operations and how accidents could be prevented. First, the maintenance-related risks were charted in three companies that provide maintenance services. The companies served 15 customer sites between them. The studies involved personnel interviews, observation and risk assessment. Second, the types and sources of fatal and severe non-fatal workplace accidents were charted by exploiting public accident reports. Third, a risk assessment method was developed for identification and management of maintenance-related risks in any company. Fourth, the utilization of public accident reports was explored to discover the extent to which companies adopt such information. Fifth, a fatal accident was remodelled using fault tree analysis.

The results of the studies showed that the most typical accident types among fatal and severe non-fatal accidents were crushing, falls, and accidents caused by tumbling objects. Additionally, the most typical risks in companies were risks

arising from physical and cognitive ergonomics, such as poor working posture, heavy lifts and hurried working. The most severe observed risks corresponded to these accident types. On the basis of the findings in the companies and the real accident data, a method was developed for use by the companies in their risk assessment. The method contains three separate parts for 1) maintenance planning and management, 2) identification of actual accident risks and 3) a brief check-list for the maintenance workers. The study on the adoption and use of accident reports in companies revealed that, though such reports are regarded favourably, they are seldom utilized in any systematic way. More effective utilization could help the companies to identify risks in their own operations and ascertain the potential risks at the various customer sites. The accident re-analysis demonstrated that a fault-tree model could help to combine the technical and human-based failures together with hazardous conditions in detail into a single model. Such a model could provide detailed information about event chains and their interconnections. This information could promote maintenance safety effectively and even reveal the possible root causes of accidents.

As a result of the findings, a set of proposals was drawn up to promote maintenance safety. Among the proposals are ways to identify maintenance-related risks, ideas for maintainability design in the system and in the workplace, and suggestions for task planning and design. Accident prevention in industrial maintenance must take into account the various components of maintenance work, i.e., task, worker, working environment and the object system of maintenance. The organizational matters play the key role due to, for example, resource allocation, and safety planning and risk management. In addition, cooperation with the operators and other workers on customer sites could help to identify and manage task- and site-specific risks.

Salla Lind. Accident sources in industrial maintenance operations. Proposals for identification, modelling and management of accident risks [Tapaturmat teollisuuden kunnossapitotöissä - Ehdotuksia tapaturmariskien tunnistamiseen, mallinnukseen ja hallintaan]. Espoo 2009. VTT Publications 710. 105 s. + liitt. 67 s.

Avainsanat industrial maintenance, accidents, risk management, accident prevention

Tiivistelmä

Teollisuuden huolto- ja kunnossapitotöihin sisältyy erityisiä tapaturmariskejä, jotka heijastuvat tapaturmalukuihin ja -tyyppeihin. Tällaisia huolto- ja kunnossapitotöissä vaikuttavia tekijöitä voivat olla muun muassa työskentely koneiden ja prosessien välittömässä läheisyydessä, töiden suorittaminen vaihtelevina vuorokauden aikoina sekä prosessien ja laitteiden purku- ja kokoonpanovaiheisiin liittyvät riskit. Huoltotyön tarve voi syntyä esimerkiksi komponentin vikaantuesssa, järjestelmän toiminnan häiriintyessä tai huolto-ohjelman perusteella huoltovälin täytyessä, vaikka varsinaista vikaa tai häiriötä ei olisi havaittu. Ennen huollon aloittamista kehittyneet olosuhteet, kuten esimerkiksi koneen vikatila, voivat aiheuttaa riskin huoltotyön suorittamisen aikana. Toisaalta työn suorittajan toiminta sekä organisaation toiminnasta tulevat vaikutukset, kuten valvonta ja työhön opastus, voivat vaikuttaa huoltotyön turvallisuuteen. Keskeinen merkitys on myös työympäristöllä ja huoltotyön kohteena olevalla järjestelmällä, jonka huollettavuus voi vaikuttaa huollon suorittamiseen merkittävästi. Vaikka huolto- ja kunnossapitotyöt on jo pitkään tunnustettu riskialttiiksi töiksi, on kunnossapitoa ja turvallisuutta koskeva tutkimus keskittynyt järjestelmän huollon jälkeiseen luotettavuuteen ihmisen huollonaikaisen turvallisuuden sijasta.

Tässä työssä tarkasteltiin huolto- ja kunnossapitotöissä sattuneita tapaturmia, tapaturmalähteiden tunnistamista ja turvallisuuden parantamista. Työn päätavoitteina oli 1) määrittää huolto- ja kunnossapitotöiden keskeisimmät tapaturmalähteet ja 2) esittää keinoja huolto- ja kunnossapitotöiden vaarojen tunnistamiseen ja tapaturmien torjuntaan. Näiden tavoitteiden saavuttamiseksi määriteltiin seuraavat tutkimuskysymykset:

- 1) Millaisia riskejä sisältyy huolto- ja kunnossapitotöihin?
- 2) Millaisia vakavia ja kuolemaan johtaneita tapaturmia huolto- ja kunnossapitotöissä on sattunut?
- 3) Miten huolto- ja kunnossapitotöiden aikaisia tapaturmia voidaan torjua?

Työ perustuu kolmeen eri tutkimukseen, jotka toteutettiin vuosina 2002–2008. Näissä tutkimuksissa koottiin aineistoa julkisista tapaturmaraporteista ja yrityksissä tehdyistä tutkimuksista. Huolto- ja kunnossapitotöihin liittyviä riskejä selvitettiin huolto- ja kunnossapitopalveluita tarjoavissa yrityksissä (n = 3) ja heidän asiakaskohteissaan (n = 15). Tässä tutkimuksessa koottiin aineistoa valituista työtehtävistä tehdyillä riskinarvioinneilla ja työntekijöiden ja esimiesten vapaamuotoisilla haastatteluilta. Lisäksi saman tutkimuksen yhteydessä analysoitiin vuosina 1985–2004 julkaisujen huolto- ja kunnossapitotöissä sattuneiden kuolemaan johtaneiden tapaturmien tutkintaraportteja (n = 33). Näiden ohella analysoitiin vuosina 1994–2004 julkaistut vakavien työpaikkatapaturmien tutkintaselostukset (n = 90). Näistä aineistoista tehdyillä analyyseillä on ollut tavoitteena selvittää huolto- ja kunnossapitotöiden merkittävimmät tapaturmatyypit ja -lähteet sekä kartoittaa vastaavien tapaturmien torjuntaa. Tapaturmien ja riskien syitä luokiteltiin olosuhdetekijöihin ja ihmisen/organisaation toiminnasta aiheutuviin virheisiin. Olosuhdetekijät jaettiin edelleen työympäristön ominaisuuksiin ja organisaation toiminnan puutteisiin. Ehdotukset tapaturmien torjumiseksi perustuvat eri osatutkimuksissa tehtyihin havaintoihin, joista osa koskee yritysten sisäistä toimintaa ja osa ulkoisen tapaturmatiedon tarjontaa. Yrityksistä ja tapaturma-analyyseistä koottua tietoa käytettiin kunnossapitotöille räätälöidyn riskinarviointimenetelmän kehittämiseen. Lisäksi metalli- ja kuljetusalan yrityksissä (n = 38) tehdyn tutkimuksen perusteella annettiin ehdotuksia tapaturmaraportoinnin kehittämiseksi siten, että se palvelisi paremmin yritysten tarpeita. Tässä työssä pohditaan myös tapaturmien syy-seurausketjujen mallintamista keskeisten tapahtumaketjujen tunnistamiseksi ja torjuntatoimenpiteiden kohdentamisen helpottamiseksi yrityksissä.

Tutkimusten tulokset osoittivat, että huolto- ja kunnossapitotöiden tapaturmien syyt juontuvat yleisimmin puutteista organisaation toiminnassa, kuten valvonnassa ja työn suunnittelussa. Vastaavasti välittömät tapaturmavaarat syntyvät työympäristön puutteista ja työn suorittajien riskialttiista toiminnasta. Yrityksissä esille nousseita muita riskejä kasvattavia tekijöitä ovat muun muassa ajan puute, tietoinen tai tiedostamaton riskinotto sekä puutteet työn suunnittelussa tai työvoiman resursoinnissa. Erityinen tekijä palveluna tarjottavassa kunnossapidossa on yhteistyö asiakkaan kanssa, johon liittyy muun muassa tiedonkulku huoltohenkilöstön ja asiakaskohteen työntekijöiden välillä sekä tiedottaminen huoltotyöstä aiheutuvista riskeistä ja asiakaskohteen vaaroista. Yleisimpiä vakavien ja kuolemaan johtaneiden tapaturmien tyyppisiä huolto- ja kunnossapitotöissä ovat puristuminen tai esineiden väliin jääminen, henkilön putoaminen ja kaa-

tumistapaturmat. Raporteista tehtyjen analyysien perusteella tapaturmien taustalla vaikuttivat yleisimmin puutteelliset työohjeet, vaaralliset työmenetelmät sekä huollon kohteena olevaan järjestelmään liittyvät viat ja puutteet. Jopa kolmasosa tapaturmista on sattunut työskenneltäessä käynnissä olevan koneen luona.

Yrityksissä ja tapaturma-aineistosta tehtyjen havaintojen perusteella kehitetylle riskinarviointimenetelmälle asetettiin joukko vaatimuksia, jotta menetelmä soveltuisi huolto- ja kunnossapitotöiden turvallisuuden kehittämiseen. Menetelmän tuli ottaa huomioon eri organisaatiotasojen roolit sekä huomioida työympäristöön, työtehtävään ja työn kohteena olevaan järjestelmään liittyvät vaarat. Lisäksi menetelmän tuli opastaa turvallisuustoimenpiteiden valinnassa. Huoltotöiden vaarojen tunnistamisen tukemiseksi tarkasteltiin ulkoisen tapaturmatiedon hyödyntämistä (työpaikkakuolemantapausten raportointi) yritysten turvallisuustoiminnan tukena. Tapaturmatietojen käyttö voisi auttaa sekä palveluja tuottavaa että niitä ostavaa yritystä tunnistamaan vastaavat omaan toimintaan liittyvät riskit. Sattuneista tapaturmista oppimista pohdittiin tässä työssä mallintamalla tapausesimerkki tapahtumapuumallilla, joka voisi havainnollistaa paremmin kriittiset tapahtumaketjut ja auttaa kohdentamaan turvallisuutta parantavia toimenpiteitä.

Huolto- ja kunnossapitotöiden turvallisuuteen vaikuttaa moni eri tekijä organisaatiossa, työympäristössä ja työn kohteena olevassa järjestelmässä. Lisäksi vaihtelut työn suorittajan toiminnassa vaikuttavat työn turvallisuuteen. Tässä työssä esitetyt tapaturmien syyt ja taustatekijät sekä toimenpiteet tapaturmatekijöiden tunnistamiseksi ja hallitsemiseksi tarjoavat kunnossapito-organisaatioille, kone- ja järjestelmäsuunnittelijoille sekä yritysten turvallisuustoimijoille perustan huolto- ja kunnossapitotöiden turvallisuuden parantamiseksi.

Preface

This dissertation comprises four articles that are based on two separate studies. The studies were financed by Finnish Work Environment Fund and Federation of Accident Insurance Institutions in Finland. I wish to acknowledge both sources of funding for their important support. I especially wish to thank all the 56 companies participating in and contributing to the studies. In particular, ABB Service, Sandvik Mining and Construction, and YIT Industrial Services helped me to gather a significant part of my research material – thank you. I would also like to thank the Finnish Work Environment Fund for the scholarship that enabled me to complete the thesis.

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List of original publications

I Lind, Salla (2008). Types and Sources of Fatal and Severe Non-Fatal Accidents in Industrial Maintenance. *International Journal of Industrial Ergonomics*, **38**, pp. 927–933.

II Lind, Salla & Nenonen, Sanna (2008). Occupational Risks in Industrial Maintenance. *Journal of Quality in Maintenance Engineering*, **14** (2), pp. 194–204.

III Lind, Salla, Nenonen, Sanna & Kivistö-Rahnasto, Jouni (2008). Safety Risk Assessment in Industrial Maintenance. *Journal of Quality in Maintenance Engineering*, **14** (2), pp. 205–217.

IV Lind, Salla & Kivistö-Rahnasto, Jouni (2008). Utilization of External Accident Information in Companies' Safety Promotion – Case: Finnish metal and transportation industry. *Safety Science*, **46** (5), pp. 802–814.

Article I summarises accident types and sources in industrial maintenance operations, together with accident preventive measures listed in the reports. The results are examined in the framework of a major accident theory (Reason, 1997). The article provides a detailed account of accident sources, based on actual accident data. Article II develops the information on potential accident sources with practical findings in companies. As a result, the article gives a holistic view of the potential and realized accident sources by combining risk assessment data with real accident data. Article III examines the assessment of maintenance risks in companies with regard to the various organizational levels and technical dimensions in maintenance operations. Finally, Article IV presents proposals for accident reporting and for the use of accident information in companies.

Articles I–III are based on a common single study and Article IV is based on a separate study. Salla Lind is the corresponding author and main contributor of each article.

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Appendix 1. Generic Model of an Industrial Maintenance Operation

Appendix 2. Study 1: Parameters in Accident Analyses

Appendix 3. Study 2: Interview Questions

Appendix 4. Original publications I–IV

List of symbols

Accident	Undesired event giving rise to death, ill health or injury (BS 8800:2004).
Accident source	An unsafe act, organizational or local workplace factor, and/or a technical failure that has caused or contributed to an accident, or has the potential to cause or contribute to an accident. See also Risk.
ELMAS	Event logic modeling and analysis software.
ETA	Event tree analysis; a inductive method to determine possible consequences of a certain event.
Fatal accident	In this study, fatal accidents include only fatal workplace accidents (see IFWA).
FTA	Fault tree analysis; a deductive method for identification of events that have lead to a certain top event/consequence.
Hazard	Source or situation with potential for harms in terms of death, ill health or injury, or a combination of these (BS 8800:2004).
IFWA	Investigation and reporting of fatal workplace accidents in Finland; coordinated by the Federation of Accident Insurance Institutions in Finland.
Incident	Hazardous event where no harm occurs (BS 8800:2004).

NAT	Normal Accident Theory (Perrow, 1999).
Occupational accident	Accidents that occur in work-related conditions, i.e. during work-related traffic, commuting, or at the workplace. In this thesis, occupational accident refers to workplace accidents.
Risk	<p>Combination of the likelihood and consequence(s) of a specific hazardous event (BS 8800:2004)</p> <p>Collective name for factors at the workplace or in the management system, increasing the risk of accidents; hazards, deviations, contributing factors and root causes (Kjellén, 2000).</p> <p>A potential accident source.</p>
Risk assessment	A process that includes hazard identification, estimation of likelihood and consequences, and choosing of risk reductive measures (BS 8800:2004).
Risk information	Qualitative and quantitative information for management purposes and accident prevention, including risk analysis, accident data and information from accident investigations.
SAM	Systemic Accident Model (Hollnagel, 2004).
Safety	Non-existence of risk (Kuivanen, 1995).
System	In this thesis, system refers to the machine or process, which requires maintenance or is under maintenance. Maintenance can extend to the whole system or to part of it.

1. Introduction

1.1 Safety challenges in industrial maintenance

In a company, maintenance has the direct and indirect aims of supporting production and management processes. Examples for such aims are the promotion of economic efficiency by ensuring trouble-free use of process equipment and minimized downtime. Indirect economic efficiency is achieved through process reliability and product quality. Maintenance also enhances overall production safety by, for example, preventing production disruptions and helping to control environmental impacts, as the components and parts of a technical system retain their normal performance. A failure in a maintenance operation can jeopardise all such benefits and become the source of accidents, which pose dangers to human health, production and/or the environment. This thesis focuses on accident sources and ways to prevent their occurrence during maintenance operations.

In general, industrial work tasks are becoming increasingly automated, leading to a decrease in the share of manual work. Automation of work tasks has also made industrial processes technically more complicated. The quest for economic efficiency means that production equipment that should be reliable and free from breakdowns and interruptions. These factors are also important in maintenance, which must satisfy the demands of efficiency demands as well as the challenges of increased technological sophistication. In Finnish industry, the total number of maintenance working hours has increased to 50 000 person-years, while the total number of persons in Finnish industry is currently 450 000 (Finnish Maintenance Society, 2008a; Statistics Finland, 2008). It has been estimated that in the year 2001, maintenance represented between 2 and 14 % of total turnover (104 milliard Euros) in Finnish industry (Finnish Maintenance Society, 2008b).

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Accident prevention is a multidisciplinary field, which has to take into account all components of work and apply different sciences, such as organizational, engineering, and human sciences. In the case of industrial maintenance, accident prevention faces multiple challenges arising from the particular factors of the work and the working environment. The major factors are the technical working environment, i.e. structures, processes and machinery, which can be the direct causes of injury. However, organizational factors, such as management and supervision, can contribute to accidents as latent factors (see e.g. Reason, 1997). Additionally, worker performance can vary for a number of reasons, which must be also considered in maintenance planning and system maintainability design.

Prevailing accident theories emphasize the role of the organization in accident prevention, instead of attributing blame to the victim in the case of an accident. This approach is supported by the finding (Reason, 1997) that a significant number of major accidents have their origins in management and technical structures. Such causal factors include inadequate supervision and instruction, established unsafe work practices, and poor workplace design. These factors have generally existed long before the occurrence of an accident. However, in the event of an accident, a local trigger such as human error compounds the danger of latent accident sources (Becker 1997; Reason, 1997; Wickens & Hollands, 2000). Learning from accidents to prevent further occurrence should concern the whole organization. However, learning from accidents and utilizing accident information appears to be a complicated issue (see e.g. Baram, 1997; Becker, 1997; Koornneef & Hale, 1997).

Industrial maintenance presents several challenges for accident prevention. In addition to the usual risks associated with any industrial working environment, maintenance operations involve several maintenance-specific risks. Typical of these include working alongside a running process, using complicated machinery, and time constraints (Reason & Hobbs, 2003). In contrast to many other areas of technology and industry, direct contact between operator and machine in maintenance activities cannot be reduced substantially. Distancing people from processes typically diminishes the likelihood of human error and other chains of events that can lead to accidents. However, maintenance is, and probably will remain, an area in the use of technology where humans need to be in direct contact with processes (Reason, 1997). Maintenance is also a good example of work that is performed in exceptional conditions, such as the time of day, especially when high-priority repairs are involved (c.f. Nag & Patel, 1998). A

maintenance operation may also be exceptional work in itself depending on the frequency it is performed. The current increasing practice of subcontracting maintenance services may also pose new challenges as the sites and tasks can vary according to the customer environment. In addition, maintenance operations typically include both disassembly and reassembly, which can be considered factors in increasing the risks of injury. Further, the numerous work phases during disassembly and reassembly can give rise to greater risk of human error (see e.g. Herrera *et al.*, 2008; Hobbs & Williamson, 2002; Reason, 1997; Reason & Hobbs, 2003). Such errors include replacing a wrong part or assembling the right parts in the wrong order. Because of human error, maintenance activities can diminish the reliability of a technical system. However, maintenance activities also have features that make them risky for the maintenance workers.

1.2 Maintenance operations

In a company, maintenance activities can be examined in terms of three main elements as follows: the technical part, the human part, and the economic conditions and consequences of maintenance (Thorsteinsson & Hage, 1992). Plant maintenance and safety are closely related since successful maintenance has been shown to promote plant safety and productivity (Hale *et al.*, 1998; Raouf, 2004). Söderholm *et al.* (2007) have approached maintenance management from the viewpoint of stakeholders. According to the study, the external stakeholder requirements have an effect on the companies' internal processes, such as maintenance. To fulfil the requirements, maintenance processes have to be aligned with the other internal processes, such as safety and environmental management, which are controlled by legislation and regulations. To ensure this kind of integration, specific information is required on aspects of system safety that can be affected by maintenance. However, safety during maintenance operations also requires specific consideration, especially in the case of industrial service-providers operating on various customer sites.

Maintenance operations can be examined in various ways. For example, Tsang (1995) utilises two main groups for maintenance operations, namely corrective (breakdown) maintenance and preventive (time-directed) maintenance. Luxhøj *et al.* (1997) have grouped the operations according to the underlying motivation for maintenance. Thus, maintenance operations can involve corrective, preventive and predictive operations. In the present work, the definition of

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maintenance operations conforms to Reason's (1997) definition of maintenance activities, according to which maintenance operations include the following:

- unscheduled operations, including corrective maintenance, and disturbance- and failure- preventive operations (opportunity-based maintenance)
- scheduled disturbance- and failure-preventive operations
- inspections
- calibration and testing.

In addition to corrective operations/repairs, the need for maintenance can also be scheduled failure-preventive operations or opportunity-based maintenance, i.e. failure-preventive operations, which are carried out while the system has been shut down for some other reason. This thesis deals with all the above-listed maintenance operations, irrespective of the motivation for maintenance.

The focus here is on full-time maintenance workers. Thus, operators and other personnel involved in activities such as unplanned repairs fall outside the scope of the present work. The maintained system can be a single machine, any part of a production system or an entire system (see Riis *et al.* 1997). The focus of the present study is the maintenance activities, irrespective of the object system.

Maintenance operations are composed of two elements which are 1) the development of the need for maintenance (pre-maintenance conditions) and 2) the maintenance operation itself (see Figure 1). The first element, or event chain, mainly relates to component and system reliability as a result of an identified need to change, inspect or repair components in order to retain or restore a system's normal functioning. In the second event chain, i.e. the maintenance operation, human activity serves to determine the progress of events.

From the event-analytical viewpoint, the development of the need for maintenance is the *cause* to initiate maintenance, whereas the maintenance operation is the *consequence* of that. From the viewpoint of safety, the pre-maintenance conditions can generate certain hazards, which can cause risks during the actual maintenance operation. Such hazards include leaks and emissions, which must be identified and controlled before entering the work area. Malfunctioning machinery poses another risk because of irregular and erratic operation. Identifying malfunctions and controlling such risks is essential before the maintenance task can be safely carried out.

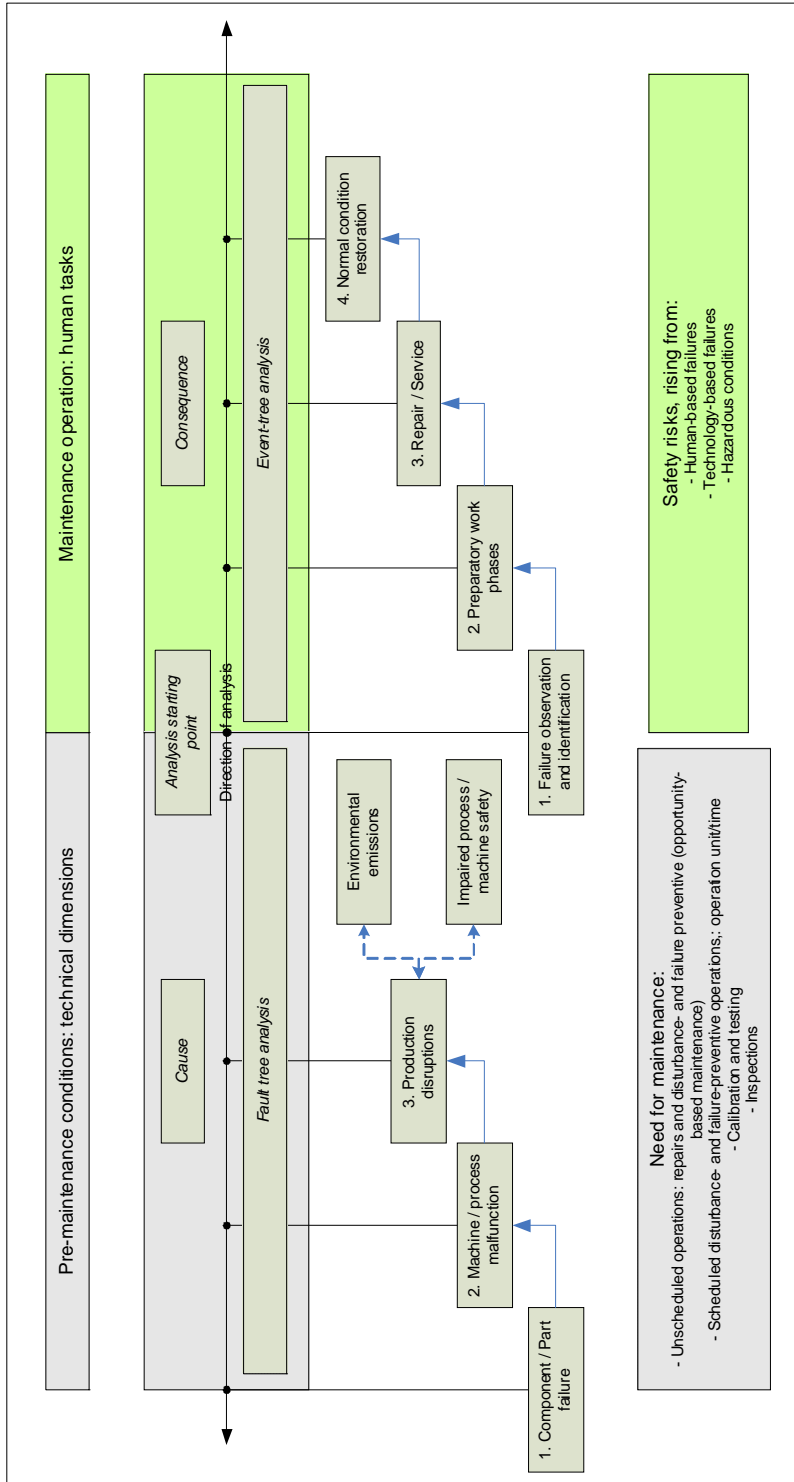


Figure 1. Maintenance: cause-consequence schema.

1. Introduction

Within the cause-consequence schema, the development of the need for maintenance (pre-maintenance conditions; left side of Figure 1) can be examined using fault tree analysis (FTA), providing information on the source and development of the system failure/malfunction. An FTA can also produce quantitative data regarding reliability of different parts and components in a system. Such cumulated information can also be utilized in maintenance operations management and planning, as the probability and frequency of repetitive faults can be estimated or calculated. An FTA analysis is also applicable in accident cases, as they help to model the events and contributors preceding the accident, together with their interconnections. Conversely, if the starting point is failure observation/identification, the possible consequences and different outcomes of a maintenance operation can be expressed by an event tree model (ETA). An ETA models the possible event chains, starting from the chosen top event, which in the case of Figure 1 is Failure observation and identification. An ETA helps to model the various event chains, which can lead to desired (successful maintenance) or undesired (accident / system reliability problem) consequences.

The various work phases during the maintenance operation can give rise to new risks. In addition to the actual maintenance work, such as disassembling and re-assembling, the preparatory and task-supportive actions on the site can increase the number of risks to which the worker is exposed during the operation. Such actions include walking on the site and gathering tools and spare parts. From the standpoint of the maintenance worker, a maintenance operation can be divided into four main phases:

1. Identification of the need for maintenance
2. Preparatory work phases
3. Repair / service
4. Normal condition restoration.

In the first phase, the need for maintenance is identified and this can be essentially fault-, time- or opportunity-based, depending on the trigger for maintenance. In the case of opportunity-based maintenance, certain types of remedial action can be taken if the object system is out of action for some other reason. The second phase involves the preparatory work phases that are necessary before actual maintenance work commences. Such work phases may involve disassembly or removal of surrounding structures and delivery of equipment to the work

place. The third phase is the actual maintenance work. The fourth phase in the model is restoration of the normal condition or functioning. During this final phase, the maintained process/process part/machine is returned to normal operation and the working area is cleared. This four-part grouping follows a situational maintenance model, which has been designed specifically for maintenance management (Riis *et al.*, 1997). The phases are detailed in Appendix 1, which contains proposals for a generic model of an industrial maintenance operation. The model is similar to the models of Hale *et al.* (1998) and Riis *et al.* (1997). However, the model of Hale *et al.* (1998) deals with safety management, whereas the generic maintenance operation model in Appendix 1 deals with task- and safety -related factors in the human-machine interface. Maintenance operations have also been modelled for management of the economic dimensions of maintenance (see e.g. Riis *et al.* 1997; Thorsteinsson & Hage, 1992). However, the conventional models focus on maintenance management in general and provide little detailed information on human activity during maintenance that could be applied in hazard identification and accident prevention.

1.3 The scope and aims of the thesis

Maintenance operations and service business are becoming increasingly important both for service-providing companies and for machine manufacturers as after-sales service. At the same time, maintenance work poses specific safety challenges, which require a holistic maintenance-specific approach. To prevent accidents successfully, a detailed analysis is required of the accident sources themselves as well as discovering ways to identify and manage them systematically in companies.

1.3.1 Accident sources: Definition

In this thesis the accident sources include such factors that can cause or contribute to an accident endangering human health or safety. In this context, the term “accident source” is used to refer to potential and realized accident causes and contributors. Accident sources are examined using Reason’s (1997) categories of causes of organizational accidents (Figure 2). Further, Reason’s grouping is complemented with technology-based failures, which are independent of human

1. Introduction

actions, but have the potential to cause accidents by damaging post-maintenance system reliability or human safety during maintenance operations.

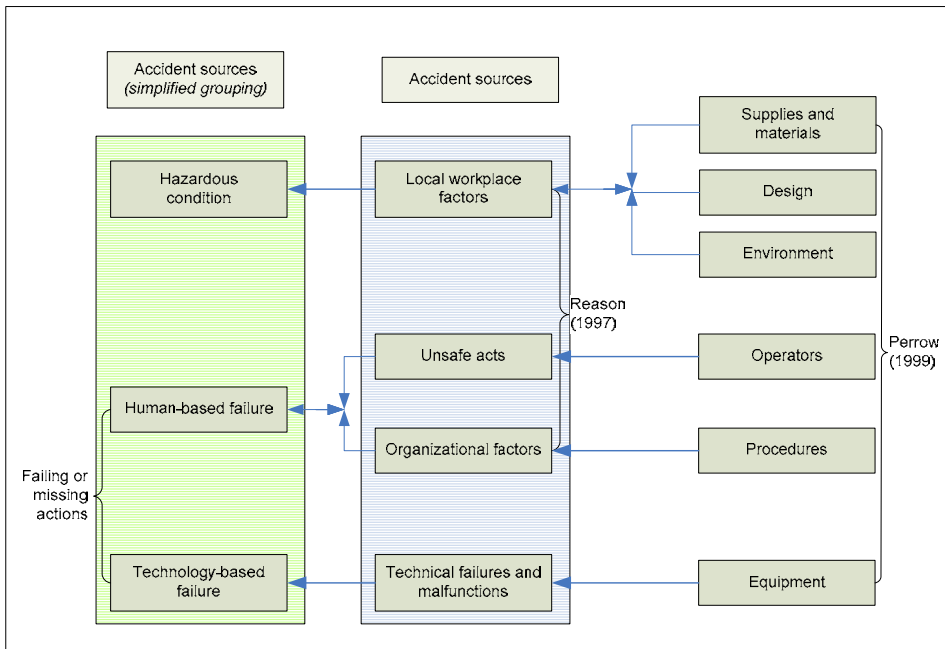


Figure 2. Accident sources: concept and main groups.

Simplifying Reason's theory, the human-based failures can be either organizational factors or unsafe acts, while the hazardous conditions refer to local workplace factors (error-provoking conditions). In Figure 2, the hazardous condition includes Reason's local workplace factors, which corresponds to supplies and materials, and design and environment in Perrow's Normal Accident Theory (1999). Similarly, human-based failures refer to human performance at different organizational levels. Thus, it includes workers (operators in Perrow's theory) and organizational factors, such as management and supervision. Finally, technology-based failures refer to technical failures and malfunctions, which can be the reasons for maintenance, but also the cause of accidents during maintenance operations. Following the simplified grouping, technology-based failures are the third group of interest, along with hazardous conditions and human-based failures. The human- and technology-based failures are basically failures or deficiencies in the functioning of people or machines. Since both human- and tech-

nology-based failures and hazardous conditions have the potential to cause accidents during maintenance work, they are referred to here as *accident sources*.

A system can be defined in various ways, depending on the focus of interest. For example, Kirchsteiger (1999) defines the system as “an assemblage of elements (components) that operate together in some relationship to achieve a common objective (a plan)”. This definition conforms to Perrow’s (1999) approach, which fulfils Kirchsteiger’s definition of humans as elements in a system. According to Perrow, “...system accidents, as with all accidents, start with a component failure, most commonly failure of a part, say a valve or a human operator”. The concept “sociotechnical system” refers to the technical system with the human operators (see Perrow, 1999; Reiman, 2007). Following Perrow’s view, the concept of failure includes such human- and/or technology-based deviations in a system that differ from the intended behaviour/use and can lead to unwanted consequences. Such consequences can be variations in product quality or system reliability, or deviations in occupational safety. In this thesis, *system* refers to the object of maintenance, which can be a machine, process or a part of a process. Finally, *root causes* are the initiating factors that launch the chain of events leading to an unwanted outcome. In common with any accident source, a root cause can also be a human- or technology-based failure, or a hazardous condition.

1.3.2 Aims and research questions

The focus of this thesis is the accident sources in industrial maintenance operations; specifically the human-machine interface. In addition to the maintenance workers and the technical dimensions in accident causation, the origins and management of accident sources are also examined in the organizational context, with particular regard to supervision and management. The topic is approached utilizing real accident data and exploring the potential accident risks in companies (Figure 3).

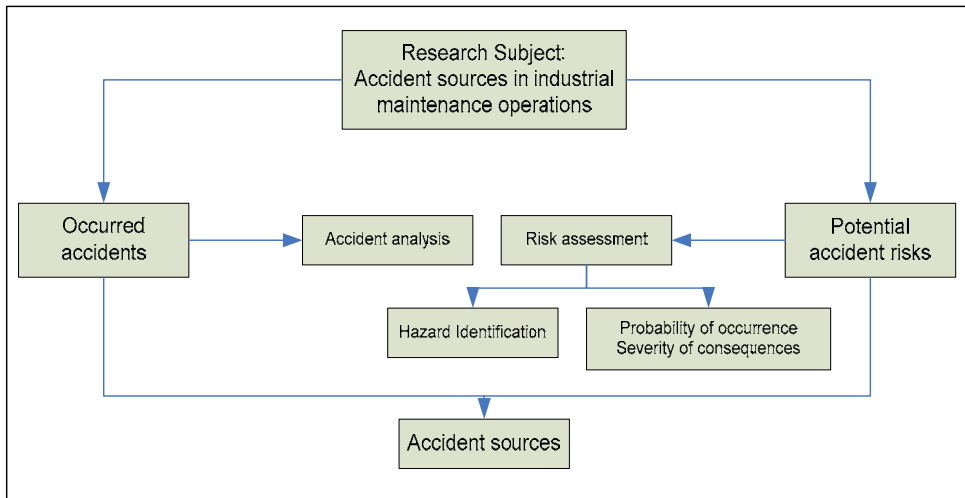


Figure 3. Setting of the study: identification of accident sources.

The primary aims of this thesis are 1) identifying the most important (typicality/severity) accident sources in industrial maintenance operations, and 2) proposing methods for maintenance-specific hazard identification and accident prevention in companies. The accident sources are examined from the viewpoint of the maintenance workers during maintenance operations. The following set of research questions has been formulated to achieve these aims:

1. What kinds of accident risk are typical in industrial maintenance operations? (Articles I and II)
2. What kind of fatal and severe non-fatal accidents have occurred in Finland in maintenance operations? (Article I)
3. How could accidents during maintenance operations be prevented? (Articles I–IV)

The primary focus of the thesis is on full-time maintenance workers and maintenance operations, as defined in section 1.2. Thus tasks performed by operators or other workers are not considered.

1.3.3 Contribution

This thesis contributes to the field in the following ways:

- Considering accident risks in industrial maintenance operations
- Integrating accident prevention with maintenance management and planning
- Providing maintenance-specific methods and safety information for companies' safety management
- Improving the dissemination and use of accident information.

The results can be applied within a machine manufacturer's after-sales service and industrial maintenance as a service business. The results can be used in maintenance and safety management, where they can enhance safety during maintenance, as well as task planning and resource allocation. Collaboration in modelling various accident sources can also improve post-maintenance reliability. The results can also be applied to other industrial tasks such as assembly (for example, building a factory or a process line) or disassembly (for example, demolition).

1.4 The structure of the thesis

The Introduction examines maintenance operations and maintenance safety in general. The research problem and scientific contribution have been defined on the basis of these. The Theoretical Framework reviews the major approaches in maintenance safety and general accident theories. The Results comprise the following: first, accident sources, as observed in companies and in real accident data, are examined (Articles I and II). On the basis of the findings in companies and other applied data, a method for identification of potential accident sources is presented (Article III). Finally, the results summarize the possibilities to support maintenance management, accident prevention and hazard identification in companies by using real accident information (Article IV). In this context, a fault tree analysis on a single fatal accident case is presented with aim of demonstrating the presentation of maintenance accident data in a tree model form. The Discussion deals with the identification and management of accident sources in industrial maintenance operations. Finally, the Conclusions present the most significant accident sources together with proposals to identify and manage them.

2. Theoretical framework

2.1 Safety research in industrial maintenance

Research that combines maintenance and occupational safety is fairly limited. Maintenance-related research has usually concentrated on system's post-maintenance condition, i.e. reliability of a process or a machine, while safety during maintenance has received less scientific interest. In general, studies on maintenance-related risks can be divided into two groups, examining either 1) human performance as a risk to the process being maintained, or 2) maintenance operations as a risk to humans (Lind, 2004).

The first group includes studies that have concentrated on post-maintenance safety and reliability (e.g. Gramopadhye & Drury, 2000; Hobbs & Williamson, 2002; Holmgren, 2005; Jo & Park, 2003; Rankin *et al.*, 2000; Taylor, 2000; Thomaidis & Pistikopoulos, 1995; Toriizuka, 2001). Most studies of maintenance-related risks examine human performance as a cause of the accident. A finding that a significant proportion of equipment failures occur shortly after a maintenance operation (Reason & Hobbs, 2003) supports this viewpoint. The approach is based on the increased risk of human error during disassembly and assembly. The problem has been well-illustrated by Reason (1997) using a nuts-and-bolts example. Essentially the example presents all the possible variations in which a system can be re-assembled in an incorrect way. Studies linking human error with the reliability of the maintained object are particularly associated with nuclear power production and commercial aviation. For obvious reasons such sectors have pioneered the assessment of human error in post-maintenance safety and reliability (Dhillon & Liu, 2006; Lind, 2004).

The second group of studies on maintenance-related risks examines maintenance operations as a risk to humans. Occupational safety during industrial

maintenance operations has not previously been examined systematically. However, maintenance is often identified as a risky operation from the perspective of occupational safety (e.g. CCPS, 1995; Hale *et al.*, 1998; Kelly & McDermid, 2001; Lin & Cohen, 1997; Reason, 1997; Rouhiainen *et al.*, 1984; Su *et al.*, 2000). Both the management and the physical working conditions play important roles in developing safety in risky environments (e.g. Rasmussen, 1997; Sasou & Reason, 1999; Williamson *et al.*, 1996). Maintenance operations can be considered as involving the same risk factors as other operations in industrial working environments, but they also increase certain specific risks. Such maintenance-related risk factors (e.g. working alone or at night) are more likely to arise from the need to make urgent repairs and rectify malfunctions. Other typical risk factors include the frequency of tasks, untidiness and disorder in the working environment, as well as defects in equipment and tools. These factors can also increase the risk of human error (Reason & Hobbs, 2003), although they are often seen as contributing to the probability of any occupational accident.

The typical basis for earlier studies has, then, been the consideration of human performance as a threat to post-maintenance reliability. Several studies have examined risks arising from human performance. However, it may also be assumed that industrial maintenance operations involve various risks for maintenance workers. Such risks can stem from technical failures in a system or result from human performance at any organizational level. To deal with such risks, maintenance-specific tools for hazard identification and accident prevention are needed.

2.2 Integrated approaches to maintenance and safety management

Maintenance is associated with various management processes, such as safety, the environment and quality management. In the case of managing safety and environmental impacts in industry, the role of successful and effective maintenance is important because of very high demands and expectations for retaining a system's inherent safety (see e.g. Edwards, 2005; Gupta *et al.*, 2003; Kletz 2003). Reliability is also important for environmental safety since failures and accidents in high-risk industries (e.g. the chemical industry) can cause major environmental impacts (see e.g. Acosta & Siu, 1993; Aneziris *et al.*, 2000). This sets high requirements on maintenance in such plants because of the essential role it has in supporting production management by ensuring trouble-free pro-

2. Theoretical framework

duction. Furthermore, the link between maintenance and product lifecycle management (PLM) is strong, as maintenance is a crucial part in PLM (see e.g. Cunha *et al.*, 2004; Takata *et al.*, 2004; Westkämper, 2003). Among PLM systems that concern maintenance during product and system design phase, certain tools and systems have been developed for maintenance management during the use of a system. An example of such a system is CMMS (Computerized Maintenance Management System), which, among other things, helps to control permits needed in maintenance tasks, machine-specific service programs, and inventory data on spare parts, and tools (see e.g. Crespo Marquez & Gupta, 2006; Kans, 2008; Keane *et al.*, 2007; Pinjala *et al.*, 2006).

It has been proposed that user needs must be incorporated in the system design process (see Blaise *et al.*, 2003). From the viewpoint of PLM, maintenance activities should also be considered already in the design phase of a technical system, as well as in the product design phase (Markeset & Kumar, 2003). In addition to user needs and maintenance activities, safety is also a critical factor throughout the product lifecycle. Maintainability analyses provide an effective tool for considering maintenance, safety and user needs already in product design phase. The common interests of product development, maintenance and safety are also important to company management, as it is responsible for safety and maintenance management, along with PLM issues. In this domain, maintenance and safety management share similar concerns in ensuring the ease and smoothness of maintenance work (see also Hale *et al.*, 1998). The findings in this study can provide new approaches to the integration of safety into maintenance management.

Machine or system maintainability can be defined quantitatively as the probability of performing a successful repair action within a given time (Sharma & Kumar, 2008). Thus, maintainability can be defined quantitatively with equation (1), where μ is repair rate.

$$M(t) = 1 - e^{(\mu * t)} \quad (1)$$

Following this definition, the qualitative maintainability features are those promoting ease and speed of maintenance tasks (Sharma & Kumar, 2008). From the worker's viewpoint, system maintainability and work fluency include, among others, features affecting ergonomics during the task execution. Maintainability design supports the aims of occupational safety and ergonomics by considering, for example, location, access and time required in task execution (see e.g. SAE

J817-2:1991; Wani & Gandhi, 1999). Thus, maintainability design helps to consider the worker's viewpoint, paying attention at the system design phase to the safety and feasibility of the forthcoming maintenance operations. However, maintainability analyses emphasize the ease and fluency of maintenance operations and produce such information for system design. Although detailed maintainability design helps to promote ergonomics and safety in maintenance operations, its primary aim is to ensure a quick and fluent maintenance operation rather than specifically focusing on safety and accident prevention during maintenance. However, it is clear that good maintainability also promotes task safety and ergonomics. Good maintainability can also have positive indirect effect on reducing the risk of human error since good system design can diminish the work phases in disassembly and re-assembly. Moreover, good system design can also direct the worker to make the right action decisions if the system design supports safe and correct task execution.

There are various types of design principles (see Blanchard *et al.*, 1995; Ivory *et al.*, 2001) and check-lists (see CDC, 2007; NASA, 2006; SAE J817-2:1991; Stephan, 2005) for maintainability design. For example, SAE J817-2:1991 produces an index that provides a reference value for a machine's maintainability. Although the index is designed for off-road machines, it can also be applied in other contexts (see Välisalo & Rouhiainen, 2000). Certain maintainability indexes include factors such as the number of tasks to complete the operation, the time required and the number of tools. In addition, such indexes also consider a system's qualitative features, such as accessibility and reachability. (see e.g. SAE, 1991; Wani & Gandhi, 1999) The maintainability indexes attempt give maintainability a quantitative value based on qualitative and quantitative system and task features. In addition to maintainability indexes, feasibility and speed of maintenance operations can be assessed with task analyses. The task analyses provide a detailed sequential list of the main and sub tasks required to complete the desired operation (see e.g. Hollnagel, 2006). Identification of these tasks can help in managing them efficiently. Maintainability is one component in RAMS (reliability, availability, maintainability, safety/supportability) engineering, which aims to enhance the maintenance-related features of a system. Applying the principles of RAMS engineering can reduce the number of failures in a system and, thereby, make the maintenance operations easier to perform. The RAMS approach can be applied in the design, manufacture and installation of a technical system. (Saraswat & Yadawa, 2008) An extended approach to RAMS

engineering is FRAMS, which also takes into account the flexibility in the system design (see Thomaidis & Pistikopoulos, 1995).

2.3 Risk assessment and analysis

2.3.1 The concept of risk

According to ISO 14121 (1999), hazard is a potential source of harm. The type of hazard should be identified on the basis of its origin (e.g. electrical hazard) or the nature of the potential consequences (e.g. suffocation). Further, hazards can exist permanently in a system or in a working environment (e.g. ergonomics problems) resulting from permanent or inherent system or workplace features. However, hazards can also appear unexpectedly if certain conditions exist (e.g. an explosion). (ISO 14121:1999).

Accident prevention is based on risk analysis, which involves the identification of the hazards. The consequences and likelihood of occurrence of each hazard are also estimated. Thus, “risk” is the product of the estimated severity of consequences and estimated likelihood of occurrence. (see BS 8800:2004; ISO 14121:1999; McCormick, 1981). The risks relating to a system can be expressed in terms of figures or statements (quantitative/qualitative information) (see e.g. Kirchsteiger, 1999). Typically, occupational risks are assessed qualitatively and reliability risks are merely assessed and presented as numerical values. In the case of occupational risks, the qualitative data is transformed to quantitative in order to provide a numerical risk value (see Table 1). This value is utilized to determine the severity of a risk and the urgency of the corrective measures. According to BS 8800:2004, very low risks are acceptable, whereas low, medium and high risks should be reduced. Very high risks are deemed unacceptable.

Table 1. Risk number (adapted from BS 8800:2004).

	Severity of harm		
Likelihood of harm	Slight harm	Moderate harm	Extreme harm
Very unlikely	1 Very low risk	1 Very low risk	4 High risk
Unlikely	1 Very low risk	3 Medium risk	5 Very high risk
Likely	2 Low risk	4 High risk	5 Very high risk
Very likely	2 Low risk	5 Very high risk	5 Very high risk

In the case of accident risks, the following criteria (Table 2) have been proposed for defining the risk components (BS 8800:2004):

Table 2. Risk – definition of components.

Likelihood	Consequences (Harm)
Very likely: Typically experienced at least once every six months by an individual	Slight harm Health: nuisance and irritation (e.g. headache); temporary ill health Safety: Superficial injuries, minor cuts and bruises
Likely: Typically experienced once every five years by an individual	Moderate harm Health: Partial hearing loss, dermatitis, work-related upper limb disorders Safety: Burns, concussion, minor fractures
Unlikely: Typically experienced once during the working lifetime of an individual	Extreme harm Health: Acute fatal diseases, permanent substantial disability Safety: Fatal injuries, amputations, major fractures, multiple injuries
Very unlikely: Less than 1% chance of being experienced by an individual during their working lifetime	

There are various established methods for assessing occupational risks in industry. Such tools can focus, for example, on occupational risks (e.g. ergonomics or injury risks) in specific tasks. Certain risk assessment methods, such as HAZOP (Hazard and Operability Study) and FMEA (Fault Mode and Effects Analysis), aim to identify the system risks.

2.3.2 Risk analysis and management

The concept of risk assessment is defined in standards, such as machine safety standards SFS-EN ISO 12100-1 (2003) and ISO 14121 (1999), quality management standard SFS-IEC 60300-3-9 (2000) and safety management standard BS 8800 (2004). The standards describe risk assessment in terms of a three-part

2. Theoretical framework

process, which consists of hazard identification, risk analysis, and choice of risk reduction measures (risk management) (Figure 4) (SFS-EN ISO 12100-1 (2003); BS 8800 (2004); ISO 14121 (1999)). The feasibility and adequacy of risk reductive/accident preventive measures are estimated to ensure that the risk has been reduced to an acceptable level (ISO 12100-1:2003).

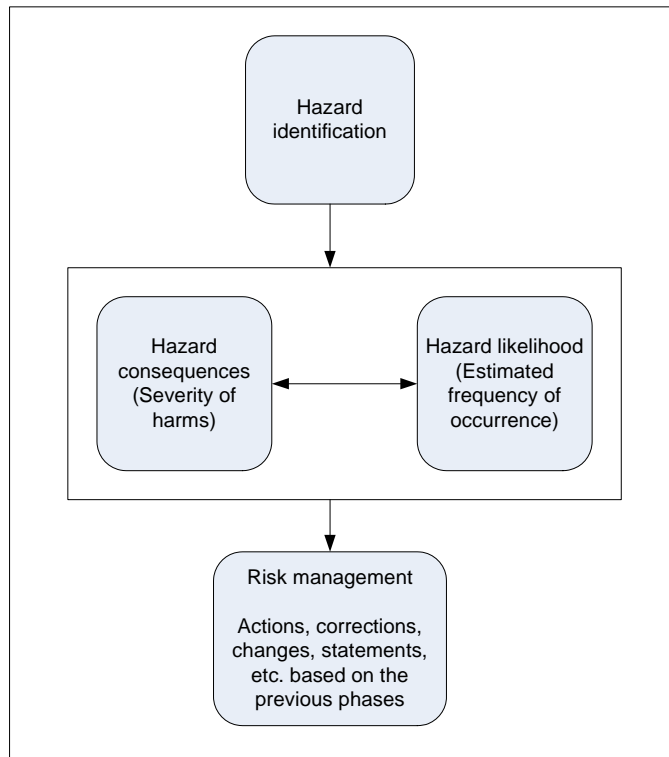


Figure 4. Risk analysis procedure.

Risk assessment is a subjective process because identifying hazards and determining the consequences and likelihood of the risk depend on the observer's own judgment which is inevitably influenced by personal experience and perception (c.f. Redmill; 2002a; 2002b). Use of validated, systematic risk assessment tools, together with standardized guidelines for determining the severity of a hazard and likelihood of the occurrence, can help to diminish subjectivity in risk assessments (see e.g. BS 8800 (2004), Tables E1–E5).

The risk management phase is intended to remove or reduce the risk. As risk is a product of two factors (likelihood and consequences), it can be reduced by

decreasing either of them (see e.g. Kumamoto & Henley, 1996). For example, risk can be reduced by setting barriers between risks and humans, as proposed by Hollnagel (2004), and in MORT (Management Oversight and Risk Tree) risk analysis technique (see e.g. Kumamoto & Henley, 1996; Koornneef & Hale, 1997).

According to Wickens and Hollands (2000), a human is likely to be more cautious and careful when working with a system or a component that is known to be unreliable. Such awareness can also prevent certain human-based failures (Wickens & Hollands, 2000). Kolich and Wong-Reiger (1999) have shown that non-work stress can also contribute to human errors due to increased cognitive load. Further, during an emergency or other exceptional situation certain intrinsic human characteristics, such as task fixation and attention narrowing, can cause the individual to misinterpret the situation thus perform faulty actions (Kumamoto & Henley, 1996; Wickens & Hollands, 2000). Based on these factors and variables, prevention of human-based failures must be holistic, taking into account various factors such as supervision, working instructions, workplace design, and variation in human cognitive capacity.

2.4 Sources and pathways of accidents

2.4.1 Technology- and human-based failures as accident sources

Accident prevention in a company can be examined from various vantage points. The hazards exist only on the actual human-machine interface where the human, working environment and the system, i.e. the injury sources and the victim, meet. However, the organizational factors and workplace design can also contribute to hazard realization. As the accidents are the sum of human- and/or technology-based failures and workplace conditions, measures intended for accident prevention usually take into account management and supervision, working environment and human factors (e.g. Heinrich, 1959; Hollnagel, 2004; Kjellén 2000; Leveson, 2004; Perrow, 1999; Reason, 1997; Øwre, 2001).

Accidents can be viewed as manifestations of erroneous human performance, defects or malfunctions in technical devices or processes, or results of unsuccessful (safety) management (see e.g. Kjellén 2000; Reason, 1997). Hollnagel (2002; 2004), Perrow (1999) and Reason (1997) view accidents in a similar way. The key issue is performance variation, which is responsible for making the human performance effective but also raises the risk of an unintended outcome.

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Accidents result from cumulated failures and accident-promoting conditions in the working environment. At the same time the prevalent approaches consider management as the most important and effective way to prevent accidents since many accident origins can be traced back to unsuccessful management, such as deficient decision-making and resource allocation, insufficient supervision and working instructions. Even indirect organizational factors, such as poor safety culture, influence emerging failures and threaten system reliability (see e.g. Clarke, 1999; Little, 2004).

Technology-based (technical) failures are independent of human actions. As such, they include malfunctions and inoperability of the technical components in a system. Technology-based failures can be caused by factors such as voltage deviations in electric current and material fatigue damage. In the field of reliability engineering technical failures are given broader consideration. In this study, technical failures are examined in so far as they pose a risk to human health or safety during a maintenance operation.

From the viewpoint of risk management, both hazards and realized risks can be considered as failures since they are deviations from the intended safe and disturbance-free conditions/performance. In the case of hazards, failures can be considered as causes, i.e. as the components or potential triggers of accidents. From the perspective of realized risks, failures fulfil the definition of an accident because they are unexpected and undesired events causing harm to humans, environment or property (see ISO 14121:1999, 3.1). In this thesis, failures are considered as independent, undesired events that can alone or in chain with other failures cause a risk to realize, i.e. an accident to happen. Thus, failures are treated as unwanted occurrences that need to be identified and prevented both as components of accidents and as accidents as such.

In comparison to the technical failures, the origins and management of *human-based failures* are more complex. Human performance exists at all organizational levels and at each phase of the product lifecycle. In all stages, human performance has certain variation, which may be a source of an accident. The human contribution to accidents can appear as test and maintenance errors, causing a latent reliability risk, or as initiating-event causes, where human actions are the first links in the accident chain (IAEA, 1991, in: Kumamoto & Henley, 1996).

For humans, a work task has different dimensions: 1) system input, 2) other humans, 3) working conditions, 4) demands and resources. These affect the out-

put, which can vary and differ from intended targets (Hollnagel, 2004). Amalberti (1996, in: Hollnagel, 2002) classifies human actions as follows:

- Actions are performed correctly and the outcomes are as intended.
- Actions, where the failure has been detected and successfully corrected.
- Actions, where the failure is detected and tolerated, i.e., it will not be corrected as the consequences are expected to be minor.
- Actions, where the failure is detected but not recovered because of lack of resources, irreversible process, the failure is detected too late, etc.
- Actions, where the failure is not detected.

The causes of such variation can be factors as fatigue, lack of skills or knowledge, or human error. Rasmussen (1986) has examined human actions with unintended outcomes by classifying them as skill-, rule- and knowledge-based errors (see also Hale & Swuste, 1998; Kirwan, 1997). The classification has been refined by Reason (e.g. 1997), so that the skill-based slips and lapses are divided into attention-based slips of action and lapses of memory. In Reason's classification rule- and knowledge-based errors are called mistakes. Kjellén (2000) has drawn up a list of factors that contribute to human behaviour. Such factors are: supervision and instructions, informal information flow, workplace norms, individual norms and attitudes, individual knowledge and experience, and special circumstances. These factors can have a significant effect on maintenance work. Since the tasks require vast individual knowledge and experience of the various tasks, the maintenance operations as such can be exceptional, and the workplace norms can vary between sites.

System and workplace design is essential to prevent accidents and support safe working. According to Kletz (2003), safety should be an inherent feature in a technical system by utilizing passive safety systems, which do not require human operation. However, maintenance can pose specific challenges to safety design and safety systems because the tasks differ from those in normal operation and use. Due to the uncertainties and variation in human performance, Kletz also argues that passive safety systems are less likely to fail than active safety systems or procedures. Inherent safety can be considered as covering all operations in a plant, aiming to reduce or substitute hazardous materials and simplify the operations (Edwards, 2005). From this viewpoint, designing inherently safe systems should also benefit maintenance. Hollnagel *et al.* (2006), and Fadier and

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De la Garza (2006) have proposed a similar approach for managing safety risks arising from a technical system. According to the authors, systems and subsystems should be resilient enough to tolerate technical and human-based failures to a certain extent (see also: Amalberti, 2001; Scalliet, 2006). To implement and improve systems' inherent safety, there is a need for detailed analyses of how and where the human- and technology-based failures have originated and how the possible risk realizes as an accident. Examining accidents that have occurred provide essential information for system safety design and safety management in a variety of industrial operations.

2.4.1.1 Accident theories and models

Heinrich (1959) modelled the chain of events leading to an accident using a domino model. The model envisages accident causes as pieces of a domino. According to the model, removing one part from the chain can stop the domino effect leading to injury. More recent accident models and theories of prevention have much in common with Heinrich's idea. Several authors have made proposals to understand the mechanisms and interactions behind an accident (see, for example, Chiles, 2002; Hollnagel, 2004; Kjellén, 2000; Perrow, 1999; Reason, 1997). The recent theories examine accidents as chains that can have an origin at different levels of organization. The accident will be realized if the accident chain manages to pass beyond the accident preventive measures. The following section reviews three theories: Perrow's (1999) normal accident theory (NAT), Reason's (1997) theory of organizational accidents and Hollnagel's theory of accident carriers and barriers (2004).

Perrow: Normal accident theory

Charles Perrow presented his theory of normal accidents in 1984. The theory focuses on identifying the origins of major accidents. Perrow (1999) examines accidents as inevitable occasions in a complex system. His approach primarily concerns complex high-risk systems, such as process plants, nuclear power production and space engineering, but the theory has also been successfully applied in other domains, especially among high reliability organizations (see Dupree & Lin, 2008; Marais *et al.*, 2004; Perrow, 1999; Sammarco, 2005; Wagner & Bode, 2006). According to Perrow, in complex systems accidents are expected, normal since the system complexity with internal couplings can provoke unex-

pected and unidentified event chains. Thus, Perrow's theory is called normal accident theory (NAT). A recent examination (Chiles, 2002) supports Perrow's view. According to Chiles (2002), accidents' sources originate from failures in complex systems. The failures can occur, for example, in human performance or malfunction in technical systems. The failures and malfunctions launch the chains of events leading to an accident.

In NAT, technical systems and entities are examined on four different levels: part, unit, subsystem and system. Parts form units, which compose a subsystem. Subsystems can have different functions, so that together they form the system. In NAT, incidents occur on system levels 1 and 2 (parts and units), while accidents appear on levels 3 and 4 (subsystems and system). In this theory, humans form a part of the system. According to Perrow, they can be subsystems or units, depending on their function. The NAT does not examine actual accident sources in detail; the focus is on accident chains and couplings in a system. Accident origins are based on failures, which can occur in six different areas: 1) design, 2) equipment, 3) procedures, 4) operators, 5) environment, and 6) supplies and materials. These components are abbreviated as DEPOSE.

In NAT, there are basically two types of accidents, depending on their origin. *Component failure accidents* involve one or more failures in parts, units or subsystems. The failures are linked in a predictable sequence. In this theory, component failures can be either failures in actual technical components or failures in human performance. According to Perrow, component failures can be common-mode failure, i.e. one component can serve two or more independent subsystems. Thus, a failure in this component has far-reaching effects. Environment can also be a source for a common-mode failure. Tight couplings and interactivity serve to make the systems more complicated, which increases the risk of system accidents. Similarly, *system accidents* involve the unanticipated interaction of multiple failures, which can happen in independent units or subsystems. Both types of accidents are launched by component failures – the difference between the accident types is in the failure interaction (expected-unexpected). Thus, the failures occur in the case of a system accident in independent units or subsystems simultaneously, while the interaction between the accident origins is unanticipated. Most component failure accidents actually involve a series of component failures. However, removing such chains or intervening in an ongoing accident is complicated for both designers and operators.

Perrow examines a system's internal interactions in an accident/incident as complex and linear. Complex interactions can those such as feedback loops,

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jumps from a linear interaction to another due to proximity, or branching paths. In a complex interaction, the failures in different subsystems may affect each other, although the subsystems are not connected. The types of linear interactions are planned, visible and predictable. According to Perrow, linear interactions are dominant in most systems. To prevent system accidents, Perrow proposes avoiding both excessive complexity and tight couplings within a system.

In the case of maintenance safety promotion, NAT could be applicable in reliability and maintenance safety promotion since both technical malfunctions and the human contribution are considered. Analysing and modelling failures, as well as accident chains, couplings and interrelations within a system can also help to prevent accidents.

Reason: Organizational accidents

Reason (1997) has examined the formulation of the chains of events leading to accidents. According to Reason, the causes of an accident are the combined result of various factors on different organizational levels. The accident causes can be grouped into “active errors” and “latent conditions”. The active errors refer to unsafe acts, while the latent condition is the collective term for local workplace factors and organizational factors. In practice, Reason takes into account all components in the work. The unsafe acts refer to human actions, local workplace factors refer to the technical and structural conditions in the working environment, and organization factors refer to management and supervision. Due to the extensive definitions of the components, this grouping is similar to Perrow’s (1999) DEPOSE -classification (see Figure 2). The unsafe acts can be the final link in the accident chain, but the latent conditions, originating from deficient management or workplace design, are the primary sources of accidents.

The latent conditions are based on organizational and local workplace factors, while it is the actual worker who makes the active errors (Reason, 1997). The accident causes can rise from any, or all, of the organizational levels and prevention of accidents can be addressed to one or more levels accordingly. However, in Reason’s theory the origin of the accidents is considered to lie in organizational problems, whereas the local workplace factors and unsafe acts enable the realization of the risks. Like Perrow (1999), Reason considers accidents inevitable in complex systems, if the system’s safety relies on calibrating safety management measures on the basis of occurred accidents. Thus, the theory of organ-

izational accidents encourages the active identification of any accident cause, especially latent conditions, in the working environment and organization.

Hollnagel: Accident carriers and barriers

Hollnagel (2004) views accident prevention as providing barriers between accident causes and the object to be protected, such as humans. According to Hollnagel's theory, accidents can be prevented if a set of effective barriers can be provided between the critical stages, i.e. the accident cause and the subject to be protected (e.g. human). Similarly, according to Freitag and Hale (1997), dangers can be controlled with physical hardware, such as inherently safe processes, protective guards and control systems, or with people, who are competent to use the hardware and handle the dangerous substances safely, to maintain the hardware and control measures and to replace them when necessary. Hollnagel's view of the origin of accident causes is similar to Reason's. The author's approach to risk management is akin to MORT, as it emphasizes organizational measures and setting effective barriers between the human and the accident cause (see also Koornneef & Hale, 1997; Kumamoto & Henley, 1996). Therefore, the defensive barriers can be effective at any organizational level in preventing occupational accidents. The barriers can be technical or organizational measures.

For modelling accident chains and the missing/required barriers, Hollnagel provides a Systemic Accident Model (SAM), which is based on Perrow's normal accident theory. With SAM, Hollnagel argues that humans are unable to control complex technical systems, through either direct (such as automation) or indirect ways (management and design). This is because of tight couplings and internal dependencies between the different parts of a system. He also argues that buffers and redundancies cannot be applied to meet unforeseen demands. Therefore, in order to create effective barriers, the hazards and possible accident chains must be identified. Although the basis in NAT and SAM are similar, Hollnagel's viewpoint differs from Perrow's (1999). Hollnagel argues that the human performance must be variable and correspond to work with the complex systems. According to Hollnagel, variability in human performance is the main reason for accidents. However, this variability is considered essential since it gives the human the capability to adapt and react flexibility in different situations (referred as "functional resonance"). These features enable the working of the system, but can sometimes be the source of failures. The main components of SAM are:

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- unintended results from variation in human performance
- technological shortcomings or failures
- latent conditions, and/or
- impaired or missing barriers.

Hollnagel's (2004) approach to modelling human actions in an organization is based on the sharp end – blunt end model. According to this model, the pathways to an accident lead from the blunt end to the sharp end, where the actual accident occurs. At the blunt end exist such actions that relate to moral, social norms and various rules and regulations. Within an organization, the blunt end represents factors rising from management and supervision, whereas in the sharp end is the actual task execution (Reason, 1997; Hollnagel, 2004). Hollnagel's view has much in common with Reason's (1997), who examines accident pathways as latent conditions and unsafe acts. In Reason's model, the latent conditions approximate to the blunt end in Hollnagel's theory, as the accident sources originate apart from the task execution. In the same way, Hollnagel's sharp end is similar to Reason's unsafe acts. Further, safety at the human-machine interface is affected by management procedures, such as preparation and application of procedures, documentation, rules, regulations and administrative controls (Reason, 1997; Kjellén, 2000; Lanne, 2007; Räsänen, 2007).

To conclude, Hollnagel's (2004) view of the creation of accident causes is similar to Perrow's (1999) and Reason's (1997): system complexity can promote accidents because human performance has variation that cannot be totally predicted or prevented. NAT concentrates on the system itself, instead of errors that humans can make while running the systems. NAT is also suitable for analyzing accidents that have their origin in component failures. Thus, it could be applied to the identification and modelling of accident sources and reliability risks in industrial maintenance operations. The primary difference between NAT and Reason's theory on organizational accidents is that NAT focuses on the socio-technical system, i.e. technical system and humans operating it, whereas Reason's theory focuses primarily on humans as the accident victims and triggers.

2.5 Accident analysis, investigation and modelling

In this chapter, accident analysis, investigation and modelling are examined together because their aims and methods are similar. Accident investigation attempts to model the event chain and to analyse the causes and contributors behind an accident in order to discover how and why an accident occurred. Furthermore, it produces information for accident prevention. The accident investigation procedure is typically carried out from the end (the accident) to the beginning (pre-accident processes and conditions).

Accident investigation has many dimensions and applications. By producing information about the causes of accidents, it helps to prevent the recurrence of similar accidents. At the same time it targets accident preventive measures to the appropriate areas not only in companies, but also in the political system (see e.g. Jørgensen, 2008). Investigation results can also have juridical applications. In a company, accident and incident investigation can have direct and indirect benefits since the results can help to prevent future accidents and also reduce the economic loss resulting from production disturbances and other incidents (see e.g. Kjellén, 2000).

Freitag and Hale (1997) have proposed a three-level learning process for safety management systems. The process concentrates on identifying the information deficiencies that have enabled an accident to happen. In this process, the learning takes place at 1) the work-process level, 2) the planning level, and 3) the structure level. In this concept, the hazards are recognised and controlled on the work-process level, while the planning level is concerned with control, planning and hazard prediction. The third level determines the safety management culture and company policies. The levels are connected to each other through a loop. Kjellén (2000) has proposed a similar feedback loop. Here experiences are gathered from the various organizational levels and used to correct actions and prevent the occurrence of similar accidents. The benefits of learning from accidents and utilizing accident and incident information are, however, rarely applied (see Baram, 1997; Bruseberg *et al.*, 2002; Harms-Ringdahl, 2004). Accident reports can be addressed to various readers, such as legal experts, other companies and/or safety authorities. However, since accident reports often emphasize juridical aspects, i.e. organizational matters, instead of practical ones, the findings can be difficult to utilize in designing and improving technical systems (Körvers & Sonnemans, 2007).

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As accidents are rare events in companies, data collection is infrequent. This makes it more difficult to utilize accident data for learning from accidents. Moreover, production renewals and changes can render the applicable parts of the accident data obsolete before the safety-promoting changes are made. Thus, accident prevention must rely on near-accident (incident) data, and information gathered during workplace inspections and risk assessments. Furthermore, the information provided to organizations in the accident reports must correspond to the complexity of the companies' operational environment. If the information provided is unsuited to the intended application, accident preventive measures can be ineffective in removing the risks. Failure to identify the link between production disturbances and accidents can be a missed opportunity for accident prevention. (Kjellén, 2000).

2.5.1 Accident investigation and modelling

The challenge of accident investigation is in finding the causes, contributing factors and their interrelations. Among organizational matters and workplace design factors, the investigation has to consider both possible technical failures, and the victim(s) in pre-accident conditions. The investigation findings can be grouped, for example, as cause contributors and consequence contributors (see Antão & Guades Soares, 2006). This grouping can help in modelling the interrelations and chains of events in an accident model. Bruseberg *et al.* (2002) have proposed a methodology that enables re-examining accidents to produce applicable information for designers. The model attempts to identify the interrelations between contributing factors and account for the dynamics in the human performance.

As accident events can lack the eyewitnesses, investigator(s) must often make assumptions regarding the chain of events while analysing and modelling the events. The investigation is influenced also by subjective factors, such as selecting the events and the stopping point (Leveson, 2001). In addition, accident investigation is a dynamic process that has to be updated and adapted as new evidence and information becomes available (Kontogiannis *et al.* 2000).

In accident investigation, it is recommended that a variety of methods be used to achieve a holistic view on the chain of events and to eliminate the weaknesses of single methods (Sklet, 2004). Kontogiannis *et al.* (2000) have summed up an assessment criteria for accident analysis techniques. The aim has been to include the human interventions with the system engineering approach. The criteria are

based on an analysis of various techniques. According to Kontogiannis *et al.*, accident analysis techniques fall in to three groups:

- Sequential and temporal aspects of the accident scenario, taking into account sequences, timing and event dependencies
- Aspects of the accident analysis process: how the uncertainties and assumptions are managed and modelled
- Aspects of accident prevention, regarding workplace and organizational issues, as well as error recovery paths and legal aspects.

Thus, in choosing the analysis technique, consideration must be given to the available information, the utilization of the findings and the feasibility of the accident model.

There are different models and tools for accident modelling. In general, the sequential models describe the accident as a chain of events, where accident causes and consequences are connected chronologically. Epidemiological models attempt to discover the accident-creating factors in the working environment, whereas systemic models consider the interrelations between different factors (Hollnagel, 2004; Table 3). Hale *et al.* (2006) have introduced a model that examines both accident causes and accident preventive barriers. The so-called core modelling technique considers the provision, use, monitoring and maintenance of the barriers. The model has much in common with Hollnagel's (2004) systemic accident model. According to these models, accident prevention should be based on effective barriers set between the hazardous events and circumstances and the object to be protected (e.g. human, environment). Hollnagel (2004) examines accident models in terms of the following three main model groups: sequential, epidemiological and systemic (see also Benner, 1985; Kontogiannis *et al.*, 2000).

Chains of events and their interrelations can be described with various models, such as sequential model, event-trees and fault trees (see e.g. Attwood *et al.*, 2006; Ericson, 2000; Freitag & Hale, 1997; Koornneef & Hale, 1997; Leveson, 2001 & 2004). An example of a sequential cause-effect accident model is the Finnish accident investigation model, which describes chronologically how human and accident causing conditions come into contact (Saari & Tuominen, 1982; Figure 5). The model is used in the investigation of fatal workplace accidents in Finland. A simplified model is used to describe the chain of events when workplace fatalities are reported to other companies in Finland (Investigation and reporting of fatal workplace accidents, IFWA).

2. Theoretical framework

Table 3. Accident models – main groups (after Hollnagel, 2004).

	Sequential models	Epidemiological models	Systemic models
Search principle	Specific causes and well-defined links	Accident carriers, accident barriers and latent conditions	Tight couplings and complex interactions
Analysis goals	Eliminate or contain causes	Make defences and barriers stronger	Monitor and control performance variability
Examples	<ul style="list-style-type: none"> - Chain or sequence of events - Tree models - Network models 	<ul style="list-style-type: none"> - Latent conditions - Carrier-barriers - Pathological systems 	<ul style="list-style-type: none"> - Control theoretic models - Chaos models - Stochastic resonance

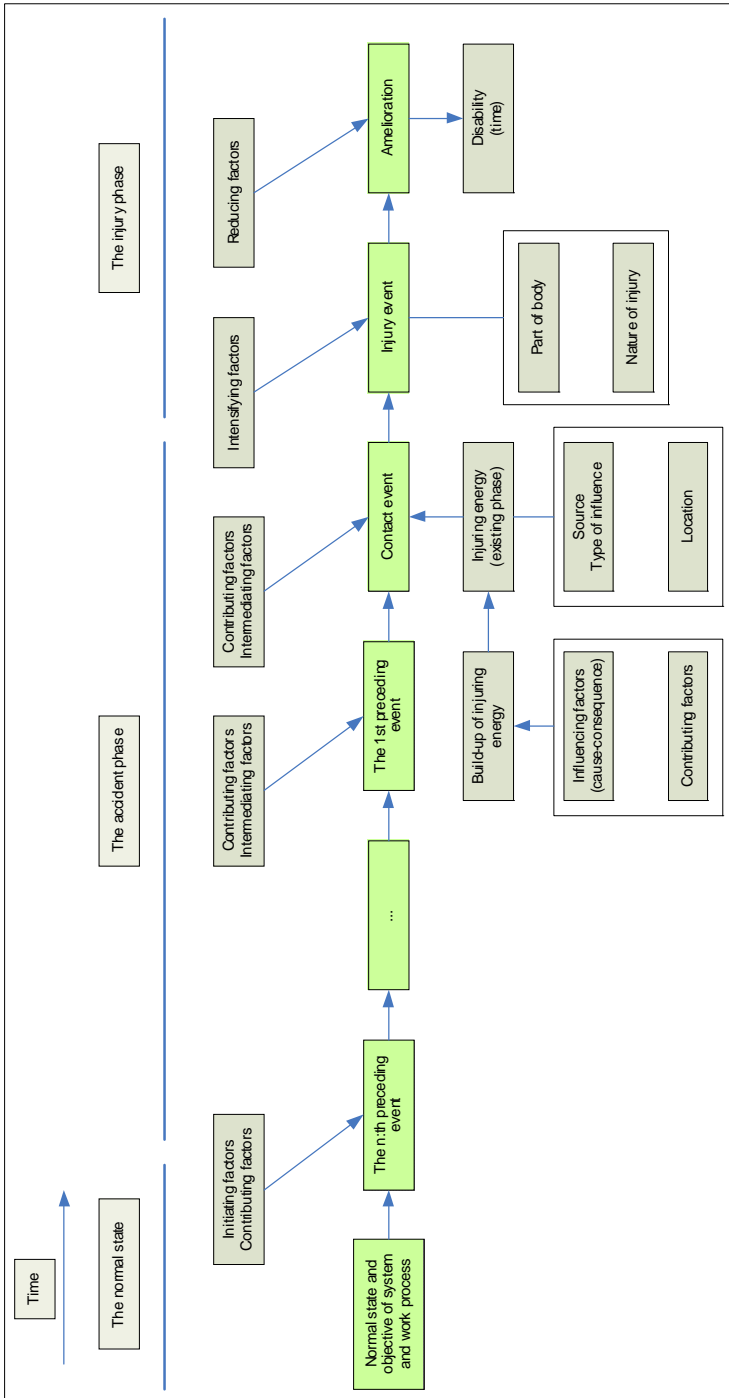


Figure 5. The operational analysis model. (Adapted from Saari & Tuominen, 1982)

2. Theoretical framework

Several authors have recently proposed new accident models for accident investigation and modelling. Leveson (2004) has introduced an accident model for engineering safer systems in response to the increased complexity of new technologies. This model attempts to minimize subjectivity and provide more information on the actual causes of accidents. Hall and Silva (2008) propose a method for analysing mishaps in human-operated safety-critical systems. Their model is concerned with the interactions between a computer system and human operators and is therefore not entirely applicable to industrial maintenance. It describes the accumulation of undesirable events that can ultimately have catastrophic results

A more generic model, which includes human and cultural factors in accident investigation, has been proposed by Lund and Aarø (2004). The model integrates process factors (attitudes and beliefs, and social norms) with risk factors (behaviour and physical and organisational environment). The preventive measures include behaviour, attitude and structural modification. Thus, the model is more suitable for identification and prevention of human-based failures. A similar limitation applies to another model by Dekker (2002), which attempts to remodel the human contribution in accident investigation. The model seeks to identify the conditions that have prompted the human into decisions or actions that have led to the accident. In common with other authors, Dekker considers “wrong” human actions as normal. The causes of failure can lie deeply embedded in the organizational practices and the system’s inflexibility can contribute to the accident.

Fault and event tree analysis (FTA/ETA), together with cause-consequence analysis, provide a chronological view of the links between errors and events. Thus, they are applicable in modelling both component failures and occupational accidents, i.e. reliability and safety problems, and their origins and interrelations within the system (see e.g. Aaltonen *et al.*, 1996; Antão & Guades Soares, 2006; Attwood *et al.*, 2006). In addition to analysis and modelling of occurred accidents, the fault and event trees can be utilized in assessing the reliability and safety risks of a system. (see e.g. Acosta & Siu, 1993; Aneziris *et al.*, 2000; Bucci *et al.*, 2008; McCormick, 1981; Rutt *et al.*, 2006; Siu, 1994; Xu & Bechta Dugan, 2004). An event tree is an inductive model, which includes all possible pathways that can lead to a certain consequence. Fault trees are deductive, as they seek to discover all the causes and conditions that have contributed to the top event, in this case the accident. (McCormick, 1981; Xu & Bechta Dugan, 2004).

To ensure that accident preventive measures (human-/ technology-based failures) are properly applied, the actual root causes must be extracted from the risk information (Hale *et al.*, 1998; Hollnagel, 2002). The root causes can be identified using an event tree analysis, such as FTA and ETA. The root causes are the initiating events, such as a valve malfunction, in the accident chain (see e.g. Kjellén, 2000; Perrow, 1999). Root cause identification can be carried out, for example, with a fault tree analysis, which enables modelling of the accident chains from the top event to the root causes. Kjellén (2000, p. 72) has proposed a model that shows the hierarchical relations between contributing factors and root causes. In Kjellén's model, the contributing factors and root causes form the input, while the three-part chain of deviation, incident and target absorbing energy are the actual process. Finally, the output is the loss of people, environment, property or reputation. In his model, Kjellén considers a root cause to be a factor in general or SHE (safety, health, and environment) management. Among other benefits, event and fault trees have been applied in the detection of root causes (see e.g. Hollnagel, 2002; Virtanen *et al.*, 2006). Irrespective of the field, a root cause is typically considered as the triggering cause of an unwanted outcome, or the first link in the chain of events. Identifying a technology-based root cause is more straightforward than in the case of human performance. In the latter finding a single root cause can be impossible because of the complexity of organizational dimensions and personal performance variation.

2.5.2 Accident prevention in industrial maintenance operations: Conclusions on the prevalent approaches to accident prevention

According to various authors, accidents can be initiated by technical or human failures, which can result from diverse factors in the organization and working environment or variation in human performance. According to such approaches, the complexity of a sociotechnical system's can increase the probability of failures, as the number of parts and units increases and their interrelations become ever more intricate. At the same time human performance varies, setting greater demands on the system's inherent safety, resilience and error-tolerance. The human action can fail at any stage in an organization, or any part of a system, although the accident chains accumulate on the human-machine interface. In the case of industrial maintenance, the challenge for accident prevention is greater because the task, work environment and the maintained object can all vary. Further, the risks and safety practices can differ between customer sites. However,

accident prevention in industrial maintenance operations has received little detailed study, even though maintenance has been recognised as a risky operation.

The major approaches to accident prevention consider the various latent conditions and the organizational factors as possible contributors to unsafe acts (see e.g. Reason, 1997; Hollnagel 2004). Several individual and momentary contributors can affect human actions (Kjellén, 2000). At the same time, technology-based failures are independent from direct human actions, although technical failures can indirectly originate from human action or inaction, such as lack of maintenance. However, the technology-based failures can also be potential accident triggers. In addition to failing actions, accidents can also result from hazardous conditions in the working environment, such as sharp edges, high concentrations of hazardous chemicals in the air, or poorly protected working surfaces. Such potentially hazardous conditions can affect the consequences and probability of an accident, in the event of a triggering cause. Hazardous conditions can contribute to accident causes and consequences, or cause an accident even when human performance is correct and/or machinery functions normally.

In order to manage accident sources in maintenance operations, the accident sources have to be identified. Identification can be based on potential and realized accident sources and possible event chains. The relevant information can be gathered through risk assessments, from accident data or other risk information. In the case of risk assessment in industrial maintenance, consideration must be given to the variations in tasks, human performance and working environment, including the object system of maintenance, in a holistic way.

According to the literature, the following conclusions can be drawn:

1. Accidents occur on the human-machine interface (the “sharp end”), although accident sources can be latent in the technological system or organization (in the “blunt end”).
2. Accident sources can be grouped to failures (human- or technology-based), which can happen in any part of a sociotechnical system, i.e. also independent of the actual human-machine interface and hazardous conditions in the working environment.
3. To prevent accidents, the failures and hazardous conditions must be identified and managed at the sharp and blunt ends, i.e. organization and human-machine interface.
4. Accident prevention can be promoted by employing organizational and technical measures, which support safe operation at the human-machine interface.

3. Methods

3.1 Selecting the research methods and research process

The materials used in this thesis were gathered during three studies. Studies 1 and 2 were carried out in two separate studies, conducted at Tampere University of Technology between 2002 and 2006. Study 3 (accident re-modelling) was conducted in 2008 while the author was working at VTT.

The studies employed various methods (Figure 6). First, the types and sources of fatal and severe non-fatal accidents were charted from public accident reports (Article I). Second, the information regarding maintenance-related risks was complemented by charting risks in service-providing companies and at their customer sites (Article II). Third, a risk assessment method was developed for identification and management of maintenance-related risks in companies (Article III). Fourth, a study was carried out in Finnish metal and transportation industries to learn how companies utilize accident information in safety management (Article IV). Finally, a fatal maintenance accident was re-analyzed in order to examine how root causes could be identified and accident sources modelled from real accident data. The sub-studies and their methods and materials are presented in the following sections.

3. Methods

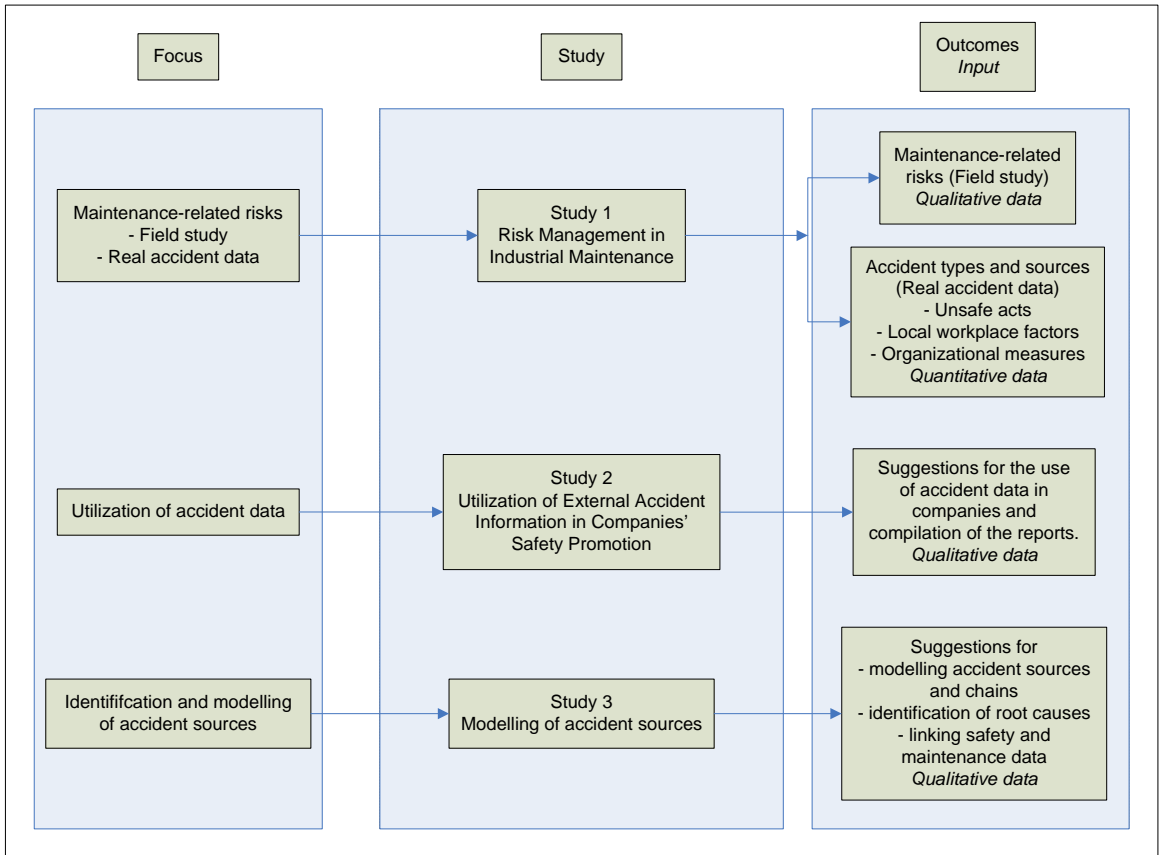


Figure 6. Topics and outcomes of studies.

The core of the study comprises quantitative data from accident sources of fatal and severe non-fatal accidents (Study 1). The risk assessments and interviews, conducted during Study 1, complement the quantitative findings with qualitative, practical data that have been gathered from companies. Study 2 explored the way in which companies utilize accident information in safety promotion. The relevant results from this study are applied to maintenance safety promotion. Finally, the results of Study 3 tested the idea of modelling accident sources and pathways by applying fault tree analysis to a fatal workplace accident.

Overall the study employs a qualitative, empirical approach, i.e. the aim has been to study industrial maintenance operations and reach an understanding of the causes and origins of accidents. Within this approach, a set of quantitative and qualitative methods have been applied. The prevalent theories have been applied to understand the mechanisms and relations underlying accidents. Fur-

ther, the phenomena (accident sources) are discussed empirically since the methods applied and the research objectives are based on practical observation and real accident data. As a result of these approaches, knowledge of the phenomena was achieved inductively. The following sections examine the approaches and outcomes of the studies in greater detail.

3.2 Methods

3.2.1 Study 1: Safety risk management in industrial maintenance

The study can be divided into three stages (Figure 7). First, the safety of maintenance operations was charted in companies. Second, a group of fatal and severe non-fatal accidents were re-analyzed. Third, a maintenance-specific risk assessment method was developed for the independent use of any company.

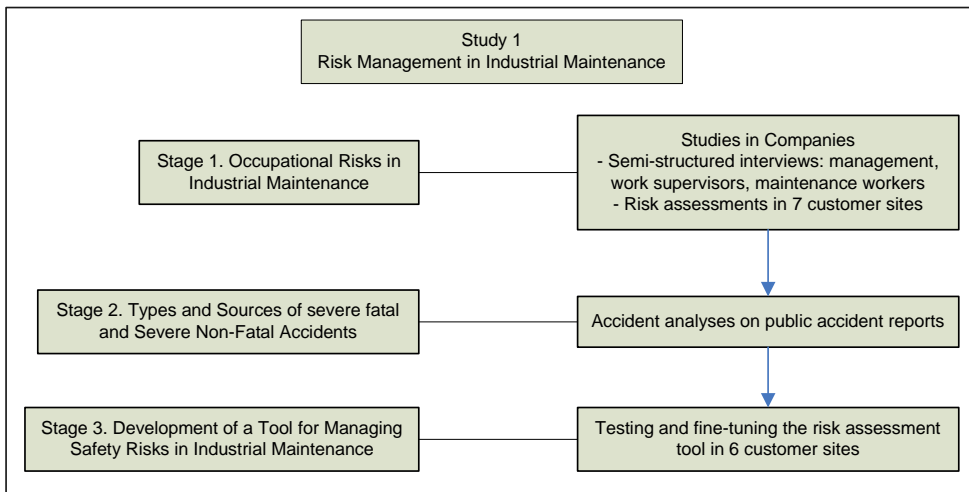


Figure 7. Studies in companies.

The study was executed in cooperation with 3 companies and their 15 customer sites. Two of the companies sell maintenance services to industry, while the third is a machine manufacturer providing after-sales services. The customer sites represented various types of industry (Table 4).

3. Methods

Table 4. Customer sites.

Paper mill	Oil refinery	Vegetable oil and protein feed factory
Underground mine	Dairy	Cable factory
Pipe mill	Dressing plant (nickel)	Plastic product plant
Maintenance workshop	Power plant	Smelting plant (copper)
Engineering works	Pulp mill	Sawmill

Stage 1 produced qualitative information on accident risks in the collaborating companies and at their customer sites. The results from this stage were merely qualitative since the aim was to create an understanding of safety problems in practice.

During stage 1, all 15 customer sites were visited. Some of the sites were in close proximity to each other; sometimes even on the same industrial plot. In such cases, the same maintenance workers were usually responsible for all the customer sites in the area. As a result, the visits involved 12 maintenance crews representing 15 customer companies. In addition, the researchers made on-site observations during the visits. The methods included free form interviews and discussions with the company management, the service-provider's supervisors and maintenance workers. The purpose of the interviews was to gain general information on the company, the types of maintenance operations, and the workers' perceptions of the risks associated with the maintenance tasks. The view was complemented with risk assessments. Due to time and economic constraints, the number of sites involved in risk assessment was limited to seven. These sites and the maintenance operations were chosen during the study's steering group on the basis of high frequency and/or perceived high risk associated with the operations. The risks were charted using a risk assessment tool (Murtonen, 2000). The risk assessments were complemented with interviews designed to elicit the perceptions of maintenance workers on the safety and risks associated with the specific maintenance operations.

Analysis on accident reports

Stage 2 involved re-analysis of reports describing fatal and severe non-fatal accidents in industrial maintenance. The materials were chosen on the basis of their availability (the reports are public), and their precision as they based on experts' investigation. Both types of report are based on investigations by safety experts; a group of safety and case-specific experts investigates the fatalities. Severe non-fatal accidents are examined by one or two industrial safety inspectors from the local industrial safety district. A list of parameters (Appendix 2) was produced for the examination, to ensure systematic analysis of each relevant report.

The analysis included all fatal accidents reported during the years 1985–2004 as well as severe non-fatal accidents that had been reported during the period 1994–2004. The analyses examined only accidents involving full-time maintenance workers in industrial maintenance operations, as defined in Chapter 1.2. The Finnish Ministry of Social Affairs and Health hosts the Safety Inspectors Accident database. Typically, a single author (safety inspector) undertakes the investigation and reporting. At the same time, the Federation of Accident Insurance Institutions in Finland (FAII) coordinates the investigation and reporting of all fatal workplace accidents. In this case, a group of experts from different fields carries out the investigation and reporting.

The relevant reports were analyzed to identify the accident types, the sources and the contributory factors in the working environment or task. In addition, accident preventive methods, suggested by the accident investigators, were collected and classified.

Development of a tool for risk assessment

Finally, a risk assessment method was developed on the basis of the findings from the real accident data and from the companies. The method was designed for independent use in any company. Thus, the method was reviewed and developed iteratively in cooperation with the supervision group (see Figure 8).

3. Methods

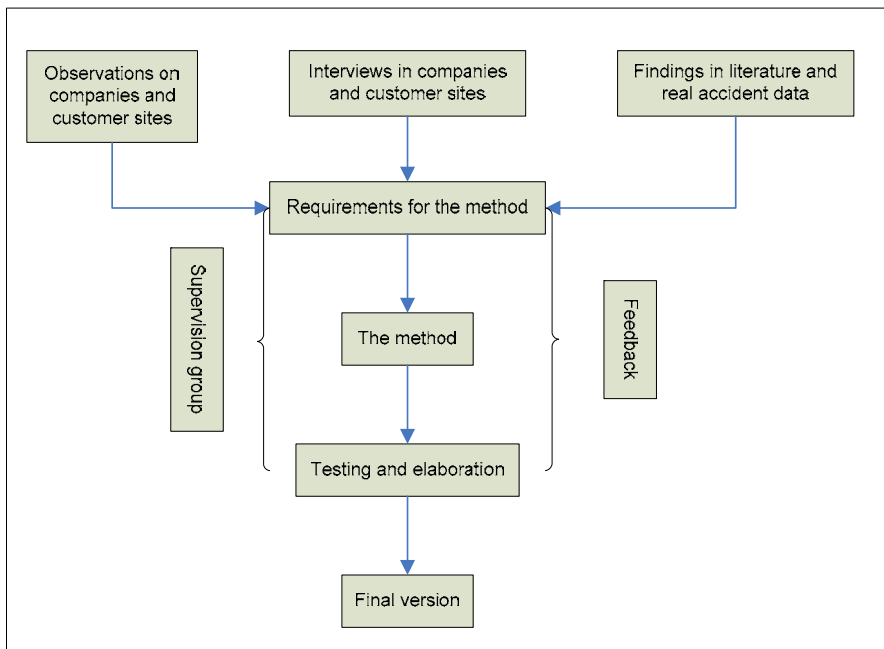


Figure 8. Risk assessment method: development process.

After the method was developed, the researcher tested it in six companies that had not been involved in risk assessments during stage 1. The aim was to gather user experience and information on the usability and feasibility of the method. In addition, the method was distributed to all customer sites and companies taking part in the study. The user experience and feedback was used to fine-tune and finalize the method.

3.2.2 Study 2: Utilization of external accident information in companies' safety promotion

During 2002–2004, a study was carried out in Finnish metal and transportation industries (Figure 9). The aim of the study was to 1) find out how companies utilise fatal accident reports in the prevention of similar accidents, and 2) how the fatal accident reporting system could be developed to provide the information in a more usable way. The study sample contained a total of 10 recently reported fatal cases; five each from the metal and transportation industries. FAII selected the cases so as to include a variety of typical accident types. The meth-

ods used were basically similar in both industries. The accident sites (five per industry) were visited. In addition, a group of other companies in the same industries were interviewed by phone or during visits. Information from certain companies was collected using mail queries because of the difficulty in arranging interviews. The sample included additional 15 companies from the metal industry and 13 from the transportation industry. Together with the ten fatal accident sites, there were a total of 38 companies in the study.

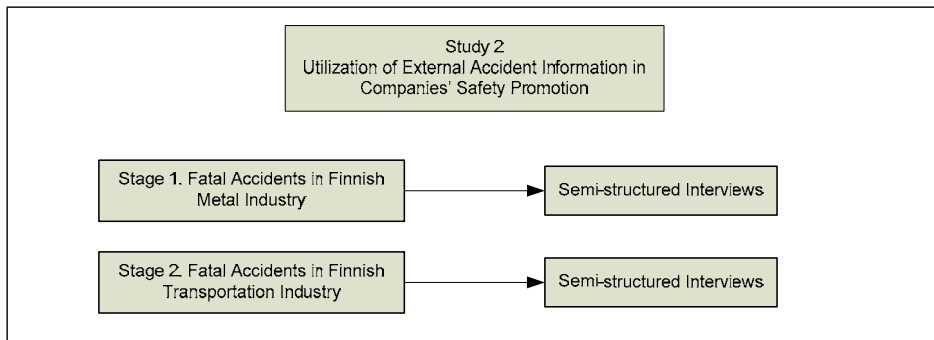


Figure 9. Study 2: Utilization of External Accident Information in Companies' Safety Promotion.

A semi-structured interview containing 62 questions was carried out in each company. The interviews included a general section dealing with the companies' operations and safety practices (see Appendix 3). Comments and suggestions for development of reporting were also gathered. Within both industries, most questions charted how the companies had considered the chosen specific accident cases in developing their safety performance. In the case of the 10 companies with the chosen fatalities, the aim was to examine, whether the fatal accident has enhanced the utilization of the other fatal accident reports. The findings were coded and summarized after the interviews. On the basis of the findings, a summary of the utilization and improvement of reports was delivered to FAII.

3.2.3 Study 3: Modelling of accident sources and pathways

A fatal accident case was selected for re-modelling. The re-modelling, in the form of a chain of events, involved joint identification and modelling of human- and technology-based failures, hazardous conditions and their interrelations. The

3. Methods

aim was to examine if such integration of data could benefit accident prevention in maintenance operations and produce information on the accident root causes. The findings are discussed in terms of maintenance accident prevention.

The analyses were carried out using a program (ELMAS, version 0.10), which was originally designed for event logic modelling of machine malfunctions and mechanical failures. However, the program can also be applied to the modelling of other event logics. In Study 3, the author chose a fatal accident case, which was re-modelled using fault tree analysis. The case examined a fatality, which occurred in 1992 in sawmill industry.

4. Results

4.1 Accident sources in industrial maintenance operations

4.1.1 Findings from sites and companies: General

The risk assessments were based on free-form group interviews with representatives of the maintenance-providing companies, their customer sites and maintenance workers. During these discussions, certain maintenance-related safety problems were highlighted. Ergonomics problems in general were frequently cited as significant challenges in maintenance operations. Most of such ergonomics problems related to physical ergonomics, such as working postures. Cognitive overload, caused by pressure of time, was also mentioned. A specific safety problem was foot injuries, which the service-providers considered as the most typical maintenance-specific accident type. The frequency of foot injuries and problems involving physical ergonomics were thought to be attributable to the *numerous work phases during disassembly and re-assembly, which include object handling*. Other problems cited were a *lack of time and resource problems, especially time and workforce allocation*. An example among service-providers is a large-scale preventive maintenance operation at a particular site that causes a temporary workload peak. In such cases, the increased need of workers on a certain customer site reflects the availability of workers on other customer sites.

The risk assessments supported the findings from the free-form on-site group interviews. Thus, most of the identified risks related to ergonomics, such as poor working postures, heavy lifts and improper working methods. Among other factors, improper scheduling and pressure of time were considered risks at all or-

4. Results

ganizational levels, i.e. by the managers, supervisors in the service-providing companies and the workers on customer sites. Lack of time and inadequate resources may not be significant risks as such, however, they can contribute to the probability of other risks. The perceived risks reflected defects in planning of maintenance operations and work environments (including processes/machinery and walking and working surfaces). The management and supervisors in service-providing companies perceived the same risks as the maintenance workers interviewed on customer sites. It became apparent that the maintenance workers considered time-pressure to be a serious concern.

4.1.2 Risk assessments: organizational factors, local workplace factors and unsafe acts

This section considers the results of the risk assessment which are examined using Reason's classification of organizational accident causes (1997). The results of the risk assessments revealed a majority of local workplace factors as opposed to considerably fewer organizational factors and unsafe acts. This can be attributed to the risk assessment method that was applied. The method is designed for hazard identification on a site and takes little account of the organizational dimensions or the error-provoking conditions. The risk assessments at customer sites indicated that the most typical risks involved physical ergonomics, while the most severe related to injury risks (Table 5).

The risk assessments supported the results from the interviews since most risks related to physical ergonomics. The risks included actual hazards (such as unsafe walking and working surfaces) and error-provoking conditions (such as missing or misleading operational safety bulletins; green-painted fields), which can contribute to unsafe acts and indirectly undermine maintenance safety. Both factors can arise from working environment, unsafe acts during task planning and execution, and organizational factors, such as management and supervision. Further examination reveals that the conditions provoking unsafe acts derive from organizational factors, whereas the actual hazards (direct accident risks) are mostly local workplace factors.

Table 5. Risk assessments: Observed risks in companies.

Typicality on sites	Risk analyses		
	Organizational factors	Local workplace factors	Unsafe acts
	Pressure of time	Unsafe walking and working surfaces (slipping, tripping, falling)	Non-use of personal protective equipment
	Defects in customer cooperation	Missing safeguards or shields	Conscious and unconscious risk-taking
		Missing or misleading operational safety bulletins	Risks relating to ergonomics (heavy lifts/holding up weight, poor working postures, inadequate work tools and methods)
	Aging of skilled maintenance crew members: skills and knowledge transfer	Cold or hot objects	Defects in safety attitudes
	Working on changing sites: managing the various risks and practices site-specifically	Falling objects	
	Large variety of maintenance tasks	Working outdoors: weather conditions	
		UV radiation	
		Lack of oxygen, suffocation	
		Site-specific safety challenges and requirements	
		Defects in working environment	
		Working on changing sites	

Pressure of time is not a significant risk itself: it can be expected to cause cognitive load in the long run. However, it can increase the magnitude of hazard of the existing risks and even create new ones, as workers may use inappropriate methods when performing a task in a hurry. Thus, work planning and resource allocation play essential roles in preventing accidents during maintenance and in avoiding post-maintenance reliability problems.

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On several sites, defects in machine and workplace design hampered maintenance workers' accessibility to the maintenance spot or area of the system. Factors affecting accessibility were, for example, structures in the working environment, or the challenging location of the maintenance spot (e.g. a hatch) requiring the worker to climb on a system. In addition, reachability was often a challenge due to a lack of sufficient working surfaces around the system part to be maintained. On some sites, subsequent changes in the working environment, such as new machinery and/or new pipelines, had impaired system maintainability. Such defects in workplace and system maintainability design can contribute to accident causation as local workplace factors. Deficiencies in maintainability are manifested as problems in physical ergonomics, which originate from two main sources: 1) poor machine or workplace maintainability design, and/or 2) inadequate working methods and non-use of aiding equipment (e.g. lifting devices). In addition to poor accessibility and reachability, the first group of sources can lead to additional preparatory work phases, such as disassembling structures in the working environment before actual maintenance work commences. There are also organizational dimensions in the second group when workers cannot identify the need of aiding equipment due to deficient supervision or poor working instructions. Non-use of aiding equipment can also lead to conscious/unconscious risk-taking, which was identified in more than half of the risk assessments. Such risk-taking typically involves failure to use personal protective equipment (PPE) and the adoption of inappropriate work methods. This behaviour leads to defects in ergonomics, such as inappropriate working postures and risks in materials handling.

The risk assessments were supplemented with separate discussions involving only the workers. During the interviews, the workers reported certain problems relating to issues such as resource allocation and task planning. The specifications were organised into seven main groups (Table 6).

Table 6. Individual specifications on maintenance-related challenges.

Group of problems	Specifications	Dominant type
Defects in customer cooperation	Flow of information between the service provider and customer; reporting unfinished tasks; instructing on common practices on site; scheduling maintenance operations (pressure of time); contents and specifications of maintenance requests	Organizational factors
Site-specific safety challenges	Chemical risks in the process industry; hot and cold working environments; lack of maintenance workshops; working alone; hygiene requirements (especially in food industry)	Local workplace factors
Defects in working environment	Lack of space around machinery/process; poor maintainability of machinery and processes	Local workplace factors
Aging of skilled maintenance workers	Increased demands for good ergonomics; difficulty of replacing experienced crew members	Organizational factors
Working on changing sites	Site-specific practices; various injury risks on different sites; traffic accident risks when travelling to sites; working instructions	Organizational factors / Local workplace factors
Defects in safety attitudes	Non-use of personal protective equipment (PPE); risk-taking	Unsafe acts
Large variety of maintenance tasks	Vast amount of different tasks; acquiring and maintaining skills and knowledge to perform the different tasks; task-specific risks and requirements	Organizational factors

The specifications listed in Table 6 present challenges mostly in terms of organizational and local workplace factors. The local workplace factors often relate to insufficient system or workplace maintainability, i.e. factors impeding maintenance task execution. In addition, the changing sites and the various site-specific risks, along with the customer's safety demands, form a group of challenges for both the workers and the maintenance organization. The local workplace factors can also include outdoor conditions (weather), which in Finland can be espe-

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cially challenging in winter due to, for example, darkness and slippery surfaces. The organizational factors are, however, even more diverse. Customer cooperation has an important role in risk management on various sites. The risks associated with the large variety of maintenance tasks may require specific information management between the maintenance workers and the customer's operating personnel. This kind of information can be considered explicit, whereas gathering the implicit knowledge from the skilled maintenance workers poses another challenge for the companies.

4.1.3 Real accident data: Role of organizational factors, workplace conditions and unsafe acts in accident causation

During the years 1985–2004, there were 33 accidents leading to fatalities in industrial maintenance. Among these, four of the cases involved two victims, thus making a total of 37 victims. During the reporting years 1994–2004, the number of severe non-fatal accidents was 90. In the case of fatal accidents, the maintenance operation was usually mentioned (Table 7), whereas among severe non-fatal accidents the operation type was mostly not stated. According to the findings, the fatalities had mostly occurred during planned disturbance- and failure-preventive operations.

The most common accident scenes for the fatal accidents were indoors at a process (46%). Of the total number, 19% of the accidents occurred while executing maintenance operations outdoors (e.g. at a process pipeline) and 15% occurred indoors in maintenance workshops.

Table 7. Fatal accidents: maintenance operations (N = 33).

Maintenance operation	%
Planned disturbance- and failure-preventive operations	48
Unscheduled repairs	24
Changes (e.g. to processes and machinery)	18
Calibrations, testing, and inspections	9
Other/unknown	1

Within both accident groups, it was often possible to identify the accident types (Table 8). In both groups, the most typical accident type was crushing or being trapped in or between objects. Further, falling or jumping, together with accidents caused by falling or tumbling objects were the next most typical accident types.

Table 8. Accident types.

Fatal accidents (N = 33)	%
Crushing or being trapped between objects	27
Persons falling	27
Accidents caused by falling/tumbling objects	15
Other	31
Severe non-fatal accidents (N = 90)	%
Crushing or being trapped in or between components	39
Jumping or falling	21
Accidents caused by falling objects	12
Other	28

It is noteworthy that the percentage of “crushing or being trapped in or between components” was greater for severe non-fatal accidents than for fatal accidents. Conversely, the share of “persons falling” is larger among fatalities.

The available real accident data was examined with aim of achieving a wider perspective on accident sources. Again, the re-examined data was grouped using Reason’s classification. In examining the accident factors in Table 9, it can be seen that several factors can appear together in a single accident.

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Table 9. Accident sources: Real accident data.

Organizational factors	<i>fatalities, %</i>	<i>non-fatal accidents, %</i>	Local work-place factors	<i>fatalities, %</i>	<i>non-fatal accidents, %</i>	Unsafe acts	<i>fatalities, %</i>	<i>non-fatal accidents, %</i>
Defective work instructions	63	38	Defective safety equipment (machinery)	30	30	Dangerous working methods, including conscious risk-taking (by workers)	48	23
Victim's insufficient experience of task	20	N/A	Device failures	15	10	Defective hazard identification / unconscious risk-taking (by workers)	30	19
			Defective walking or working surface	N/A	14	Non-use of personal protective equipment	17	N/A
						Working at a running machine/process	15	30
						Other (e.g. carelessness, missing information)	N/A	18

According to the findings, the most significant organizational factors were defective work instructions, whereas dangerous working methods were the most common unsafe acts. Victim's insufficient experience of task was identified among 20% of fatalities. Among unsafe acts, it is notable that working at a running machine or process is a cause in 15%–30% of accidents. The dangerous working methods refer to conscious risk-taking where the task is executed in an unsafe way or without sufficient safety measures. Within both accident groups, defects in machine equipment are the most significant local workplace factors.

4.2 Prevention of accidents in industrial maintenance

4.2.1 Proposals for accident prevention in accident reports

The analyses of the accident reports also provided information about accident prevention in industrial maintenance operations. The recommendations given in the reports were collected and grouped according to Reason's classes (Table 10).

In the case of fatalities, most of the recommendations for preventing similar accidents concern organizational factors, while there are much fewer for the unsafe acts. In contrast, for severe non-fatal accidents, the preventive measures highlight local workplace factors. The reasons for these differences are discussed in Article I.

Table 10. Recommendations and suggestions for preventing accidents of similar types.

	Group of recommendation	Most typical recommendations	Fatal accidents % (N = 33)	Severe non-fatal accidents % (N = 90)
Organizational factors	Instructions and task planning	Adding information (incl. instructions, directions and training)	75	29
		Development of work planning	30	16
	Management and supervision	Employer's supervision of safe working methods (incl. acquiring and use of personal protective equipment)	39	15
		Enhancement of safety management (incl. hazard identification)	60	21
Local workplace factors	Machine and process safety	Adequacy and condition of machinery (incl. machine safety equipment)	27	34
		Prevention of unintended start-ups, switching off live parts reliably	24	30
	Workplace design	Development of workplace conditions (incl. occupational hygiene, walking and working surfaces)	30	28
Unsafe acts	Human performance	Use of safe working methods (incl. choosing proper tools, care)	12	13
		Following orders and instructions	12	6

4.2.2 Identification of accident sources: A tailored tool for maintenance risk assessment

Due to the specific characteristics of maintenance, such as varied tasks and working in close contact with machinery, a tailored tool was developed for maintenance risk assessment. Based on the findings from companies and supported with findings from real accident data, a tailored method was developed for risk assessment in industrial maintenance (Article III). A set of requirements were defined, based on the findings from the phases of Study 1. The method was further developed and validated with the collaborating companies.

The method needed to be suitable for all working environments and take into account a variety of conditions, such as working during the night, working alone, and the presence of workers having a foreign cultural background. It must support safety management, e.g. by identifying hazards in machinery, working methods, and working environment. It must also draw attention to safety measures. In particular, the tool should emphasize the importance of task planning activities such as scheduling, resource allocation, and risk assessment of new, unfamiliar maintenance operations and sites. In all, the method had to take into account the following factors:

1. Planning, management, and supervision of the work,
2. Risks relating to the working environment,
3. Risks relating to the maintenance tasks and the maintained object (including, e.g. machinery, chemicals, and the handling of objects), and
4. Choice of relevant safety measures to manage the risks.

Due to the necessity of unscheduled repairs and to the fact that some workers work alone, the risk assessment tool must also include a specific section for the worker. Since the tool was designed for the use of any company, two major requirements were ease of use (usability) and feasibility in different kinds of maintenance operations.

The method was further developed and validated in the collaborating companies. It consists of three main parts: safety planning (Part A), hazard identification (Part B), and worker's checklist (Part C) (Table 11). Further, in the light of Reason's classification, the organizational factors are included in Part A, workplace factors in Part B, while unsafe acts are discussed in all three parts, but

emphasized in Part C. The entire method (Parts A–C) was intended for use when receiving an unfamiliar and unplanned operation or a new customer site.

Table 11. Contents of the method.

Guide for risk assessment in industrial maintenance		
Part	Contents	Used, for example
A	Safety planning	When receiving a new customer site or before planned maintenance operation; after changes on old established sites
B	Hazard identification	When receiving a new customer site or before planned maintenance operation; after changes on old sites
C	Worker's checklist	On site, before performing a maintenance task

The method is the form of a check-list and includes questions. “Yes” is the optimal answer, in case of a “no”, the user is advised to take further action, for example, making a detailed analysis of the problem in question. The anticipated users include management, supervisors and workers. A guide was designed to enable the successful, independent use of the method in companies. The guide covers the basics of risk management, including hazard identification and risk assessment according to standard BS 8800 (2004). The guide also refers to relevant Finnish legislation, and includes a completed model page to help users of the method.

Planning of safety

Taken together, the results from companies and real accident data indicated typical defects in safety planning and management (organizational matters). As a result, a specific part was designed to examine these areas in maintenance risk assessment. Part A contains 46 questions concerning work planning and supervision, scheduling, resource planning, etc. It forms the broadest part of the method. The purpose of Part A is to enable systematic safety planning already at the negotiation phase, when the resource allocation and scheduling are being decided. Part A also helps to ensure site-specific requirements by emphasizing customer cooperation and site-specific safety practices. The questions apply to the man-

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agement, supervision and performance of maintenance operations. Part A consists of 10 subsections (Table 12).

Table 12. Part A, contents and examples.

Subsection	Sample content
Planning of work	Resources, work permits, responsibilities and obligations
Working instructions	Work-related risks, re-instructing in case of changes in working environment
Task performance	Flow of information, supervision, safety if working alone, visibility and marking of unfinished work
Dangerous operations, such as working in a container, hot work, and electrical work	Specific risks and work planning, work permits
Protective equipment and safety devices	Availability and need of personal protective equipment and machine safety devices
First aid and rescue planning	Instructing in case of emergency, first aid courses
Dangerous substances	Safe use, transport, and storage of substances
Environmental issues	Prevention of environmental hazards, environmental requirements on customer site
Moving on/between sites	Tidiness and appropriateness of walking and working surfaces, internal and external traffic on site
Ergonomic issues	Physical, psychological and social workability

Hazard identification

The second part of the method focuses on occupational hazards (Table 13). The purpose of Part B is to highlight dangers in the working environment and especially in specific tasks. Part B contains 10 questions, two of which include checklists concerning condition-based risks and accident risks. The other eight questions focus mainly on technical issues in accident prevention, such as machine safety devices, prevention of unattended start-ups, and awareness of whether a machine is starting or running. The aim is to ensure that the energy

supply, such as electricity and mechanical energy, are reliably removed or disconnected from the object being maintained.

Table 13. Part B, examples of questions and specifications.

Sample questions	Sample specifications
Are the hazards identified and removed?	Specifying checklist, e.g. slipping, tripping, falling objects, drowning or suffocation, etc.
Have the risks of the working environment been considered?	Specifying checklist, e.g. lighting, vibration (hand, arm, whole body), noise, weather, etc.
Are the moving parts of machines guarded?	Entanglement, cutting, ejection of parts, splashing; checking of safeguards
Have energy supplies been disconnected reliably?	Disconnection and removal of electricity, mechanical energy, compressed air, steam, chemicals, etc.; hydraulic appliances and loads
Can safety be ensured if safeguards must be bypassed while the process or engine is running?	Use during maintenance, testing, calibration, troubleshooting

Worker's checklist

During the study it became clear that the workers need their own checklist for on-site hazard identification. This kind of a checklist serves as a reminder of possible risks and safe working procedures with changing sites tasks. The aim of the list (Part C) is to provide a concise resource for hazard identification on site before work commences. Thus, the list, which contained only seven statements, was devised as a handy, pocket-sized reference suitable for use in all working conditions (Table 14). The contents of the list were based on the following criteria: 1) the most typical and 2) the most severe risks, as identified in the earlier phases of study 1.

Table 14. Part C statements.

Sample risks to be checked	Sample specifications for hazard identification and management
Becoming entangled or crushed	Moving parts
Lifting and holding heavy loads	Lifting accessories, lifting position
Slipping and tripping	General tidiness and orderliness
Falling of persons and falling objects	Fall protection equipment
Splashing and ejection of objects	Emptying pipelines and tanks, PPE
Eliminating unexpected start-ups	Isolating flowing substances and energy: chemicals, electricity, compressed air, gas, vapour, water, etc.; safety switch, personal locks
Touching objects	Dangerous parts of objects and tools

Among the statements concerning identification of the most important accident sources, Part C includes two checklists for task-specific safety planning. The check-lists focus on management of accident sources and the consequences in the event of an accident. The first list deals with the location of emergency safety facilities (e.g. emergency showers and fire extinguishers), while the second list helps to chart the necessary PPE (personal protective equipment; e.g. helmet, face shield, pneumatic appliance).

4.2.3 Utilization of accident data for accident prevention

Pre-maintenance events together with the actions and conditions during the actual maintenance operation can affect maintenance safety. Thus, identification of the causes and consequences of technical failures and human/organizational factors, together with hazardous conditions, could all benefit accident prevention in maintenance operations. In addition, internal and external accident data can both provide important input for a company's accident prevention and safety management (Article IV). External accident information can support internal information, which might otherwise be limited. However, results of the study in Finnish metal and transportation industries indicated that external accident data is rarely utilized. In the case of industrial maintenance, such data could provide new information on issues such as customer cooperation, establishing task-

specific safety practices, as well on machine and workplace safety design. In the case of industrial maintenance, relevant accident reports could also be of value in the identification and management of accident risks at customer sites.

In the analysis below, N.N. refers to the victim. Various events are linked with “AND”, which means that both of the events mentioned below the box must have occurred to cause the accident. “COND” indicates that the event in that box is a conditional result. For example, the top event (Number 1) could also have resulted in injury.

The test analysis produced a set of root causes, identified within the limits of the data in the report. The root causes (round-cornered boxes on the lowest row of the tree) include:

- Design flaw on the maintained system: an opening on the machine
- Organizational factors: for example, incorrect instruction on troubleshooting and safe work
- Technology-based failures: for example, repetitive faults on the strapping machine.

Removing any single root cause could have prevented the accident occurring. In addition to the identified root causes, certain factors had a contributory effect on accident causation. Such factors include the following:

- Unsafe acts: N.N. had not stopped the production line
- Organizational factors: N.N. was working alone, with no cooperation or visual contact with the other worker(s).

The fault tree analysis helps to extract the various accident causes (root cause analysis), their interrelations and the chains of events leading to accidents. Thus, such models can also help to channel the accident preventive measures in the right direction. Due to the limitation of available data, it was not possible to make a deeper analysis of the identified “root causes”. In this analysis, the root causes are identified within the limits of available data, which were originally not intended for such use. In an ideal case, the root causes, especially the technical failures, could be analyzed in detail. In the case of technical failures, quantitative data, such as fault frequency, could be integrated in the analysis. Information on fault frequency could also be utilized to assess time intervals between failures and frequency of the need for maintenance.

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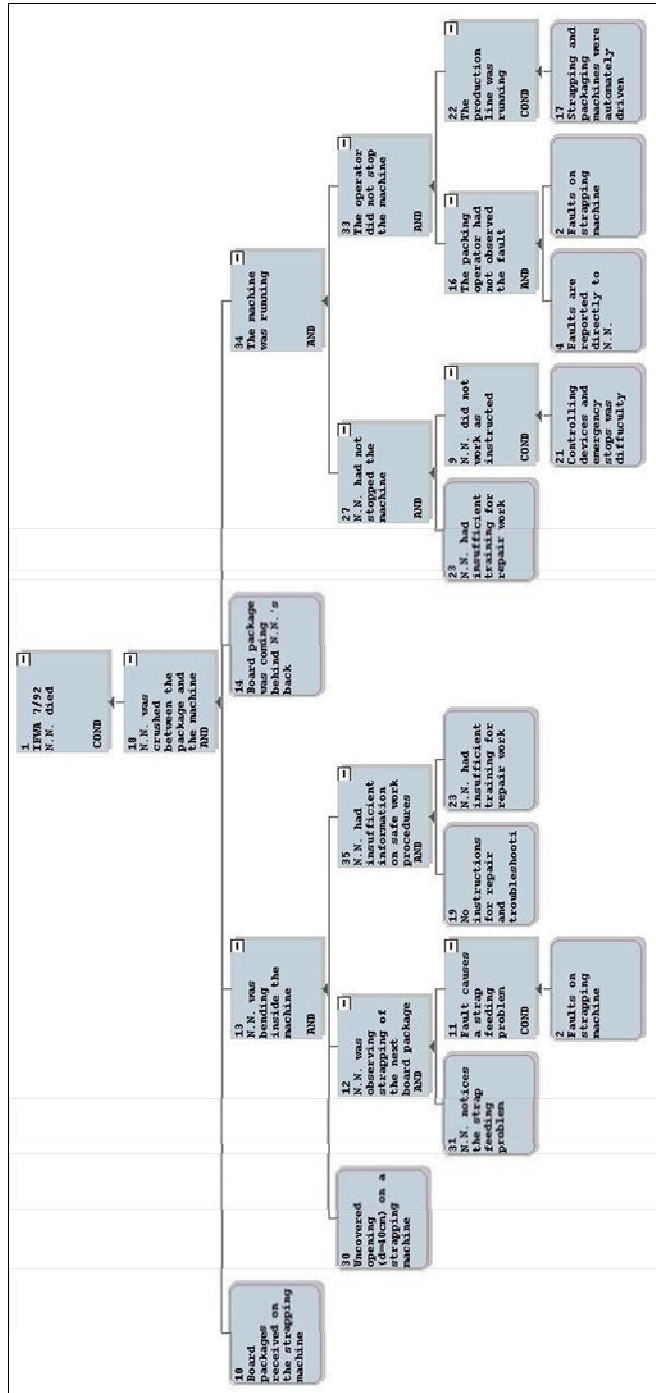


Figure 10a. Fault tree analysis of the selected fatal accident case.

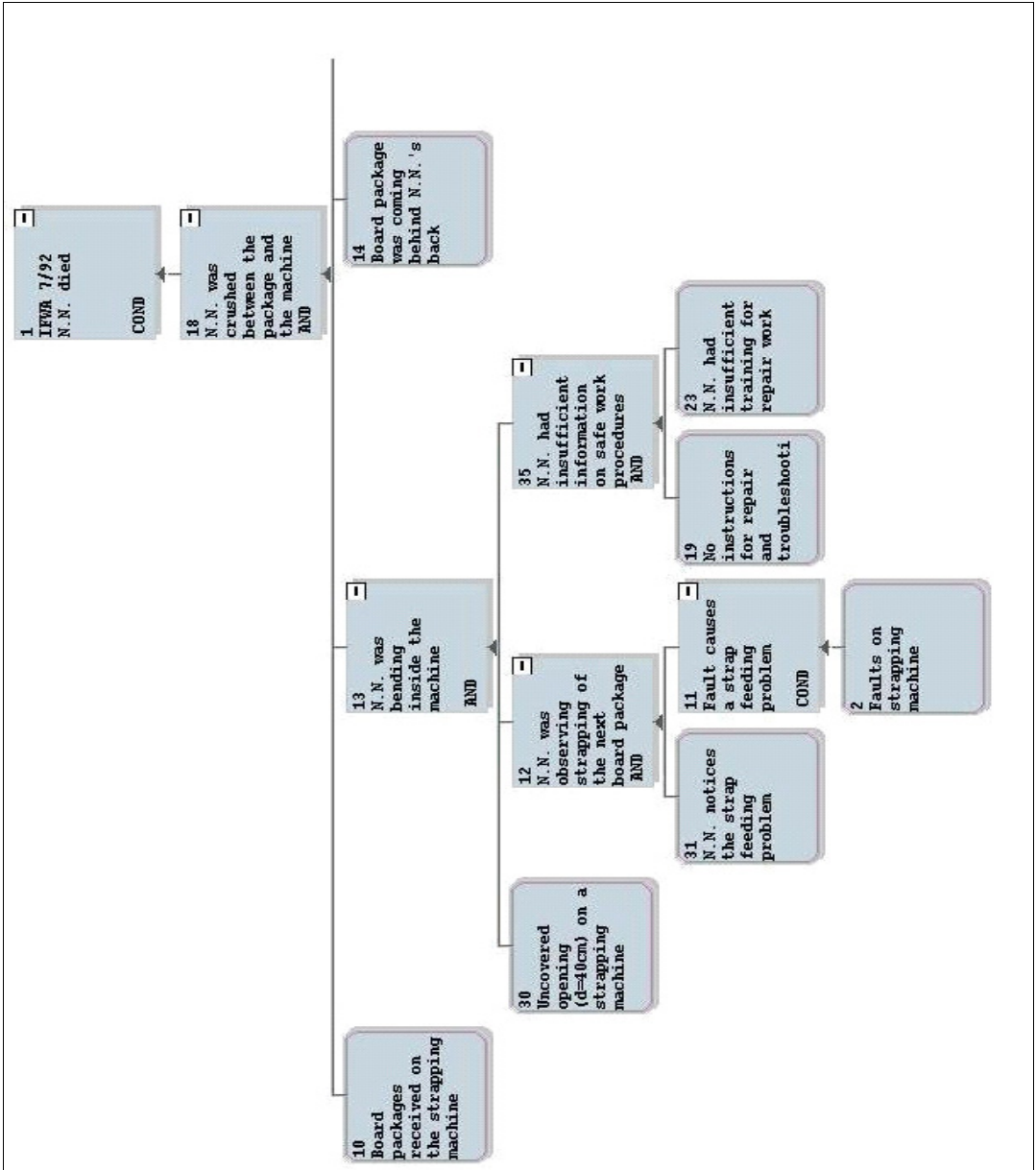


Figure 10b. Fault tree analysis, left part of the tree.

4. Results

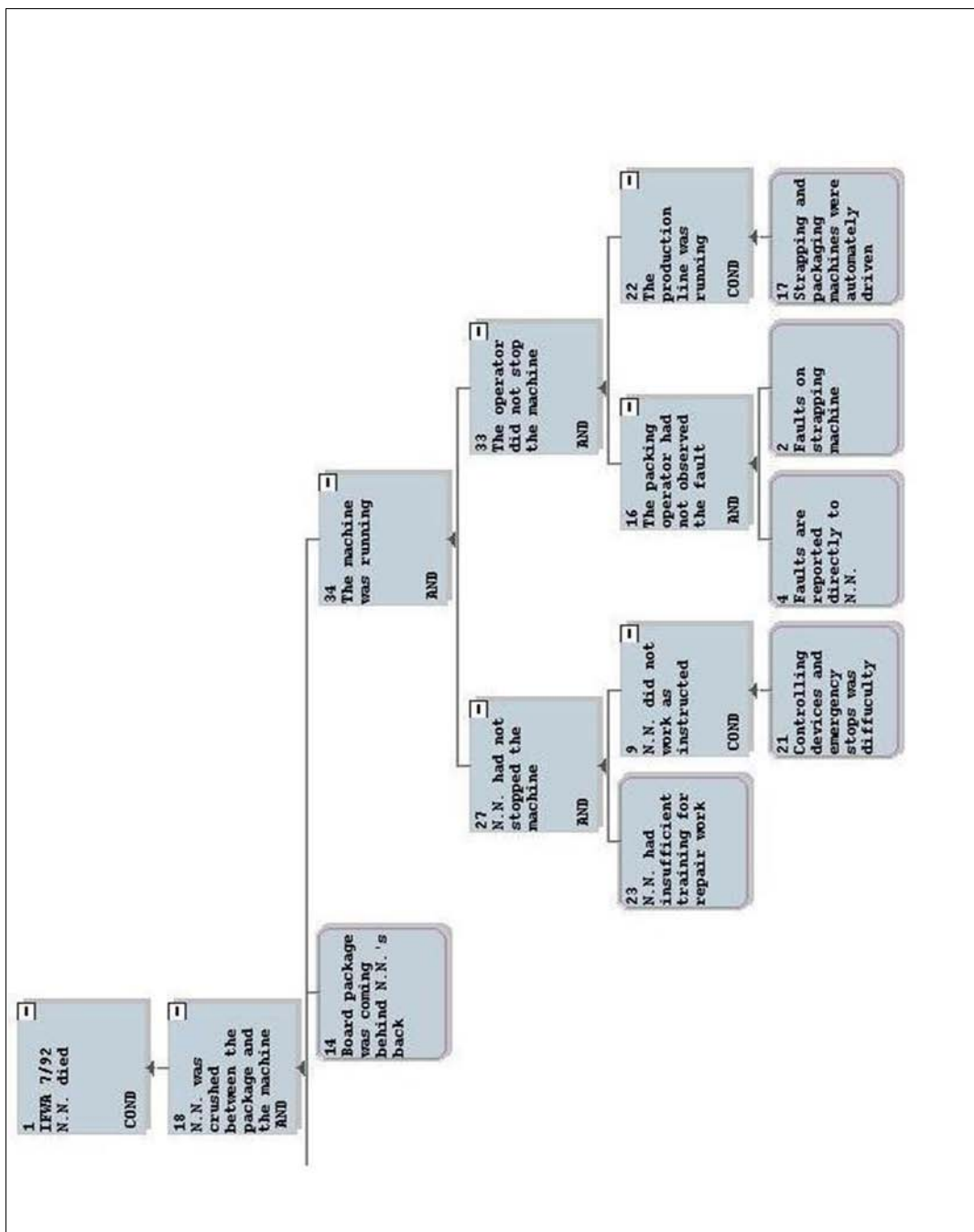


Figure 10c. Fault tree analysis, right part of the tree.

The test analysis with the selected fatal accident case revealed that the event chains of technical failures, human actions, organizational factors and workplace conditions could all be modelled together. The analysis data was limited in terms of the details in technical malfunctions and failures (the pre-maintenance conditions). However, the outcome is encouraging for the promotion and analysis of maintenance safety combining fault data from pre-maintenance conditions with other information on events during the maintenance operation. Such information can include the organizational practices and unsafe acts that occurred during maintenance operation.

The test analysis of a fatal accident case showed that hazardous conditions, technology-based failures, organizational factors and unsafe acts can be modelled together (Figure 10a–c) using a fault tree analysis. This finding is significant for the analysis of maintenance accidents because the accident sources can have various origins. Grouping the accident sources and event chains in this way could help to eliminate the accident sources and manage safety more efficiently. The accident sources can also be developed long before the actual maintenance operation begins. Further, the risks can be “activated” during the different phases of the maintenance operation and be attributable to earlier actions. Modelling of event chains, their interactions and the role of technical- and human-based failures, along with the hazardous conditions are all important elements in safety prevention. Together, they can provide essential information on maintenance safety for maintenance and safety management, task planning, and for machine and workplace design.

5. Discussion

5.1 The studies

In this thesis, maintenance safety has been examined on the basis of accidents and accident prevention. The central focus here is the human-machine -interface rather than just safety management. Unlike most previous studies of maintenance safety, this thesis has focused on safety during the maintenance operations, instead of post-maintenance reliability risks and system safety.

In order to prevent accidents on the human-machine interface, actions are required at every organizational level, in addition to workplace and machine safety design. In this thesis, accident prevention has been approached in four different ways. First, a group of fatal and severe non-fatal accidents were analyzed. Second, the maintenance-related risks were identified in companies. Third, prevention of accidents was examined on the basis of findings from accident analyses and studies in companies. Fourth, accident prevention was further developed considering use of accident information in safety management and identification of accident sources. At this stage, a fault tree analysis was performed to determine its efficacy in analysing and modelling maintenance accidents.

The Study 1 was conducted with three companies, representing one machine manufacturer (after-sales service) and two industrial service providers. Despite the limited number of companies, the variety and number of the sites ($N = 15$) in the study were relatively extensive. In addition, an important part of the results was gathered from accident reports, which describe fatal and severe non-fatal accidents in detail. Since the aim of the study was to identify the most important accident sources in industrial maintenance, it can be assumed that this was successfully achieved. Study 2 was conducted in Finnish metal and transportation industries. Although the study did not focus solely on maintenance, the general

findings on the use of real accident information in safety promotion are also applicable in promoting maintenance safety. The results from Study 3 (modelling of accident sources) are merely indicative, giving clues as to the feasibility of FTA in joint modelling and in the identification of various accident sources in maintenance accidents. In this respect, the findings provided encouraging results to support the use of FTA in the modelling and identification of accident sources. The study could be repeated using different accident cases with more detailed data on the technical and organizational dimensions.

This thesis covers a group of studies, which have been executed applying a variety of materials and methods. A major part of results has been gathered directly from various companies and different organizational levels. Therefore it can be expected that the accident sources and factors affecting safety in industrial maintenance have been explored extensively and that the results reflect reality.

5.1.1 Review of the studies and results

The studies in this thesis have employed a variety of methods. A common aim has been to determine the accident types and the potential and realized accident sources. The potential accident sources were explored in companies by interviewing the workers, supervisors and management. The risks were charted by means of observations and risk assessments. The number of companies and sites was relatively limited (three companies and 15 sites). However, the companies represented a variety of industries and the risk assessments, interviews and observations complemented each other as research methods. The objective risk assessments and observations supported the interviews, which reflected the subjective views of workers and company representatives. Thus, it may be presumed that the risks within the subject companies and chosen tasks were charted reliably. It may be claimed that the inclusion of a larger number of companies and sites would have produced different results. However, a major part of the materials consisted of real accident data describing accidents that had occurred in various industries. Thus, the realized and potential accident sources in industrial maintenance have been explored extensively.

Choosing the real accident cases for accident re-analysis (Study 1, stage 2) may have contained certain errors. The cases were selected according to a strict classification. However, in some cases the background of the victim(s) (full-time maintenance worker/other personnel) or the type of the task (maintenance opera-

tion/other operation) was not explicitly stated. Such cases were considered carefully before their inclusion in the analysis. Ascertaining the type of employment was more complicated than determining the type of task. Thus, it is possible that the applied material contains certain accident cases, which may not be entirely relevant. Conversely, certain relevant accident cases may have been excluded despite a careful selection process. Moreover, the analyses of the accident types and sources were based on the actual details contained in official accident reports. Though this could have given rise to misinterpretations, most of the facts examined were largely unambiguous.

The purpose of the accident reports is to prevent the recurrence of similar accidents and thus they describe the accident event with limited detail of background information and contributory factors. In addition to descriptive text, the event chain with core information is modelled sequentially. Using such reports as sources for research material has both advantages and disadvantages. The reports provide large amounts of real accident data from various industries providing valuable information on what actually took place. In addition, the reports include accident data, which has been investigated and reported by experts. Thus, they can be considered as reliable sources of data. The drawback is that the reports are not intended for use as research material. Thus, the accident sources with contributing factors and other details had to be extracted from the text. This sometimes required interpretation on the part of the researcher and often left certain details unresolved. Extracting the details from the accident descriptions can have led to misinterpretation. In cases where the details being researched were not explicit in the text, no assumptions or interpretations were made. In such cases, the missing information was reflected in the amount of available data in the analysis of the details.

Finally, the accident re-analyses are the result of a series of interpretations, which may have appeared in various phases after the actual accident. For example, the following links may have included certain assumptions:

- accident event – investigators: the investigators make the interpretations on the assumed chain of events (e.g. in the case of no eyewitnesses)
- investigators – reporting: the event chain is described for publication so that the important facts regarding the event chain, accident contributors and accident prevention are presented in clear and rather brief terms to reader

- reporting – reader (re-analysis): the accident causes and contributing factors are extracted from the descriptive text and model describing accident sequentially.

Thus, the interpretation of what happened can differ from what actually happened. However, in the case of fatalities, the investigation and reporting have been carried out by a group of experts, which probably provides an objective view of the chain of events. Furthermore, this thesis is based on studies, which have applied a variety of methods and materials. Thus, it can be presumed that the findings provide a realistic account of the potential and realized accident sources.

5.2 Findings

Maintenance management and planning have been approached from various viewpoints, such as managing and reducing the economic impacts of maintenance, and promoting system reliability through maintenance. At the same time, most of the studies combining maintenance and safety have explored post-maintenance conditions, particularly reliability that can be undermined by human error during maintenance. Management of occupational safety during maintenance has been of lesser interest, although it has been widely recognised that maintenance operations include a variety of safety risks. This thesis focused on identifying such risks and proposing ways to manage them.

The present study approaches the risks and accident sources by applying Reason's (1997) theory of organizational accidents. Thus the findings from the studies were grouped according to organizational factors, local workplace conditions and unsafe acts. As maintenance safety can be significantly affected by pre-maintenance incidents, this grouping is supplemented with technology-based failures, i.e. system malfunctions and faults that can make the system or the working environment unsafe. The technology-based failures are independent of human action (see Figures 1 and 2). This grouping provides a holistic view of the various factors affecting maintenance safety at the human-machine interface. This kind of approach also supports the accident theories' view (e.g. Perrow, 1999; Reason, 1997), according to which accidents are the sum total of multiple failures within a socio-technical system that includes humans on different organizational levels, together with technology. Furthermore, maintenance management and accident prevention have been successfully integrated within one in-

dustry (Hale *et al.*, 1998), encouraging expansion of the approach and also its application to other domains.

In order to identify and plan all the phases in a maintenance operation, a general model of maintenance operation was proposed (Appendix 1). The model focuses on human tasks during the entire maintenance operation. The model starts with the observation of a need for maintenance and then considers sequentially all the main parts of a maintenance operation. Among the work phases and tasks, the model (Appendix 1) evaluates the data needed to execute a maintenance operation successfully. The model focuses on the identification of human tasks and inputs to the system during a maintenance operation. It employs a task-analytical approach to identify and model the primary tasks, the possible supportive tasks and the different work phases chronologically. The model also takes into account cooperation with the operating personnel/other workers on customer sites.

The first steps in the model are similar to the Operator Action Tree (OAT), proposed by Wreathall in 1982 (In: Kumamoto & Henley, 1996). The OAT model explores the steps that the operators take during an accident to control the losses and manage the consequences. The generic model of an industrial maintenance operation could be utilized in companies for identifying the actual work tasks needed in the maintenance operation. This kind of integrated approach has been successfully tested with task analysis and FTA (Doytchev & Szwillus, 2008). However, that integrated model focuses on accident analysis in order to identify human errors during a task and is therefore narrow in scope. The maintenance operation model could be of use in resource allocation, hazard identification, task planning and development of system and workplace features (safety/maintainability). However, the model needs further testing and refinement in companies to ensure its feasibility. It could be developed and adapted to give more weight to issues such as customer cooperation, the effects of faults, troubleshooting, or task-related safety risks.

5.2.1 Accident sources

The studies in companies and the findings from real accident data highlighted the role of local workplace factors as sources of accidents. Despite this finding, the accident preventive measures were typically directed to the level of organization in the real accident data. This supports the generally held view in accident prevention theories that organization is best placed to enhance safety. In indus-

trial maintenance operations, multifarious tasks and solitary work in close proximity to machines suggest that the workers' own initiative to ensure safety may play an even greater role than in other industrial work tasks. For the same reasons, machine safety and maintainability design, together with other local workplace factors can also have a significant impact on maintenance safety.

The analyses of real accident data revealed that the organizational factors relate to knowledge of correct and safe working procedures. The most typical factors contributing to accidents were defective work instructions, while victim's insufficient experience of task was identified among 20% of fatalities. At least in some cases, such problems can relate to the multifarious nature of maintenance tasks and the difficulty of giving adequate instructions for each and every maintenance task. In addition, fault identification and the effects of faults in the machine/process play a major role in making the required safety preparations before task execution. Safety information on task execution, the system to be maintained, as well as the other activities and processes in the working environment should all be readily available so that the risks they pose could be considered and managed before and during the maintenance operation.

The findings from companies showed that system and workplace maintainability have repercussions for maintenance work. Traditionally, maintainability has considered machine features. The findings in study 1 show that the surrounding workplace with the processes, structures and activities can also have a major impact on maintenance operations. Maintainability design should include both machine/process features, such as accessibility and reachability (see SAE J817-2:1991; Stephan, 2005). In contrast to just machine maintenance (machine after-sales service), in the case of industrial maintenance, workplace design is another significant factor to be considered in maintainability design. The findings in companies revealed that workplace maintainability design was often poor because structures and process parts hampered access to maintenance areas. Poor accessibility often necessitated considerable preparatory work before the actual maintenance tasks could begin. This probably increases the number of work tasks, and indirectly, the risk of errors and accidents during the phases of disassembly and reassembly. Such maintenance-related factors should be considered in the design or renewal of production plants.

Workplace and machine maintainability are also key issues in maintenance ergonomics though in many companies these seemed to be somewhat neglected issues. Poor maintainability has several effects on maintenance work, such as impairing safety during the work, prolonging the task, and complicating the

5. Discussion

work more complicated, all of which can increase the risk of human error during the working operations (see e.g. Altman, 1991). Maintainability and ergonomics, especially task fluency and working postures, seemed to be closely interdependent. Thus, good maintainability ensures that the work task is safer and easier to execute. This promotes both worker wellbeing and time- and cost-effective maintenance. Ergonomic design also has implications for workplace safety design. Poor safety design can contribute to maintenance accidents when, for example, workers are unable to identify or detect the warning signals or vital safety markings on the object system of maintenance. Conversely, good ergonomics design can prevent accidents if it is made difficult or impossible to perform a maintenance task incorrectly or even dangerously. Finally, maintainability is linked with cognitive ergonomics. Minimizing the number of components to be replaced, connected, disconnected etc. promotes both effective task execution and reduces cognitive load during the task (see Altman, 1991; Imrhan, 2000). Thus maintainability design plays an important role in promoting maintenance safety and effectiveness.

The other important aspect of system design concerns the functions of the system. For system safety, inherent safety design is a central issue, which could also be extended to cover safety during maintenance (c.f. Edwards, 2005). Considering inherent safety in maintenance is especially important in cases when the maintenance operation has to be executed while the system is active and/or the safety systems have to be overridden. Although inherent system safety may not increase safety in maintenance operations, it can reduce safety risks indirectly by decreasing the need for unplanned maintenance (system reliability) and increasing system's maintainability. In addition, fail-safe functioning and easy fault identification are crucial for maintenance safety, especially in cases when the system utilizes various energy sources and chemicals. During system design and/or during maintenance planning, various failure conditions could be assessed using a FMEA (Failure Mode and Effects Analysis) method, paying particular attention to risks to humans. A disadvantage of FMEA is that it focuses on single failure conditions and consequences instead of multiple or common cause failures (McCormick, 1981). However, FMEA could be supplemented with other analysis methods, such as ETA to identify the possible risks, their origins and interrelations, and accident scenarios.

The development and prevention of an unsafe act should also be considered in task and operation planning. Therefore, the unsafe acts and their effects on maintenance safety and system reliability should be taken into account in risk as-

assessment and system design. Within risk assessment, failure prevention could adopt, for example, a “what-if” -approach, where the possible misuse or failure scenarios and their outcomes are examined systematically (c.f. Khan & Abbasi, 1998; Marhavilas & Koulouriotis, 2008). Such an approach could help to identify the consequences of possible variation in human performance and technical failures. An ETA would greatly assist in the identification of potential event chains which could lead to accidents or failures. ETA could also help to estimate possible consequences even in situations when multiple human- or technology-based failures accumulate. In system design, the unsafe acts should be taken into account so that the system design supports safe use. This kind of design could also help the human to use and maintain the system in the way intended. In such cases, maintainability design is a key factor: together with the system’s inherent safety and robustness, it can help promote tolerance to failures. An ideal example of post-maintenance reliability would be a system that is designed in such a way that re-assembling the components in wrong order is made impossible. However, it is unlikely that this would guarantee successful maintenance since the scope for errors would remain, such as replacing a wrong part.

Finally, the findings of the field studies revealed that the number of work phases in maintenance operations is also reflected in the number of accident risks. From the perspective of post-maintenance reliability, it can also be assumed that there is an increased likelihood of unsafe acts leading to accidents or reliability problems. In contrast, the technology-based failures are independent of the number and complexity of tasks.

5.2.2 Identification and management of maintenance-related accident sources in companies

During Study 1, a method was developed for maintenance risk assessment. The method enables the identification of maintenance-related hazards, assessment of the risks and selection of the relevant safety measures to prevent accidents. The method could be utilized together with the general model of maintenance operation to ensure identification of hazards at every stage of a maintenance operation. Moreover, the risk assessment creates a basis for choosing the safety measures to prevent the accidents from happening. The hazard identification and the selection of the relevant safety measures can be supported with the real accident data that is provided to Finnish companies. However, Study 3 revealed that such external risk information is commonly underutilized by Finnish companies oper-

ating in metal and transportation industries. For the purpose of maintenance safety promotion, the reports could provide important information on maintenance-related risks and the possible risks at customer sites. The information provided in a fatal accident report was re-modelled using a fault tree model. The re-modelling showed that a fault tree model enables joint modelling of the causes and consequences of technical failures, organizational factors, local workplace factors and unsafe acts. Such modelling would be particularly useful in the management of accident sources in maintenance. In the modelling or investigation of maintenance-related accidents such an approach could also be useful since it could facilitate the assessment of the interrelations between technical failures, hazardous conditions and human-based failures (i.e. unsafe acts and organizational factors).

Since the causes of accidents are considered to have their origins at different organizational levels and in the system complexity, preventive procedures should also be examined and implemented at all organizational levels. Accident prevention is based on risk information, which can be gathered, for example, from risk assessments or real accident data, i.e. occurred accidents. Minor accidents are usually investigated internally in companies so the companies may only have ready access to their own data. This may mean there is a limited amount of data available, and diminish the chances of identifying and managing the sources of accident in the company. Further, McCormick (1981) has summarized the factors affecting the acceptability of risks. Such factors include the controllability of a risk, understanding the origins and effects of a risk, voluntary/involuntary exposure to risk, and the benefit/risk relationship. These factors can also have implications for the risks taken at work. To prevent unconscious risk-taking, hazard identification and information delivery is crucial. In the case of conscious risk-taking, workers' unsafe acts could be seen as decisions, which have been considered despite the fact that the potential harms are known. In the case of maintenance, or any industrial work, management and supervision have a key role in preventing such consciously unsafe activity. Nonetheless, maintenance operations can often be carried out on a customer site with limited supervision. This leaves many safety-critical decisions to be taken by the workers. At the same time, system and workplace design is important because deficient safety design can give rise to unsafe behaviour. An example of a design flaw allowing conscious risk-taking is the uncovered opening in the machine (event nr. 30), as presented in Figures 10 a–c.

The increase in outsourcing and subcontracting maintenance has highlighted the importance of safety cooperation between customer and service provider. The developed risk assessment method supports safety cooperation from the negotiation phase to the execution of work tasks. The method developed consists of three parts, which cover all the critical safety factors relating to service production and subcontracting. The results presented on the accident sources, along with the risk assessment method, concur with the concept of total maintenance management, where the three major areas are maintenance management, maintenance operations and equipment management (see Raouf & Ben-Daya, 1995).

Analyzing the real accident data showed that the accident sources in maintenance operations have their origins in the organization and in human performance because deficient work instructions and dangerous working methods represented the major causes of fatalities. Among severe non-fatal accidents, the most frequently cited accident sources were defective work instructions and defective safety equipment. These findings were supported by the risk assessments on sites, where the same problems were frequently identified. As with any accident investigation and analysis, re-analysis of the real accident data also has certain limitations. The parameters were chosen and classed by the research group. This can affect the identified results – using different classifications could have produced different outcomes. However, in this study the real accident data consisted of accident reports, which had been compiled objectively by independent researchers. The accident analyses of the real accident data extracted the parameters from this material in order to identify the accident sources as precisely as possible.

5.2.3 Modelling of accident sources

Maintenance operations involve a variety of accident risks that can result from human- or technology-based failures and/or hazardous conditions. Furthermore, a maintenance operation is a process with several work phases and conditions, as described in the Appendix 1 and Figure 1. Pre-maintenance conditions can significantly affect maintenance safety along with unforeseen eventualities and hazardous conditions during any phase of the actual maintenance operation. Thus, it could be beneficial to determine the origins of the various accident sources, their causes and consequences, together with the cause- and consequence-contributing factors. Assessment of the relationship between different accident sources and contributory factors would also be important in the identifi-

cation of the latent accident sources. A fault tree could provide specific information for maintenance accident prevention. Such an approach could be supported by the use of a generic model of an industrial maintenance operation, which supports task, condition and risk identification throughout the maintenance operation. Hale *et al.* (1998) have successfully integrated reliability and safety management functions. In their study, a major role was played by internal and external accident data in developing maintenance functions that can be utilized together to promote management and system reliability. Although Hale *et al.* considered the chemical process industry, their results indicate the value of applying accident data to the development of maintenance operations and management as well as other areas.

An accident case was re-analysed in the form of a fault tree to model the chains of causes and consequences. The objective was to test if and how the real accident data on human victims can be examined with event logic modelling and if such an analysis can provide detailed information on the root causes of accidents. The findings from this test data indicated that the possible root causes, within the limits set by the available data, can be identified, at least to some extent. Such limited and structured data, as provided by the IFWA reports, also supports event chain modelling and root cause identification. Due to the limited and processed data, the identified causes should not be considered as the actual root causes of the accidents in the strict sense used by authors such as Hollnagel (2004), Kjéllen (2000) or Perrow (1999).

The fault and event tree models provide an effective tool for modelling accident scenarios for risk management. The actual incidents and accidents can be analysed using fault trees, which enable more accurate identification of failures and accident origins. According to Antão and Guades Soares (2006), removing any of the root causes would prevent the accident from occurring. The test with the chosen accident case bore out this finding. Due to this benefit, root cause identification and analysis could provide an effective tool in accident prevention.

The results of an FTA can be utilized in learning from accidents and preventing their recurrence. Xu and Bechta Dugan (2004) have introduced a dynamic fault tree model, which is designed for complex systems where the interrelations between subsystems can be complicated. The main benefit of fault tree analysis is gained by modelling the events in a way that shows the root causes, cause and consequence contributors and their relationship in the event chains leading to accidents. In the case of accident prevention in industrial maintenance, a fault tree model could provide more information than the sequential analysis. This is

because the accident contributors, (i.e. organizational and local workplace factors, unsafe acts and technology-based failures in safety equipment and the maintained object), can all be modelled together. Although the experiments with these cases are encouraging, this scenario needs further examination and validation in companies.

5.2.4 Future research

A review of the literature suggests that relatively few studies have dealt with the subject of safety in maintenance operations. The present study showed that industrial maintenance operations have specific features that increase the number of risks and make these risks more difficult to manage. The thesis provides a qualitative view of the factors affecting maintenance safety. However, more detailed study of particular industries, systems or tasks, for example, could provide more specific information for maintenance and safety management, maintainability design and maintenance operation planning. These studies raise the following questions for the future studies:

- 1) What kind of additional analyses could be integrated into the generic model of maintenance operations? Are the outcomes applicable for safety and maintenance management? (c.f. Raouf & Ben-Daya, 1995)
- 2) How could the various (potential and realized) accident sources be modelled together in order to gather information for promoting both system reliability and safety in any industry? (see Hale *et al.*, 1998)
- 3) How could the new technologies, such as virtual and augmented reality, help in identifying system risks and prevent unsafe worker practices? How could such new technologies be utilized in maintenance task planning and training?
- 4) Would the new technologies help in managing the maintenance and safety information jointly, such as safety information for specific tasks, system condition and occurred accidents?
- 5) How could accident reporting be developed to ensure safety promotion in companies?
- 6) What factors, for example in the system or in the working environment, have greatest effect on workers' safety performance? What kinds of systems are inherently safe for maintenance?

6. Conclusions

6.1 Accident sources

The risks associated with maintenance operations arise from specific factors. Firstly, the tasks and working environments undergo constant change. In the case of after-sales service, the number of various tasks is limited but the working environment can vary according to the customer site. Conversely, in the case of a stable customer site in industry, there can be a huge variety of tasks that change according to the different operations assigned to the maintenance personnel. Secondly, the maintenance operations are typically carried out in close contact with the machinery. In some cases, the task can also require working in the presence of a live system. Poor task planning, together with unidentified risks and working to a deadline can all pose a risk for the maintenance workers. In addition, defects in machine or workplace maintainability can undermine ergonomics or cause accident risks. Thirdly, maintenance operations may require working alone or without supervision. Thus, safety-related decisions and planning certain tasks may be left to the individual maintenance worker.

The analyses of fatal and severe-non-fatal accidents revealed that the most typical types of fatal accident in industrial maintenance involve crushing, persons falling, and accidents caused by falling objects. In the case of severe non-fatal accidents, the types of accident are the same. Thus, the types and sources of severe non-fatal and fatal accidents in maintenance work are similar to those for severe non-fatal and fatal accidents in Finnish industry in general.

The findings indicated that accident sources in maintenance operations have various origins in the organization and at the human-technology interface. In addition, maintenance-specific features, such as the numerous work phases in disassembly and re-assembly, task urgency and problems in resource allocation,

and working on different types of sites, increase the frequency and importance of safety challenges.

6.2 Identification and management of accident sources

Industrial maintenance operations invariably include the five elements listed below. To prevent accidents efficiently, each element on its own and with others, must be safe. For example, the following aspects must be considered:

1. Task – What is the procedure, how much and what kind of preparation is required (e.g. disassembling the surrounding structures, preparatory work phases)? How can the task be identified and planned with all the preparatory and supportive work phases?
2. Maintained object – What kind of risks are included in the system? How it can be made safe (e.g. turning off, slowing down, avoiding sharp edges)? How does system maintainability affect maintenance work and safety?
3. Working environment – What kinds of risks arise from the working environment? What are the surrounding processes/activities (e.g. moving machine parts, chemicals, energies). How can the risks arising from other activities and processes on site be identified and managed?
4. Human factors – What kind of cognitive and physical load does the task demand (e.g. frequency, time of the day, working alone, working postures, heavy lifts)? Is the experience and knowledge of the task-related matters (including safety) adequate?
5. Organization – How is safety management applied to the human-machine interface (e.g. safe work practices and supervision, site-specific safety instructions)? Is supervision adequate? How can safety be ensured on varying sites and/or with varying tasks?

Identification of the related risks is approached in detail in the risk analysis method developed in Study 1 (Article III). Furthermore, the task can be examined in detail using, for example, the generic model of an industrial maintenance operation (Appendix I).

6. Conclusions

Industrial maintenance operations can be executed on a permanent site such as a factory, or on a customer site, in case of subcontracting or after-sales service (e.g. machine maintenance). Depending on the case, the tasks can vary greatly on a particular site (e.g. subcontracted maintenance on a permanent site) or be alike, even if the site or working environment varies (e.g. machine after-sales service). In some cases, both site/working environment and task can vary (e.g. moving between sites in order to distribute workload peaks). In addition to the task and the working environment, the organization has a great impact on safety in maintenance operations. The organization influences the safety culture, but practical decisions, such as resource allocation, also have a bearing on the actual man-machine interface. Such resources include time and number of persons available for a task. As Reason (1997) has noted, management is best placed to influence safety in industrial maintenance operations. In maintenance operations this involves, for example, deciding on resource allocation already when negotiating maintenance contracts, in addition to planning and executing the routine maintenance activities (Figure 11).

Maintenance safety is also greatly dependent on the system, i.e. machine or process, design and safety. System design, therefore, plays an important role in preventing maintenance accidents. System design can also contribute to maintenance through factors referred to as maintainability. Such factors affect ergonomics and safety during maintenance, as well as promoting ease and effectiveness of maintenance work. In addition to the actual system, workplace design can impact on maintenance work. The concept of “workplace maintainability” is proposed for the role of workplace design. This refers to those surrounding structures, processes, activities, etc., in the object system of maintenance that affect the performance of the maintenance operation. The risk assessment tool developed for maintenance operations takes into account the above-listed factors, creating a basis for safety management in maintenance operations. The findings of the risk assessment, such as resource allocation and customer cooperation, can also be integrated to maintenance management.

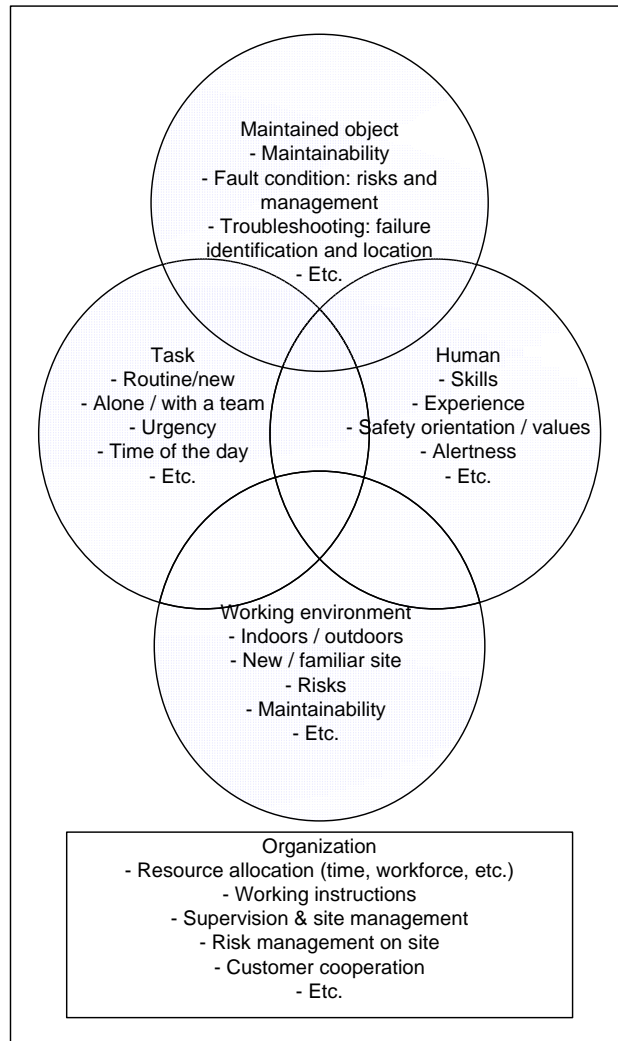


Figure 11. Factors and variables in maintenance operations and the role of organization.

The risk information provides the basis for identification and management of accident sources. This study has produced encouraging results for the use of fault trees to present the chains of events and the interrelations between hazardous conditions and technology- and human-based failures. To promote maintenance and safety management, a generic maintenance operation model is proposed (see Appendix 1). The model examines a maintenance operation in terms of four main stages:

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- 1) Failure observation and identification
- 2) Preparatory work phases
- 3) Repair/Service
- 4) Normal condition restoration.

The model begins from fault observation and progresses systematically to the final phases of the maintenance operation, i.e. removing tools and parts, and cleaning the working area. It helps to model a maintenance operation, by identifying the work phases and supportive tasks. In addition, it enables identification of different work phases together with parallel and complementary tasks.

Maintenance-related accident sources and the prevention of accidents should be considered in a wide perspective. All the various risks and their interrelations should be taken into account in order to identify even the latent risks and chains of events. Subcontracting maintenance services pose special challenges. Specifically, attention is needed to prevent crushing, and falling accidents, in addition to accidents caused by falling objects. Accident reports provide essential information on occurred accidents and how similar accidents can be prevented in the future. However, companies could make better use of such reports. To manage the various maintenance-related risks, a specific risk assessments method is proposed. In addition, a generic model of a maintenance operation is proposed. The model can help to identify and design the main and sub-tasks of a maintenance operation. Finally, the modelling potential and realized accident chains in a fault tree could help in exploring the interrelations between various risk factors, in addition to risks arising from pre-maintenance conditions.

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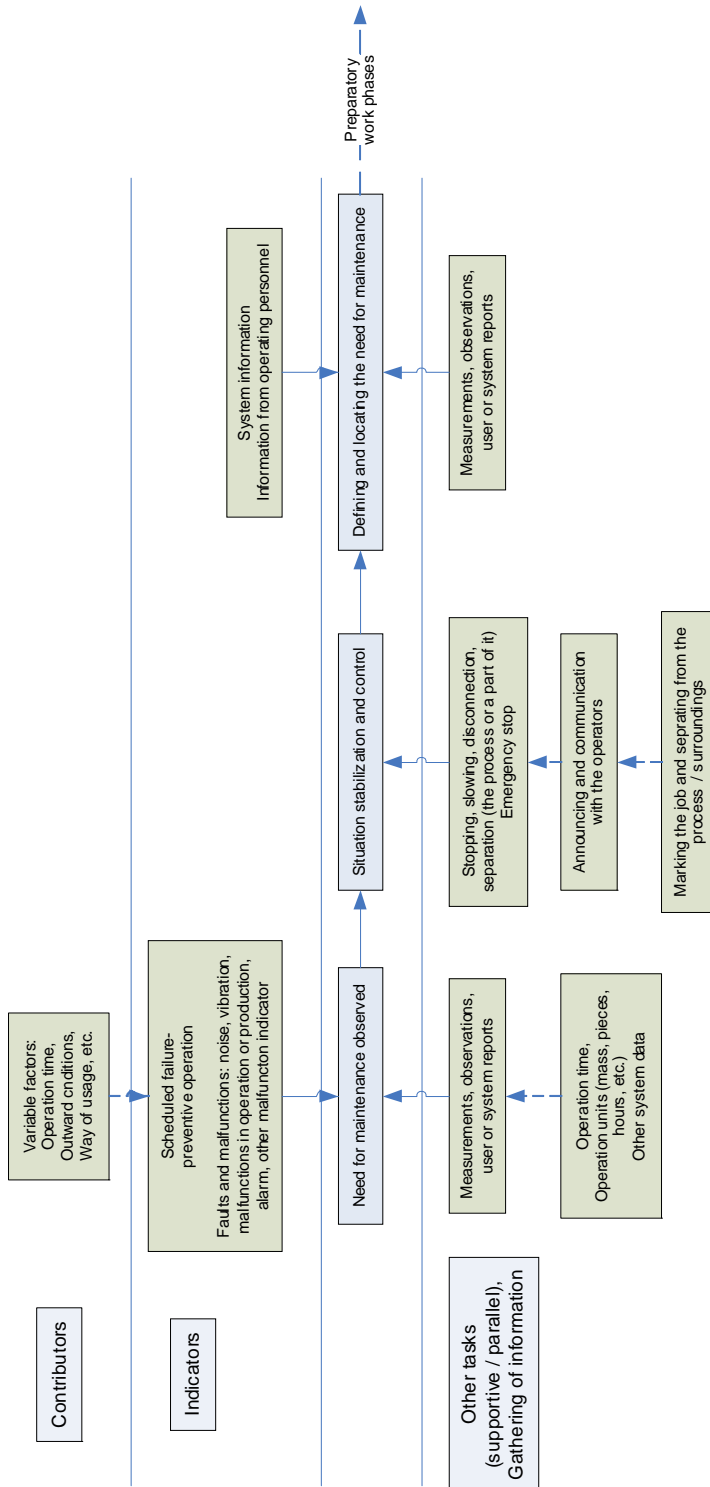
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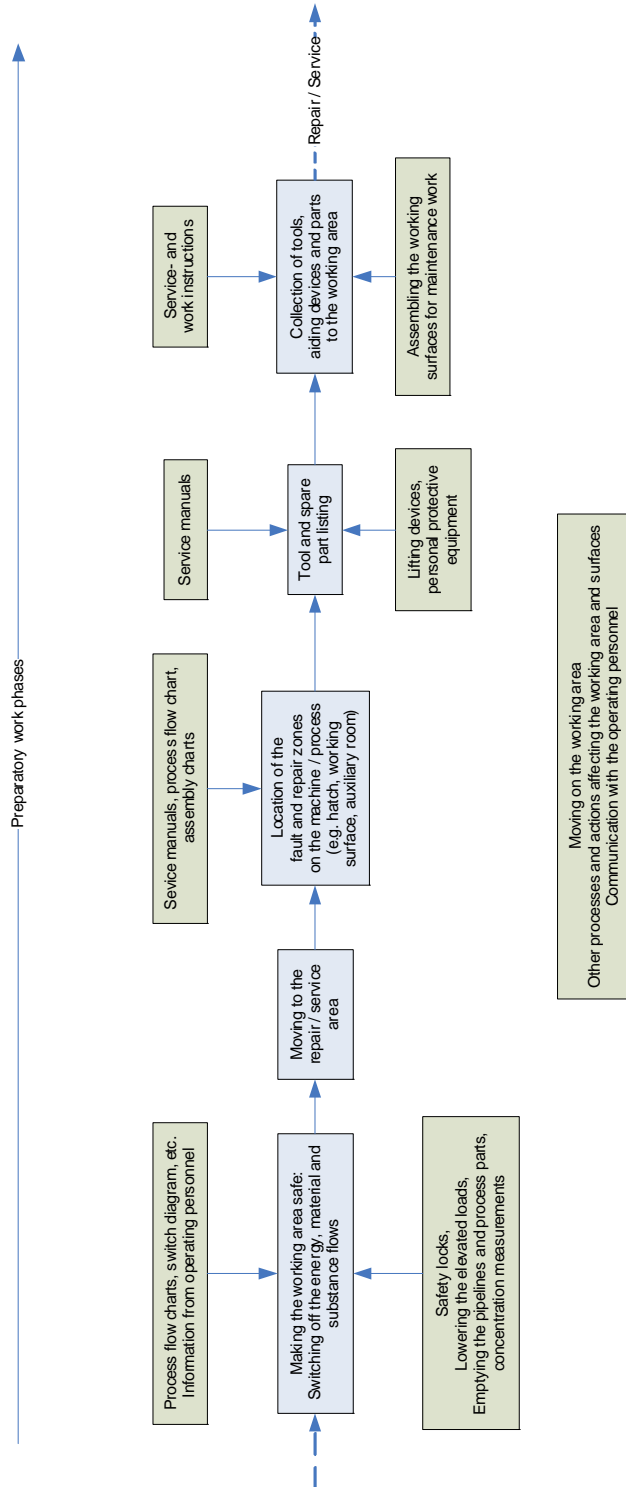
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Appendix 1: Generic Model of an Industrial Maintenance Operation

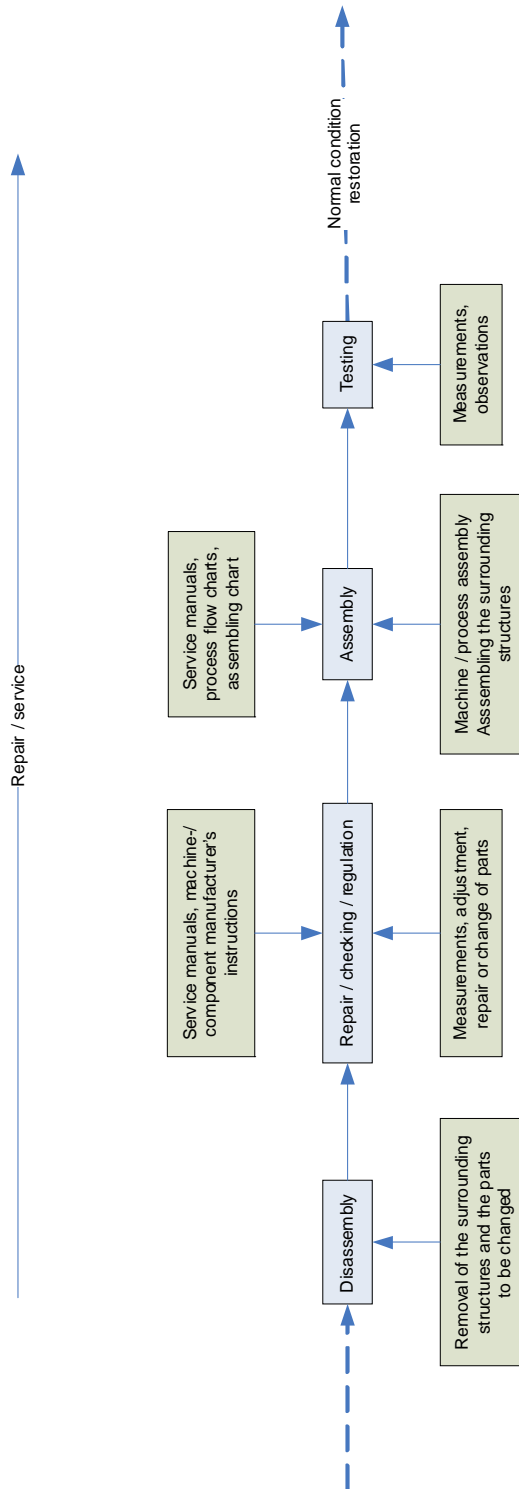
Appendix 1: Generic Model of an Industrial Maintenance Operation

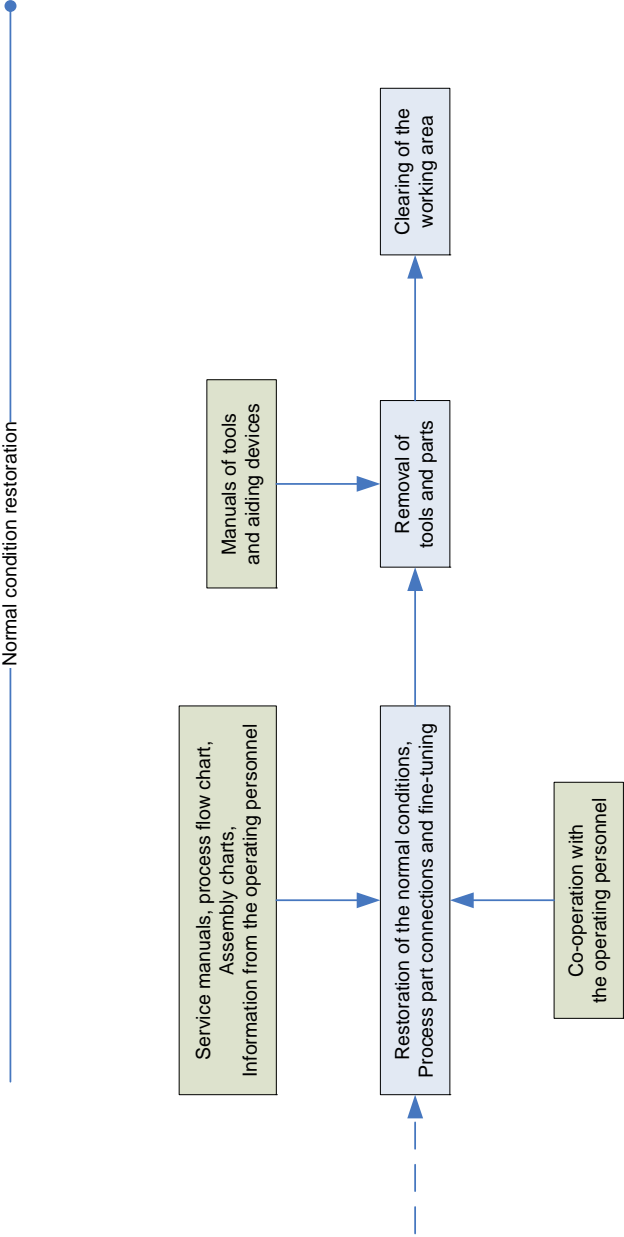


Appendix 1: Generic Model of an Industrial Maintenance Operation



Appendix 1: Generic Model of an Industrial Maintenance Operation





Appendix 2: Study 1: Parameters in Accident Analyses

Appendix 2: Study 1: Parameters in Accident Analyses

Year

Industry code (according to Statistics Finland)

Industry: specified code (according to Statistics Finland)

Worker's occupation (in the accident report)

Task

Disturbance control, unplanned machine and equipment maintenance

Normal working at the machine

Moving goods or materials

Moving on the workplace

Other

Work phase

Working experience (years)

Duration of employment (current employer)

Employment: type

Permanent

Temporary

Part-time

Summer job or trainee

Entrepreneur

Number of victims

Frequency of the task

Machines and tools in use when the accident occurred

Lifting devices, transmitters

Motor-driven machines and vehicles

Machining and cutting tools

Process equipment

Handtools and equipment

Other machines and equipment

Electronic devices and conductors

Walking and working surfaces

Structures under construction and mounds of materials

Other

Accident type

Jumping or person falling

Crushing or being trapped between components

Slipping, tripping and falling

Accidents caused by falling objects

Electrocution

Suffocations and poisonings

Accidents caused by splashing substances

Other

Contributing factors

- Human error
- Technical malfunction
- Pressure of time
- Established unsafe work practice
- Occasional risk-taking
- Ignoring user instructions
- Ignoring work instructions
- Ignoring other orders and instructions
- Recklessness
- Working when the machine is running or live
- Defects in the flow of information
- Inappropriate walking or working surface
- Dangerous working method
- Misinterpretation of the work instructions
- False start
- Other

Specifications to the contributing factors

Recommended ways to prevent similar accidents

- Improving education or professional skills
- Instructions
- Written work instructions
- Work planning
- Design of devices and machines
- Guards
- Following rules and orders
- Ensuring switching off electrical equipment
- Stopping machinery
- Greater care
- Hazard identification
- Improving working environment
- Machine inspections
- Development of occupational hygiene
- Appropriate working environment
- Acquisition and use of personal protective equipment
- Appropriate working environment
- Defining and specifying responsibilities
- Appropriate tools and equipment
- Safe working methods
- Improving reporting
- Appropriate warning signs and notices
- Prevention of accidental start-ups
- Safety management
- Other

Specifications for accident prevention

Appendix 2: Study 1: Parameters in
Accident Analyses

Accident occurred

- At the process
- In a workshop
- On a walking surface
- Ladder
- Outdoors at a process
- Other

Time of the day when accident happend

- Morning
- During the day
- Evening
- Night
- In the beginning of the work shift
- At the end of the workshift
- Maintenance break
- Other

Observed defects in

- Ergonomics
- Occupational hygiene
- Working environment
- Work instructions
- Victim's education or work experience
- Written instructions
- Work planning
- Guards and safety equipment
- Hazard identification: general
- Hazard identification: by the workers
- Use of personal protective equipment
- Walking/working surfaces
- Warning signals and notices
- Prevention of machine start-up
- Safety management
- Other

Other observed faults and defects

Additional analyses for severe non-fatal accidents:

Injured body part

- Eye
- Upper limbs
- Lower limbs
- Back
- Head
- Hearing
- Torso
- Several body parts
- Other

Injury type

- Cuts, sores and minor bruises
- Broken bones
- Burns
- Amputations
- Squeezing or crushing
- Other

Appendix 3: Study 2: Interview Questions

Company

Reports

- are received
- are not received
- not known by the interviewee

Reports are sent to

- CEO
- industrial safety delegate
- industrial safety manager
- other
- not known by the interviewee

Preferred form of delivery

- printed report
- electronic delivery
- both

Number of copies

- sufficient
- insufficient

Appearance and layout of report

- good
- requires improvement

Contents

- good
- requires improvement

Correct working practices

- relevant
- not relevant

Front page (case summary)

- good
- requires improvement

Company safety indicators

The indicators are collected

yes

no

Number of accidents / year (in length of sick leave)

1–3 days

3 days –1 month

1–6 months

Over 6 months

Reporting system for incidents and near-misses

Available in the company

Not available

Appendix 4: Original publications

ARTICLE I

**Types and sources of fatal and severe
non-fatal accidents in industrial
maintenance**

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Types and sources of fatal and severe non-fatal accidents in industrial maintenance

Salla Lind*

VTT Technical Research Centre of Finland, P.O. Box 1300, FI-33101 Tampere, Finland

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ABSTRACT

Due to the various work phases in disassembly and assembly, coupled with, for example, the pressure of time and working in close contact with machinery, industrial maintenance operations include several occupational risks. This article presents the results of an analysis based on real accident data. The data consisted of public Finnish accident reports describing fatal and severe non-fatal accidents in Finnish industry. The examination was limited to those accidents that involved full-time maintenance workers executing industrial maintenance operations. In the case of fatal accidents, the examination included the reports that were published during the years 1985–2004. The analysis of severe non-fatal accidents included the publication years 1994–2004. The accident types as well as their sources were examined in the light of Reason's theory on organizational accidents. During the reference periods, a total of 37 maintenance workers died in 33 accident cases. The respective number of victims among severe non-fatal accidents is 90. The findings indicate that the most typical accident types in both fatal and severe non-fatal accidents are crushing, falling, and accidents involving falling objects. The most frequently identified unsafe act leading to fatal accidents is dangerous working method (including conscious risk-taking), while the severe non-fatal accidents occur most often due to working at a running process. Within both types of accidents the most typical latent causes are defects in work instructions and machinery safety equipment. Based on the findings, the most essential roles in accident prevention are played by organizational factors, such as safety management and operations planning.

Relevance to industry

Analyzing accidents creates a basis for more effective safety and risk management, which can be expected to face new challenges as more and more maintenance operations become subcontracted. It also provides valuable information regarding machine and process design, and the planning of maintenance operations.

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1. Introduction

The consequences of an accident in high-risk industries may be catastrophic. This sets high requirements on technology and management (e.g. Kjellén, 2000). It is also reflected in maintenance, which must be kept at a high standard to ensure reliability. In addition, maintenance operations must be carried out in a cost-effective way to minimize the economic losses that result from production disturbances.

From the occupational safety viewpoint, maintenance operations are challenging. In addition to risks that are connected with the industrial working environments, maintenance operations include several maintenance-specific risks. Such risk factors are,

for example, working at a running process, complicated machinery, and the pressure of time. In contrast to many other areas of technology and industry, the direct contact between the operator and machine in maintenance activities cannot be reduced substantially. Typically, distancing people from processes diminishes the likelihood of the occurrence of human errors and other chains of events that can lead to accidents. However, maintenance is, and probably always will be, that area in the use of technology where humans will be in direct contact with processes (Reason, 1997). Maintenance is also a good example of work that is performed in exceptional conditions, such as the time of day, especially when high-priority repairs are involved (c.f. Nag and Patel, 1998). A maintenance operation may also be exceptional work in itself, depending on the frequency with which it is performed. Maintenance operations typically include both assembly and disassembly, which can be considered to increase the number of risks of injury. Subcontracting maintenance services,

* Tel.: +358 20 7223004; fax: +358 20 7223499.
E-mail address: salla.lind@vtt.fi

which is currently becoming more and more typical, may also raise new challenges.

1.1. Maintenance and “safety”

According to the Federation of Accident Insurance Institutions in Finland (FAII), the most typical accident type in Finnish industry is crushing (24% of all accidents) and impact with solid/static structures (17% of all accidents) (FAII, 2006a). During the years 1996–2004, the three most typical types of fatal and severe non-fatal accidents in industry were caused by being trapped in or between components, persons jumping/falling from heights, and accidents caused by falling or tumbling objects (FAII, 2006b). The total number of maintenance professionals in Finnish industry is currently approximately 50 000, while in 2004 the total number of workers in industry was 418 298 (Finnish Maintenance Society, 2006; Statistics Finland, 2006).

In general, studies on maintenance-related risks can be divided into two groups, examining either: (1) human performance as a risk to the maintained process, or (2) maintenance operations as a risk to humans (Lind, 2004). The first group includes studies that have concentrated on post-maintenance safety and reliability (e.g. Hobbs and Williamson, 2002; Holmgren, 2005; Jo and Park, 2003; Rankin et al., 2000; Taylor, 2000; Thomaidis and Pistikopoulos, 1995; Toriizuka, 2001). Most of the studies concerning maintenance-related risks discuss human performance as a cause of the accident. A finding whereby a significant proportion of equipment failures occur shortly after a maintenance operation (Reason and Hobbs, 2003) supports this viewpoint. The approach is based on the increased possibility of human error during disassembly and assembly. The problem has been clarified by Reason (1997) with the nuts-and-bolts example. The basic idea is in all the possible variations in which a process or a machine can be re-assembled in an incorrect way. Studies connecting human errors with the reliability of the maintained object have been carried out, especially within nuclear power production and commercial aviation, which have obviously been the pioneering branches in assessing the role of human error in post-maintenance safety and reliability (Dhillon and Liu, 2006; Lind, 2004).

The second group of studies on maintenance-related risks examines maintenance operations as a risk to humans. Occupational safety in industrial maintenance operations has previously not been examined systematically. However, maintenance is often identified as a risky operation from the perspective of occupational safety (e.g. Kelly and McDermid, 2001; Lin and Cohen, 1997; Reason, 1997; Su et al., 2000). Both the management and the physical working conditions play important roles in developing safety in risky environments (e.g. Rasmussen, 1997; Sasou and Reason, 1999; Williamson et al., 1996). Maintenance can be considered to include the same risks as other operations in industrial working environments, and also boasts some certain specific risks. Such maintenance-related risk factors (e.g. working alone or during nights) especially arise from the need for urgent repairs and disturbance controls. Other typical risk factors are, for example, frequency of tasks, lack of tidiness and order of the working environment, as well as defects in the equipment and tools. These factors can also increase the risk of human error (Reason and Hobbs, 2003), although they are often considered to increase the probability of any occupational accident.

To conclude, the typical basis for earlier studies has been the consideration of human performance as a threat to the post-maintenance reliability. However, it can be presumed that industrial maintenance operations also include several risks for the maintenance workers that should be particularly examined and managed. Reason (1997) has examined how the chains of

events leading to organizational accidents are formed. According to Reason, the causes of an organizational accident are the combined result of various factors at different organizational levels. The accident causes can be grouped into “active errors” and “latent conditions”. The latent conditions are based on organizational and local workplace factors, while the actual worker makes the active errors. Basically, the active errors (unsafe acts) appear only if the organizational and local workplace factors enable them. An accident occurs if the accident causes manage to pass through the defenses protecting the object (e.g. a human) from danger (Reason, 1997).

Although Reason’s theory is particularly related to organizational accidents leading to catastrophic consequences, the concept may also be applicable in the case of individual accidents. This article aims to utilize the theory of organizational accidents in examining a group of individual accidents (i.e. fatal and severe non-fatal accidents) that have occurred in industrial maintenance operations.

1.2. The scope and aim of this study

In practice, maintenance operations in industry can vary greatly depending on the actual working environment and/or the maintained object. In this article, the term “maintenance” complies with Reason’s (1997) definition of maintenance activities:

- unscheduled repairs;
- inspections;
- planned disturbance—and failure—preventive operations;
- calibration and testing.

Further, in this context, the terms “maintenance crew” and “maintenance worker” refer to full-time maintenance workers, while “maintenance operations” and “industrial maintenance” refer to tasks that are performed by full-time maintenance workers in various industrial workplaces. Building (property) maintenance was excluded from the study. The article is based on public accident reports describing fatal and severe non-fatal accidents in Finland. In the case of fatal accidents, the examination covers the publication years 1985–2004, while the examination of severe non-fatal accidents involves the publication years 1994–2004.

This article focuses on industrial maintenance, with an aim to examine: (1) what kind of fatal and severe non-fatal accidents have occurred during industrial maintenance operations in Finnish industrial workplaces and (2) how such accidents could be prevented. The findings are examined in the light of Reason’s theory of organizational accidents. Thus the first question concentrates on accident types together with their sources, i.e. latent conditions (including organizational and local workplace factors) and unsafe acts. The second question examines the role of unsafe acts, local workplace factors, and organizational factors in accident prevention. The examination in this article is based on the findings and preventive methods proposed by the accident investigators.

2. Materials and methods

2.1. Accident reports

In Finland, there are two types of publicly available accident reports. Thus the material used in this study consisted of: (1) investigation reports on fatal workplace accidents (IFWA) from the years 1985–2004 and (2) accident reports written by industrial safety inspectors concerning occupational accidents resulting in serious injuries, known as safety inspectors’ accident

(SIA) reports, from the years 1994–2004. The first group includes all relevant fatal workplace accidents. The second group includes reports on accidents that are serious but did not result in deaths.

In both groups, the examination was limited to cover only such accidents that have occurred during a maintenance operation, and where the victim was a full-time maintenance worker. Thus repairs carried out by machinists or operators (i.e. any workers other than maintenance workers) were excluded.

2.1.1. Investigation reports on fatal workplace accidents

In Finland, the FAII, in cooperation with labor market organizations, coordinates the investigation and reporting of fatal workplace accidents. The investigation system has been on stream since 1985. During the years 1985–2004, the FAII published 678 investigation reports (FAII, 2006a).

A group of experts carries out the actual investigation and reporting—the aim of which is to determine what happened, rather than to identify the people responsible for any accident. Upon completion, the results are delivered to other companies within the same industry, with the aim of preventing similar accidents from occurring. The reports are also made available on FAII's website in PDF format.

The reports typically extend to five or six pages, and generally include some black-and-white pictures and a flow diagram summing up the chain of events. The text in the reports describes the accident in a precise way. The IFWA reports include a detailed description of the chain of events based on the findings of the accident investigation group. However, the actual injuries suffered are seldom mentioned. The reports give background information on the victim, accident scene, task execution, and fatal chain of events. They also give suggestions on how to prevent similar accidents.

2.1.2. Safety inspectors' accident reports

Finland has been divided into eight industrial safety districts that operate under the supervision of the Finnish Ministry of Social Affairs and Health (Finnish Industrial Safety Administration, 2007). Industrial safety inspectors from the company's local industrial safety district investigate and report on severe non-fatal accidents. Thus, the SIA reports are generally composed by a single author. The form and length of the report varies, but they are typically shorter and include fewer details than IFWA reports.

Like IFWA reports, the SIA reports also aim to promote safety in companies by providing external accident information accompanied by recommendations for preventing similar accidents. However, the SIA reports are available only on an Internet database that is administrated by the Finnish Industrial Safety Administration (2007). The database currently includes over 7000 accident cases, dating from 1987.

2.2. Methods

The relevant accident descriptions were examined with the aim of finding information concerning: (1) the characteristic features of fatal and severe non-fatal accidents in industrial maintenance and (2) the recommended corrective measures for preventing similar accidents listed in the IFWA and SIA reports. The charted features included:

- background information on a victim's task and work experience, and on the circumstances at the accident scene;
- accident types (e.g. falling, being trapped between components);
- identified sources of accidents, including latent conditions and unsafe acts;
- causes of injuries (in the case of severe non-fatal accidents).

The findings were coded and the quantified data were analyzed.

Furthermore, the collected recommendations for accident prevention were divided into three groups based on Reason's (1997) theory of organizational accidents: unsafe acts, local workplace factors, and organizational factors. Grouping of the findings was based on the following criteria:

- organizational factors: executing recommendations is primarily the duty of the management (e.g. work planning, supervision);
- local workplace factors: recommendations primarily apply to workplace (e.g. machine/process) design;
- unsafe acts: recommendations primarily involve human (operator/user) performance.

The respective degree of involvement of each group was analyzed to identify which of them could be considered the most critical in preventing accidents in industrial maintenance in the future.

3. Results

3.1. Workplace fatalities

During the years 1985–2004, 33 accidents occurred, leading to fatalities in industrial maintenance, of which four accident cases involved two victims each. Thus the total number of victims was 37. On average, the victims had 14 years of work experience. Typically, fatal workplace accidents occurred during planned operations and unscheduled repairs (Table 1). The typical accident scenes for fatal accidents were indoors at a process (46%), while 19% of accidents occurred while executing maintenance operations outdoors (e.g. at a process pipeline). In addition, 15% of the accident cases occurred indoors in maintenance workshops.

3.1.1. Types and sources of fatal accidents

It appeared that close contact with machinery and working in industrial environments are reflected in maintenance-related fatalities (Table 2).

Among the most common unsafe acts, the degree of involvement of "dangerous working methods" stood out clearly (Table 3a). In practice, "dangerous working methods" include conscious risk-taking as the task is executed in an unsafe way or without sufficient safety measures. Thus, the most important latent conditions were defects in planning or managing the work (Table 3b).

In examining the accident factors in Tables 3a and b, it must be noted that several factors can have appeared at the same time in one accident. Among unsafe acts, it is noteworthy that working at a running machine or process is a cause in 15% of fatalities.

Table 1
Fatal accidents: maintenance operations (N = 33)

Maintenance operation	%
Planned disturbance—and failure—preventive operations	48
Unscheduled repairs	24
Changes (e.g. to processes and machinery)	18
Calibrations, testing, and inspections	9
Other/unknown	1

Table 2
Fatal accidents: accident types ($N = 33$)

Accident type	%
Crushing or being trapped between components	27
Persons falling	27
Accidents caused by falling/tumbling objects	15
Other	31

Table 3
Fatal accidents

(a) Unsafe act	%
Dangerous working methods, including conscious risk-taking (by workers)	48
Defective hazard identification/unconscious risk-taking (by workers)	30
Non-use of personal protective equipment	17
Working at a running machine/process	15
(b) Latent condition	%
Defective work instructions	63
Defective safety equipment (machinery)	30
Victim's insufficient experience of task	20
Device failures	15

3.2. Severe non-fatal accidents

During the years 1994–2004, there were 90 severe non-fatal accidents in industrial maintenance involving full-time maintenance crew members. About 59% of accidents were associated with maintenance work indoors at a process. Maintenance workshops were an accident scene in 5% of the cases, while 6% of accidents occurred outside a building. The accident scene was not mentioned in 27% of the SIA reports.

3.2.1. Types and sources of accidents

Various categories of severe non-fatal accidents were defined, and the most typical accident type was crushing or being trapped between components (Table 4). The percentage of “Crushing or being trapped in or between components” was larger than the equivalent percentage in the case of fatal accidents.

In assessing the most common unsafe acts and latent conditions leading to accidents, it appeared that a large proportion of them involved working instructions (Tables 5a and b). Again, several factors might have been involved at the same time.

3.2.2. Causes and types of injury

Machines and devices were typical causes of injury in the case of severe non-fatal accidents, being involved in 76% of the cases (Table 6). Scaffolds, in addition to walking and working surfaces, were involved in 12% of severe non-fatal accident cases.

The most typical injury type was fracture, which occurred in 38% of severe non-fatal accidents (Table 7). Most injuries were caused to upper limbs (39%) or to several body parts at the same time (28%). The head or feet were injured in only 10% of accidents.

3.3. Accident reports: recommendations to prevent similar accidents

Both the IFA and SIA reports list recommendations and measures for preventing accidents of similar types. When comparing the recommendations in both groups of fatal and severe non-fatal accidents, it appeared that recommendations after a fatal accident are more often directed towards organization than in the case of severe non-fatal accidents. The recommenda-

Table 4
Main types of severe non-fatal accidents

Accident type	%
Crushing or being trapped between components	39
Jumping or falling	21
Accidents caused by falling objects	12
Other	28

Table 5
Severe non-fatal accidents

(a) Unsafe act	%
Working at a running machine/process	30
Dangerous working methods, including conscious risk-taking (by workers)	23
Defective hazard identification/unconscious risk-taking (by workers)	19
Other (e.g. carelessness, missing information)	18
(b) Latent condition	%
Defective work instructions	38
Defective safety equipment (machinery)	30
Defective walking or working surface	14
Device failure	10
Other	1

Table 6
Severe non-fatal accidents: injury causes

Cause of injury	%
Other machines and devices	30
Lifters, transmitters, and transport devices	22
Process equipment	14
Walking and working surfaces, scaffolds	12
Machining devices (e.g. lathes, cutters)	10
Electric devices and conductors	6
Hand tools and equipment	2
Structures under construction	1
Other	2

Table 7
Types of injury in severe non-fatal accidents

Type of injury	%
Fracture (broken bones)	38
Cuts and minor bruises	20
Burns	14
Crushing of limbs	14
Amputations	8
Other (e.g. eye injuries, skin damage, arrhythmia)	25

tions were categorized and the more typical recommendations are presented in Table 8.

4. Discussion

This study charted the accident types and sources within the framework of reported severe non-fatal and fatal accidents in industrial maintenance in Finland. As incidents and minor accidents are investigated internally in companies, the results in this article reflect only the more serious cases that have been investigated and reported externally by safety authorities and experts. Still, it can be assumed that measures intended to prevent serious accidents will also affect the probability of minor accidents and incidents.

Table 8
Recommendations and suggestions for preventing accidents of similar types

	Group of recommendation	Most typical recommendations	Fatal accidents % (N = 33)	Severe non-fatal accidents % (N = 90)
Organizational factors	Instructions and task planning	Adding information (including instructions, directions and training)	75	29
		Development of work planning	30	16
	Management and supervision	Employer's supervision of safe working methods (including acquiring and use of personal protective equipment)	39	15
Enhancement of safety management (including hazard identification)		60	21	
Local workplace factors	Machine and process safety	Adequacy and condition of machinery (including machine safety equipment)	27	34
		Prevention of unintended start-ups, switching off live parts reliably	24	30
	Workplace design	Development of workplace conditions (including occupational hygiene, walking and working surfaces)	30	28
Unsafe acts	Human performance	Use of safe working methods (including choosing proper tools, care)	12	13
		Following orders and instructions	12	6

This study adopted a quantitative approach, although the total number of cases was small—due to the strict focus on maintenance operations and maintenance crew-related incidents. However, the study involved all reported fatalities and severe non-fatal accidents over a 10-year time period. Thus, the results are strongly indicative of actual accident types and their latent and direct sources. The IFWA and SIA reports are in fact qualitative descriptions and partial interpretations of what occurred (e.g. often due to lack of eyewitnesses). Also, there have been many phases of investigation, analysis, and reporting after the actual accident events, and investigation- or author-based variation in the quality of reports may also occur. These aspects may have had an influence on the findings reported in this article.

4.1. Accident reports

In general, the accident reports avoid directly alluding to specific persons being responsible for an accident. This principle is highly emphasized, especially in the investigation and reporting of fatal accidents (IFWA cases), where the investigation and reporting is coordinated by FAII. The form of the SIA investigation and reporting is somewhat freer, and the same person describes the results and gives recommendations. On the other hand, this may also lead to subjective variations and interpretations regarding what happened and how such accidents could be prevented, whereas the IFWA reports give the joint results of an investigation and coordinating group. The differences in reporting practices may partially explain the differences in findings between the two groups. For example, when comparing the reported accident causes between the two types of reports, it appears that IFWA reports are more focused on the chain of events than on defining the direct causes of fatalities. In contrast, the SIA reports often leave some aspects of the chain of events open.

In the case of fatal accidents, most recommendations for accident prevention concern organizational factors (Table 8). The local factors, as well as unsafe acts, play only a minor role. In the case of severe non-fatal accidents, the recommendations are mainly directed at local workplace factors. These findings may partly result from the reporting practices, as previously described. An observation made by Rasmussen (1997) and supported by Körvers and Sonnemans (2007) applies also to the SIA and IFWA

investigations: as the accidents are investigated by experts of safety and legal matters, the results often emphasize the violated rules, instructions, and laws, i.e. organizational matters.

The emphasis on organizational means in accident prevention supports the idea that accidents are manifestations of different organizational failures (c.f. Hollnagel, 2004; Körvers and Sonnemans, 2007; Little, 2004; Perrow, 1984; Reason, 1997). Such failures can be, for example, missing or defective barriers that enable the human to get in contact with the accident cause (Hollnagel, 2004, 2007). In the context of organizational accident prevention, an important issue is the issue of learning from accidents, which, in Finland, also includes accidents reported in the IFWA and SIA reporting systems. The internal and external accident information of companies could provide important input to accident prevention on different organizational levels, but in practice companies may have difficulties in learning from internal and/or external accidents (see e.g. Baram, 1997; Hale, 1997; Lind and Kivistö-Rahnasto, 2008). In order to support accident prevention in companies with accident reports, the critical points in safety management, as well as practical solutions (defining what can be done), should be clearly stated in the reports.

4.2. Findings

The types of fatal and severe non-fatal accidents in industrial maintenance seem to be in line with the accidents in Finnish industry in general (see also Jeong, 1999). For example, the three most typical types of fatal maintenance-related accidents (Table 2) are the same as accident types among all severe non-fatal and fatal accidents in Finnish industry (FAII, 2006b).

In the case of fatal and severe non-fatal accidents in industrial maintenance, latent conditions and unsafe acts tending to cause accidents are often different kinds of shortcomings in the planning or performance of work (Table 5b), although the victims appeared to have been relatively experienced workers. Thus it can be assumed that a planned maintenance operation does not automatically include systematic safety planning. On the other hand, sources of accidents may result from some typical problems in maintenance operations, such as the pressure of time, and changing projects and tasks. Such problems may also affect the workers' choice of tools and working methods. Despite the

importance of organizational means, the role of workers should not be underestimated or neglected in accident prevention. On the contrary, the role of workers should be emphasized in safety management by finding ways to positively affect safe working. It also seems that the planning of maintenance operations requires some systematic approach towards integrated safety planning, including task-specific safety planning.

Working at running machinery and/or processes is a specific issue in maintenance safety. Executing maintenance tasks (e.g. unscheduled repairs) may require working at a running process. Such situations should be taken into account and avoided when planning the maintainability of the machine or process. Working at a running process or machine can also result from conscious or unconscious risk-taking, which can be a result of, for example, time pressure or a worker's defective hazard identification. Such factors should also be taken into account in the safety and risk management. To promote safety, it is essential to focus efforts on developing work instructions and ensuring they are followed. In the best case, the running parts can be turned off or safeguarded when executing a maintenance operation. If this is not possible, the planning of maintenance operations and/or working instructions should carefully account for such situations. The maintainability and maintenance of processes outdoors should be planned even more carefully, taking into account the seasonal variations in working conditions. For example, in Finland the wintertime can be very challenging due to darkness, ice, and snow. Again, supporting the hazard identification abilities of workers could help to make work performance safer.

It can be assumed that planned operations represent the biggest group in all maintenance operations, which would then be reflected in the number of working hours and even accident rates. On the one hand, the more infrequent (atypical) tasks, like unplanned repairs, may include unexpected hazards. However, the workers may be more careful and take more time to carry out some infrequent task. Also, the total risk exposure time is probably smaller in the case of infrequent tasks. From a company's viewpoint, the frequency and hazards of different tasks should be considered as a basis for safety management procedures and practical means of accident prevention. Thus, the different maintenance tasks should be charted and classified depending on their frequency and the associated risks. One option could involve listing all planned operations and charting also different kinds of unplanned/unexpected tasks that are allocated to maintenance personnel on customer sites. This could be a good basis for the instructions given to workers regarding maintenance tasks and safety. It would also help to estimate, for example, how much time and workforce is required in different situations.

Finally, due to increasing subcontracting of industrial maintenance, in the future it can be expected that maintenance operations will be increasingly carried out alone on customer sites, and/or without supervision (i.e. a supervisor may be far away from the actual site of the work). This means several safety-related decisions, such as the use of personal protective equipment, the choice of working methods, and the task-specific hazard identification, are decided by the worker. In addition, the increase in automation and more complicated machinery (e.g. remotely operated machinery), together with time pressures arising from customer demands, can also make safety management in maintenance more challenging. To tackle these new challenges, relevant measures for safety management could involve improving site- and task-specific safety planning and hazard identification. Again, safety planning, including adequate scheduling, should be a relevant part of maintenance operations planning and instruction, and not a separate procedure. Such aims could be supported through customer cooperation.

5. Conclusions

5.1. Types and sources of accidents in industrial maintenance

The most typical types of fatal accidents in industrial maintenance involve crushing, persons falling, and accidents caused by falling objects. In the case of severe non-fatal accidents, the types of accidents are the same. Thus, the types and rates of severe non-fatal and fatal accidents in the case of maintenance are similar to those for severe non-fatal and fatal accidents in Finnish industry in general. It appears that fatal accidents generally involve the working environment and structures, while severe non-fatal accidents also involve machinery or devices.

The most typical unsafe acts among fatal accidents are dangerous working methods, such as conscious or unconscious risk-taking in task execution. The most typical latent condition is defective work instructions. An essential unsafe act among severe non-fatal accidents is working at a running machine/process. Also in the case of severe non-fatal accidents, the most typical latent condition is defective work instructions. Practical differences in the utilized information sources may have affected these results to some degree.

5.2. The role of unsafe acts and latent conditions—prevention of accidents

In this study, the preventive methods were charted from the public Finnish accident reports. The identified sources of accidents involved both unsafe acts and latent conditions (local workplace factors and organizational factors). Although unsafe acts were more often identified as the sources of accidents, most of the accident preventive measures were directed at organizational and local workplace factors.

Accidents can be considered to demonstrate unsuccessful safety management and, for example, inappropriate supervision (organizational factors), although, in the end the decision to use unsafe working methods or not to use personal protective equipment is up to the workers (unsafe acts). To avoid such unsafe acts, the management, work supervision, and task planning should support and emphasize safe working, even when the job is executed in exceptional situations, such as with haste, alone, and/or during the night. Thus, the accident preventive measures should highlight the role of the workers in accident prevention, in addition to management and/or workplace design.

Machine design was only of minor importance in the assessment of the sources of accidents and suggested preventive methods. This may indicate advances in machine safety design, but it also underlines the essential role of management in accident prevention, as accidents can be a consequence of inappropriate use of machinery and/or defects in machine safety devices. To provide more information for accident prevention through machine design, a detailed technical examination of accident causes is required.

A significant issue for a worker engaged in a maintenance operation is tasks planning. In case maintenance, operations are carried out alone, in foreign working environments, without work supervision, or at short notice with no time for detailed job-specific planning, it is important that the worker assesses the risks arising from such conditions before starting a work operation. Such situations also emphasize the need of careful operations planning (by management and supervisors), which should include safety planning. In addition, the planning should take into account adequate scheduling so that the worker has time for task preparations, including an independent safety check at

the workplace. For such purposes, a brief checklist that enables independent hazard identification by workers is proposed.

A more detailed investigation is required to examine the challenges arising from the subcontracting of maintenance services. It may be assumed that subcontracting makes site-specific safety planning more important due to the differences in sites, varying practices in customer cooperation, and the greater distance between individual workers and the company management. In the long run, this may also be reflected in the accident rates of maintenance operations.

It appears that maintenance-related risks should be controlled by improving and strengthening safety management. On the basis of the findings in the literature, there are no specific tools for managing occupational safety in industrial maintenance. On the other hand, the special characteristics of industrial maintenance, such as increasing subcontracting, more complicated processes and machinery, and the various risks associated with disassembly and assembly clearly show the need to provide tailored organizational and technical tools for maintenance risk management. In addition, safety planning should be an integral part of maintenance operations planning.

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ARTICLE II

Occupational risks in industrial maintenance

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OCCUPATIONAL RISKS IN INDUSTRIAL MAINTENANCE

Salla Lind*^a & Sanna Nenonen^b

^a *VTT Technical Research Centre of Finland, Systems Engineering
P.O. Box 1300, FIN-33101, Tampere, Finland*

^b *Tampere University of Technology, Institute of Occupational Safety Engineering
P.O. Box 541, FIN-33101 Tampere, Finland*

Purpose – Subcontracting is becoming increasingly common as an industrial service. Maintenance is a typical subcontracted service, which is often carried out on changing customer sites. Among other maintenance-related risks, changing of sites can create new challenges to the service provider’s risk management. Although maintenance has been considered a risky operation, there have not been any systematic task-based examinations of occupational risks related to it.

Methodology – This study analysed all maintenance-related fatalities since 1985 together with one group of severe accidents in Finland. In connection with the study, risk assessments were carried out in companies with the aim of charting the risks on sites.

Findings – The results indicate that the typical risks in maintenance operations involve poor ergonomics and that the most severe risks among these can lead to direct injury. Severe or even fatal injuries are mainly caused by crushing or falling.

Practical implications – To manage the risks, maintenance operations should be taken more carefully into account when designing and reconstructing machinery and work environments. It should be ensured that workers have relevant safety knowledge by means of risk assessments and instruction in safe working practice. In addition, safety cooperation with the customer is essential.

Originality/value – The findings indicate that maintenance operations include certain occupational risks. Among such risks, subcontracting offers a specific challenge to the service provider’s safety management. The findings of this study provide advice on the safety measures necessary for accident prevention and how to execute them.

Keywords – occupational safety, risks, maintenance operations

Paper type – Research paper

* Corresponding author

tel.+358 20 7223004, fax: +358 20 7223499

E-mail address: salla.lind@vtt.fi

INTRODUCTION

Subcontracting is becoming increasingly common as an industrial service. From the service provider's perspective, this raises challenges e.g. in customer cooperation and for the occupational safety of workers on customer sites. For instance, hazard identification on sites may in practice remain the task of workers when they are located a long distance from management or work supervisors. Further, changing customer sites may involve completely new risks that the worker needs to take into account. It is already known that maintenance operations include specific risk-increasing factors. Such risks are, for example, working under the pressure of time, shift work (i.e. also during nights), working alone and working in close contact with complicated machinery (see e.g. Reason and Hobbs, 2003). However, there have not been any task-based studies which chart maintenance-related risks from the service provider's perspective.

Industrial maintenance is a typical subcontracted service, both as in the form of manufacturers' after-sales service and subcontracted industrial service. According to the Finnish Maintenance Society (2006), the total number of maintenance professionals in Finnish industry is currently approximately 50 000, while in 2004 the total number of workers in industry was 418 298 (Statistics Finland, 2006). In this context the term "maintenance" is defined according to Reason (1997) and includes unscheduled repairs, inspections, planned preventive maintenance, and calibration and testing. Furthermore, in this context the term "maintenance crew" refers to full-time maintenance workers and the term "maintenance operations" to tasks that are performed by full-time maintenance workers in industrial workplaces.

As a technical operation, industrial maintenance may endanger the reliable functioning of the maintained object (Dhillon and Liu, 2006, Holmgren, 2005; Jo and Park 2003; Lind, 2004; Sasou and Reason 1999; Taylor 2000; Thomaidis and Pistikopoulos, 1995; Toriizuka, 2001; Vidal-Gomel and Samurçay 2002). Such problems have been examined especially within high-risk industries, such as commercial aviation and nuclear power production (see e.g. BASI, 1997; Hobbs and Williamson, 2002; Hobbs and Williamson, 2003; Rankin et al., 2000; Reason and Hobbs, 2003; Sachon and Paté-Cornell, 2000; Wiegmann and Shappel, 2001). In comparison, maintenance-related risks endangering the safety of maintenance crew members have been much less examined, although maintenance is considered a risky operation from the viewpoint of occupational safety (e.g. Lind 2004; Reason, 1997; Reason and Hobbs, 2003).

The aim of the present paper is to describe the most important occupational risks in maintenance operations. The article is based on a study carried out in Finland during 2005-2006. The materials consist of real accident data and risk assessments in companies. The discussion section looks briefly at safety promotion on the basis of the findings and the conclusions section sums up the maintenance-related risks.

MATERIALS AND METHODS

Real accident data

Two public Finnish databases consisting of real accident data were used to study accidents that had happened to full-time maintenance crew members in industry. The data involved 1) safety inspectors' accident reports describing severe accidents in Finland during the years 1994-2004 and 2) investigation reports on fatal workplace accidents in Finland published during 1985-2004. The Finnish Ministry of Social Affairs and Health hosts the first of the databases. A single author (safety inspector) carries out the investigation and reporting. At the same time, the Federation of Accident Insurance Institutions in Finland coordinates the investigation and reporting of all fatal workplace accidents. In this case, a group of experts from different fields carries out the investigation and reporting. The databases were studied in order to find such accidents that involved full-time maintenance crew members.

During these time periods 90 severe accidents occurred, each causing injuries to one employee, and 33 fatal accidents occurred which involved a total of 37 persons. The causes of fatal and severe accidents concerning maintenance personnel were examined from the data. Also risk factors and deficiencies contributing to the accidents were studied. In addition, these risk factors and deficiencies were examined in terms of how they differed in the case of fatal and severe accidents. The analyses examined only such accidents that involved full-time maintenance workers in industrial maintenance operations. The relevant reports were analyzed with the aim to determine the causes and consequences of severe and fatal accidents.

Occupational risk information in companies and at customer sites

The study involved 3 large companies with altogether 15 customer sites. Two of the companies sell maintenance services to industry, while one of the companies is a machine manufacturer providing after-sales services. The customer sites represented different industries (Table I).

Table I. Customer sites.

Paper mill	Oil refinery	Vegetable oil and protein feed factory
Underground mine	Dairy	Cable factory
Pipe mill	Dressing plant (nickel)	Plastic product plant
Maintenance workshop	Power plant	Smelting plant (copper)
Engineering works	Pulp mill	Sawmill

The study involved different phases in order to chart more fully the risks in companies. First, the representatives of service-providing companies' were interviewed in an unstructured way. The interviews involved both managers and workers and charted the observed and perceived occupational risks in maintenance operations. The accidents which had occurred were discussed.

Next, all customer sites were visited. During the visits, customers' representatives and maintenance crew on site were interviewed. These interviews charted the types of maintenance operations and occupational risks on site. Also safety cooperation between subcontracted maintenance crew members and the members of the customer's own crew on site was charted.

Following that, a certain group of customer sites were re-visited and selected maintenance works were observed. During the visits the researchers carried out the risk assessments using a general risk assessment tool with an extensive list of typical industrial hazards (Murtonen, 2000). The works were selected by the supervising group, using criteria such as the frequency and perceived risk exposure of the operation. These works consisted mainly of planned preventive maintenance work, like changes of paper machine cylinders and maintenance of a cream tank in a dairy. The risk assessments followed the concept published originally in the standard BS 8800 (1996). Thus, the risk assessments included both hazard identification and estimation of the probability and expected consequences of the observed hazards (Table II). The magnitude of the risk is the result of the severity and likelihood of occurrence of an observed hazard.

Table II. Risk estimation (adapted from BS 8800:1996).

<i>Likelihood of harm</i>	<i>Severity of harm</i>		
	Slight harm	Moderate harm	Extreme harm
Unlikely	1 Very low risk	2 Low risk	3 Medium risk
Likely	2 Low risk	3 Medium risk	4 High risk
Probable	3 Medium risk	4 High risk	5 Very high risk

Discussions with the maintenance crew members were used to complete the risk assessments. The sites and the maintenance operations examined were chosen by the companies on the basis of wide applicability and perceived high risk potential. The actual risk assessments involved altogether 6 maintenance operations within different areas of industry.

RESULTS

Real accident data

Types and causes of severe and fatal accidents

The most common types of severe and fatal accidents during maintenance operations in industry were crushing and falling. More than one third of accidents were caused by falling and almost every fourth by crushing. Falling is the cause of a relatively greater proportion of fatal accidents than severe ones. In the case of crushing, the proportions are the opposite. The differences are not statistically significant. Proportions of accident causes in fatal and severe accidents are given in Table III.

Table III. Accident causes of severe and fatal accidents

Accident cause	Severe accidents (n=90)	Fatal accidents (n=33)	Total (n=123)
Crushing or being trapped by a component	39 %	27 %	36 %
Falling	21 %	27 %	23 %
Falling objects	12 %	15 %	13 %
Electricity	7 %	6 %	7 %
Splashing of dangerous substances	6 %	0 %	4 %
Touching objects or getting tangled	3 %	3 %	3 %
Suffocation or poisoning	0 %	9 %	2 %
Other (e.g. cold, fire, explosion)	12 %	12 %	12 %

Factors and deficiencies contributing to accidents

In the accident data several risk factors contributing to severe and fatal accidents were reported. The most common factors were working while a machine is in motion and dangerous working practices. Of these two factors, a statistically significant difference can be found in the case of dangerous working practices. This factor contributed to almost half of the fatal accidents while such dangerous practices were a contributing factor in only 11 % of severe accidents. Of all the other contributing factors, dangerous working method, inappropriate walking or working surface, misinterpretation of instructions and accidental engine start-ups differed significantly in the degree to which each of them contributed to fatal and serious accidents. The proportions of all contributing factors reported in the accident data are presented in Table IV.

Table IV. Factors contributing to severe and fatal accidents.

Contributing factor	Severe accidents (n=90)	Fatal accidents (n=33)	Total (n=123)
Working while machine is in motion	25 %	15 %	24 %
Dangerous working practice	11 %	48 %	21 %
Ignoring the rules and instructions	18 %	13 %	16 %
Machine malfunction	10 %	15 %	11 %
Inappropriate walking or working surface	14 %	0 %	10 %
Human error	9 %	4 %	7 %
Working in a hurry	9 %	4 %	7 %
Established dangerous working method	8 %	0 %	6 %
Recklessness	6 %	4 %	6 %
Lacks in communication	4 %	4 %	4 %
Misinterpretation of instructions	0 %	7 %	4 %
Accidental engine start-up	0 %	7 %	4 %
Occasional risk-taking	1 %	0 %	1 %
Other (e.g. wrong tool, working overtime)	24 %	56 %	32 %

Contributing factors and deficiencies as accident causes

For severe and fatal accidents also various kinds of contributing deficiencies were reported. Generally deficiencies existed in machinery safety devices (31 % of cases), work guidance (30 %) and risk assessment (27 %). Deficiencies were found also in written work instructions, personal protective equipment, employee's education or

experience, working environment, task planning and safety management. In comparing the percentage contributions of different deficiencies to fatal and severe accidents, few statistically significant differences can be found. Differences occur in work guidance, employee's education or experience, risk assessment and safety management. In all of these cases the percentage contribution was greater in the case of fatal than in that of severe accidents. The most common factors and deficiencies contributing to different accident types are presented in Table V. It is noteworthy that there may be many separate causes and deficiencies behind one accident. Different factors and deficiencies must be identified and controlled simultaneously.

Table V. Most common contributing factors and deficiencies by accident cause.

Accident cause	Most common contributing factors	Most common contributing deficiencies
Crushing or being trapped by a component	- Working while machine is in motion (46 % of cases) - Human error (15 % of cases)	- Machinery safety devices (50 % of cases) - Work guidance (43 % of cases)
Falling	- Inappropriate walking or working surface (46 % of cases) - Dangerous working practice (25 % of cases)	- Walking or working surface (31 % of cases) - Personal protective equipment (25 % of cases)
Falling objects	- Dangerous working practice (43 % of cases) - Machine malfunction (36 % of cases)	- Work guidance (36 % of cases) - Risk assessment (28 % of cases)
Electricity	- Working while machine is live (83 % of cases)	- Risk assessment (60 % cases)
Splashing of dangerous substances	- Machine malfunction (40 % of cases)	- Risk assessment (50 % of cases)
Touching objects or getting tangled	- Recklessness (50 % of cases) - Dangerous working practice (50 % of cases)	- Machinery safety devices (50 % of cases) - Employee's education or experience (50 % of cases)
Suffocation or poisoning	- Misinterpretation of instructions (33 % of cases) - Machine malfunction (33 % of cases)	- Work guidance (67 % of cases) - Written work instructions (67 % of cases) - Personal protective equipment (67 % of cases)

Interviews and risk assessments

Perceived and observed risks in companies

Most of the risks in companies were considered to involve ergonomics, i.e. poor working postures, heavy lifts and improper working methods. This finding was confirmed in the companies' safety and health statistics. Among other factors, improper scheduling and pressure of time were considered as a risk both within companies and on customer sites. The perceived risks reflected defects in planning of maintenance operations and work environments (including processes/machinery and walking and working surfaces). The

management and supervisors in service-providing companies perceived the same risks as the interviewed maintenance crew members on customer sites.

Risk assessments on customer sites

The risk assessments on customer sites indicated that the most typical risks involved ergonomics, while the most severe risks related to injury risks (Table VI). The risk assessments supported the results from the interviews, as most risks related to ergonomics. In general, it became obvious that the work phases of disassembly and assembly double the number of risks in maintenance operations.

Table VI. Observed risks on levels 3-5.

3 (medium risks)	4 (high risk)	5 (very high risk)
Other risks relating to ergonomics (heavy lifts/holding up weight, work tools and methods)	Unsafe actions and risk-taking	Person falling
Slipping and tripping	Non-use of personal protective equipment, missing safeguards or shields	
Poor working postures: head, neck, shoulders, upper and lower limbs, back	Missing or misleading operational safety bulletins	
Cold or hot objects	Slipping	
Person falling	Tripping	
Pressure of time	Poor working posture: back	
Falling objects	Heavy lifts/holding up weight	
Working outdoors		
UV radiation		
Lack of oxygen, suffocation		
Non-use of personal protective equipment, missing safeguards or shields		
Missing or misleading packaging symbols for chemicals		

Pressure of time is not a significant risk itself: it can be expected to cause psychological stress in the long run. However, it can increase the degree of danger of the existing risks and even create some new ones, as workers may use inappropriate methods in carrying out a task in a hurry. The observed risks can be grouped into three: ergonomics-related risks, risks related to work environment and injury risks which cause danger to human safety or health.

Ergonomics-related risks

The findings in companies, i.e. from interviews and risk assessments, highlighted the poor ergonomics in maintenance operations. There are two explanations for this. First, the workers may be unaware of proper working postures/methods. They may also be unwilling to give up unsafe routines, especially under pressure of time. Second, on many sites the design of machine/process or work environment was poor from the perspective

of maintenance. In such cases carrying out maintenance operations was very challenging, as objects were difficult to reach.

Poor maintainability originates partly in machinery/process design, but many of the observed sites had also gone through significant changes with time. Thus, the objects to be maintained were covered or otherwise difficult to reach (e.g. between new pipelines and process equipment). It became obvious that the workers are the most adjustable part of the maintenance operation, in a case where there are defects in work environment or tools. The flexibility of humans was especially required if operations were carried out under pressure of time.

Risks relating to work environment

On many customer sites certain maintenance operations are performed outdoors. In Finland, this involves significant variations in conditions between summer and winter. In the case of temperature, wintertime is especially challenging because of darkness and ice, leading to, for example, slippery tools and walking and working surfaces. Other weather-related factors are for example strong wind, snowing, darkness, excessive UV radiation and rain. Such conditions must be taken into account while planning the execution and scheduling of outdoor maintenance operations. Besides working, also travelling to and between customer sites involves varying risks in different seasons. Of all risks, those relating to weather might be the most difficult to manage.

Some risks were related to indoor work environment. It became obvious that maintenance is seldom considered in workplace design. The consequences of poor design are reflected both in ergonomics and injury risks. Although safety of maintenance work may have been taken into account in machine design, it may be eliminated by the overall design of the workplace as well as by alterations in the work environment.

Poor general order and tidiness, such as storing goods on walking and working surfaces, caused risks on some sites. Other indirect accident risks were inappropriate chemical packaging marks. Such risks highlight the need for common established safety practices between customer and maintenance crew members. The common practices should advise on e.g. general order and tidiness, and the storing of chemicals on site.

Injury risks

In general, injury risks involved a variety of different risks. In the risk assessments, the most typical injury risks are slipping, tripping and a person falling. A person falling was also the only risk of “very high” type. It was identified with risk level 5 on one site where one frequently performed task required working on machinery approximately 5 metres from the ground. The workers did not use any personal protective equipment. Other risks of falling were related to occasional climbing to a high place. Such risks were identified especially outdoors, where ice and rainwater may make surfaces slippery.

Some of the problems related to ergonomics may also lead to immediate injuries. Such situations are e.g. heavy lifts, which in some cases had caused injuries to a worker’s back or limbs.

A very maintenance-specific risk type is feet injuries caused by falling objects. This accident type came up during interviews. It was also identified during several risk assessments. The risk may occur during both assembly and disassembly. The probability of occurrence may increase if the available working space or lifting tools are limited.

DISCUSSION

The occupational safety of workers is the duty of management also while workers are on unfamiliar sites. Sites may be stable or temporary. Thus, safety management must be flexible and constantly take into account changing work environments. Also on stable sites maintenance crew members may change, e.g. due to varying work loads. The time for work planning (including safety planning) may also be limited. This may be problematic, especially on new sites and in the case of new maintenance tasks.

Pressure of time increases the likelihood of hazards, but can also create some new ones. Thus, it is very important to plan and schedule work assignments carefully. It is also important that a worker should plan his/her work before beginning an operation. Another indirect risk is unconscious/conscious risk-taking, which may be a result of either not knowing the right practices (e.g. due to an established unsafe practice on site) or disregarding safe working methods (e.g. due to pressure of time). In case of both of these indirect risks, work supervision and management are essential. Irrespective of the cause of unsafe actions, management and supervision must underline the importance of safe practices to achieve a good safety culture. The importance of managements' commitment for safe work may even increase when the workers are on customer sites and make decisions by themselves. In any case, safety planning must be a consistent procedure, covering all forms and phases of maintenance. Thus, safety planning must be a regular part of planning, scheduling and performing maintenance operations.

The service provider must also take into account the different situations that may occur in maintenance operations. Such situations are, for example, working alone, environmental conditions, shift work (nightshifts) and changes in a customer's processes and practices. The observed risks depended strongly on operations and production at customer sites. Thus, the risks must be assessed and controlled site-specifically. Customer cooperation in risk assessment and safety management is essential as it enables safety promotion, such as implementation of common safety practices on site.

The risk assessments are basically subjective, i.e. the observed hazards and the rating of severity and assumable harm can vary, depending on the observer. Although the magnitude of risks is subjective, the systematic assessments can be considered to have identified the relevant hazards. In this study, the number of risk assessments was relatively small. The assessments were completed by means of with interviews and discussions. The total conception of maintenance-related risks was completed with real accident data. The utilization of different methods and sources makes the conception of

maintenance-related risks more reliable. Thus, it can be assumed that the results give a reliable picture of the most significant maintenance-related risks in Finnish industry.

Safety promotion

There are certain important factors in promoting the safety of maintenance operations. First, maintenance crew members should have relevant safety information. Safety information should include 1) information about work-related hazards and 2) knowledge (including skills) regarding how work should be done. Second, the working conditions should make it possible to work safely. Thus, planning of maintenance operations (e.g. scheduling and resource allocation) and workplace design must enable working safely.

It was observed that maintenance crew members had both appropriate and inappropriate safety information. The first type of information related to e.g. safe working practices, planning of work and independent hazard identification. The second type was identified during this study, one example being conscious or unconscious risk-taking. In practice this takes the form of established unsafe practices, poor safety culture (e.g. carelessness with regard to safe working methods) and/or failure to identify hazards on sites.

To support safe working practices, it must be ensured that workers are instructed in safe working methods before they carry out maintenance operations independently on sites. Workers should also be advised to carry out independent hazard identification, especially if they are working alone. Further, it is important to promote good safety culture by emphasizing responsible and proactive thinking in safety issues.

Management/supervisors should ensure that there is enough time to plan and perform tasks on site. Maintenance crew members must be encouraged to perform independent hazard identification and to inform supervisors/management about observed risks. To achieve good safety culture among workers, the safety climate on sites and in companies must support such aims. Thus, it is important that the customers' representatives and co-workers on sites have the same goal. Workers must be advised to use safe working methods while being instructed on work-related issues. The risks related to operations and the work environment must be clarified. In preventing accident risks, workers should also be advised on ergonomic working methods.

CONCLUSIONS

In Finland 90 maintenance crew members were severely injured during 1994-2004 and 37 died during 1985-2004. The most common causes for these accidents were crushing and falling. Crushing was reported as the accident cause in 40 % of severe accidents and in almost 30 % of fatal accidents, while falling caused 20 % of severe and nearly 30 % of fatal accidents. Many factors contributed to the accidents, the most common of which were working while a machine is in motion and dangerous working practices. Also various kinds of deficiencies contributed to the accidents. Most deficiencies were

connected with machinery safety devices, work guidance and risk assessment. The contributing factors and deficiencies were different in the case of fatal and severe accidents.

The risks on sites can be placed in three groups: risks related to ergonomics, risks related to work environment and direct injury risks. The most typical risks relate to ergonomics, while injury risks are the most severe ones. Many risks on sites originate in human factors, i.e. management, planning or the execution of operations. Among human factors, technical solutions in the work environment can create risks. Such factors are e.g. poor maintainability of machinery and processes. The execution of maintenance operations should be taken into account more carefully in designing and reconstructing work environments.

Due to the practice of subcontracting, maintenance operations are nowadays often carried out on customer sites. Workers may carry out operations very independently, e.g. during the nights. This must be taken into account in managing maintenance-related safety risks. Although the most probable accident victims are blue-collar workers, risk management in maintenance operations must involve all organizational levels within the service-providing company. In practice, supervisors and managers must ensure that there are sufficient resources (such as time) and knowledge for safe work. Close customer cooperation is essential to ensure a sufficient flow of occupational risk information and to promote good safety practices on sites.

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ARTICLE III

Safety risk assessment in industrial maintenance

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SAFETY RISK ASSESSMENT IN INDUSTRIAL MAINTENANCE

Salla Lind^{*a}, Sanna Nenonen^b, Jouni Kivistö-Rahnasto^b

^a *VTT Technical Research Centre of Finland, Systems Engineering
P.O. Box 1300, FI-33101, Tampere, Finland*

^b *Tampere University of Technology, Institute of Occupational Safety Engineering
P.O. Box 541, FI-33101 Tampere, Finland*

Purpose – Maintenance operations involve a variety of occupational risks that require systematic assessment. Risk assessment is the basis for risk management that, in case of maintenance, must tackle with several factors, such as varying working environments and varying tasks. In addition, the increasing inclination towards subcontracting makes risk management even more challenging. Safety risk management must cover management, planning, and execution of maintenance operations also on customer sites. It must also advise the service provider in safety cooperation with the customer.

Methodology – This study was based on analyses concerning: 1) maintenance-related risks in companies, 2) literature review, and 3) real accident data. The development process was carried out in cooperation with companies providing maintenance services.

Findings – Based on the findings, the method takes into account various risks relating to maintenance operations. The method includes specific parts for safety planning and hazard identification for managing maintenance safety. In addition, it provides a safety checklist for the worker.

Research limitations/implications – The usability and feasibility of the method should be reassessed and developed. The method could especially be useful in an electronic form.

Practical implications – The method can be utilized for assessing maintenance-related occupational risks in different working environments. The results from the assessments create the basis for risk management in industrial maintenance.

Originality/value – Due to certain specific safety challenges, maintenance operations require a specific risk assessment method. However, such a method has not been previously available. The findings and feedback indicate that this kind of a risk assessment tool can be useful in companies.

Keywords – Maintenance operations, risk assessment, occupational safety.

Paper type – Research paper.

* Corresponding author

tel. +358 (0)20 722 3004, fax +358 (0)20 722 3499

e-mail: salla.lind@vtt.fi

INTRODUCTION

Occupational risk assessments have traditionally been based on the identification of hazards in the workplace. As subcontracting industrial services becomes more and more typical, the focus of risk assessment changes. While the maintenance services are sold to other companies, the subcontracted workers may virtually be permanent workers with varying tasks on some certain site. On the other hand, the workers may instead specialise on some certain tasks that is executed on varying customer sites. In both cases, the workers face a variety of work tasks and risks in different working environments and unfamiliar organizations. The changing customer sites and/or tasks present new challenges to the service provider's risk management, which must ensure occupational safety also in changing working environments and among changing tasks. Therefore, there is a need for new kinds of risk assessment methods and risk management procedures specifically aimed at assisting the subcontracted companies promote safety on customer sites.

In this article, the term "maintenance" complies with Reason's (1997) definition of maintenance activities including unscheduled repairs, inspections, planned preventive maintenance, together with calibration and testing. Further, in this context the term "maintenance crew" refers to full-time maintenance workers and "maintenance operations" to tasks that are performed by full-time maintenance workers in industrial workplaces. According to the Finnish Maintenance Society (2006), the total number of maintenance professionals in Finnish industry is currently approximately 50 000, while in 2004 the total number of workers in industry was 418 298 (Statistics Finland, 2006).

This article examines risk management in industrial maintenance from the service provider's perspective. The article aims to answer the following questions:

- 1) What conditions must be taken into account in order to manage maintenance-related risks, and
- 2) How can the service providing company assess and manage maintenance-related risks?

The results describe the development of a safety risk assessment method for industrial maintenance operations, based on a study that was carried out with service-providing companies and their customers.

THEORETICAL BACKGROUND

Risks and risk assessment in industry

Hazards are sources of potential harm to human health, property or environment. And hazards under certain conditions may lead to accidents. (IEC 300-3-9, 1995; OHSAS 18002, 2000; BS 8800, 2004) Accidents typically occur suddenly and unexpectedly; causing immediate injuries and losses. On the other hand, many health problems may also develop slowly over time. Accidents can also be seen to be an organizational problem. Reason (1997) suggests that accidents are produced by unsafe actions, error-provoking conditions and organizational factors. Thus, accidents can be prevented by removing hazards or conditions, or by interrupting the series of events by the application of appropriate defences. The defences are, however, dynamic in nature and the active failures and the latent conditions may change the effectiveness of the defences.

Work tasks and working environments vary in industrial maintenance. Therefore, companies need occupational health and safety management systems that help them to prevent and mitigate accidents by identifying and selecting the most essential hazards and by managing the hazards and the preventive measures. The concept of risk is used to measure the potential of losses caused by human activities and technical systems together with environment. The risk is a combination of the harm and the likelihood that the harm occurs. Risk assessment should consist of the hazard identification, evaluation of the preventive safety measures and their functionality, estimation of the exposure to the hazards and the evaluation of consequences (Modarres, 2006), as well as the evaluation of the tolerability of the risk (BS 8800, 2004). Risk assessment then serves as basis for controlling intolerable risks.

Maintenance-related risks

From a task-based perspective, industrial maintenance is risky. Maintenance operations cause risks to machinery, company, and humans carrying out the operations. Traditionally, safety-related maintenance research has focused on post-maintenance process reliability (see e.g. Dhillon and Liu, 2006; Hobbs and Williamson, 2002; Holmgren, 2005; Jo and Park, 2003; Rankin et al., 2000; Reason and Hobbs, 2003; Taylor, 2000; Thomaidis and Pistikopoulos, 1995; Toriizuka, 2001). Defects in maintainability design and planning of maintenance operations can create an indirect economic risk by endangering the production continuity.

Among others, maintenance operations pose several risks to maintenance crew (e.g. Kelly and McDermid, 2001; Reason, 1997; Su et al., 2000). The occupational risks are related to, for example, various phases in disassembly and assembly, work done on running processes, and process chemicals. Risks are coupled with time pressure, as well as defects in work planning and safety management. Due to increasing inclination towards subcontracting, customer cooperation becomes more and more important also in occupational risk management. Despite notified safety

challenges in industrial maintenance, there has not been any maintenance-specific risk assessment tool.

METHODS AND MATERIALS

The research reported in this paper was conducted at the Institute of Occupational Safety Engineering of the Tampere University of Technology in cooperation with 3 companies that provided maintenance services. The project also involved 15 customer companies of the service providers. The research was carried out through 6 phases.

The study was supervised by a group which included representatives from the cooperating companies (service providers), the researchers, and the financier (The Finnish Work Environment Fund). The progress of the study is illustrated in Figure 1.

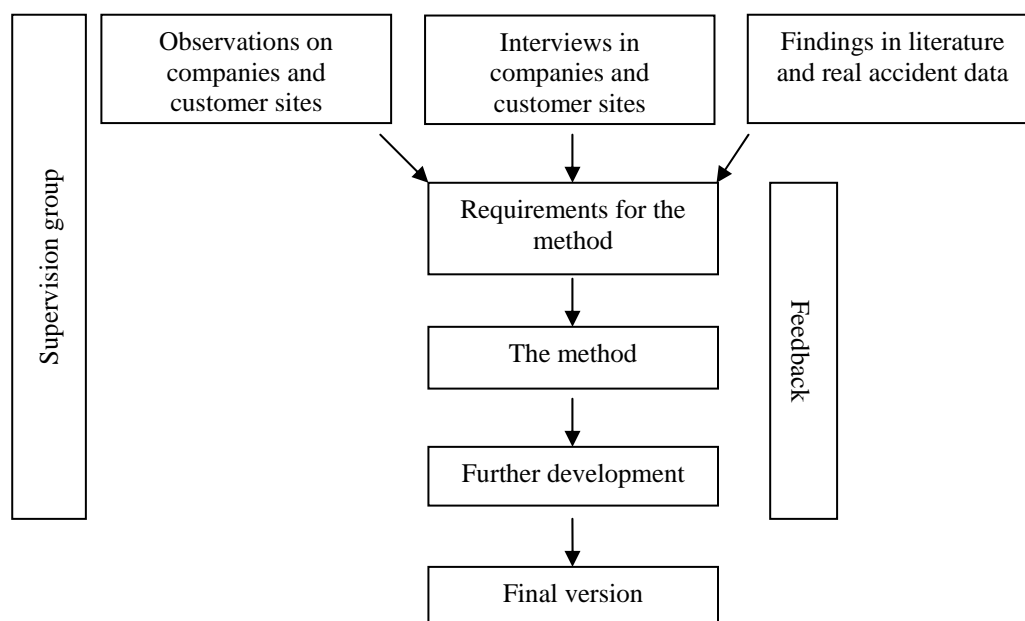


Figure 1. The progress of the study.

Firstly, real accident data from two public Finnish databases was analyzed. The databases involved: 1) industrial safety inspectors' accidents reports describing severe accidents in Finnish industry, and 2) investigation reports on fatal workplace accidents in Finland. The Finnish Ministry of Social Affairs and Health hosts the first of the databases. A single author (safety inspector) carries out the investigation and reporting. At the same time, the Federation of Accident Insurance Institutions in Finland coordinates the investigation and reporting of all fatal workplace accidents. In this case, a group of experts from different fields carries out the investigation and reporting. The databases were studied in order to find such accidents that involved full-time maintenance crew members. The analyses included the years 1985-2004 for fatal accidents and 1994-2004 for severe accidents. The analyses examined only such accidents that involved full-time maintenance workers in industrial maintenance operations. The relevant reports were analyzed with the aim to determine the causes and consequences of severe and fatal accidents.

All 15 customer companies were then visited. Some of the sites were in very close proximity of each other, and sometimes even on the same industrial plot. In such cases the same subcontracted maintenance crew members were typically responsible for all the customer sites on the area. Therefore, the visits involved 12 maintenance crews representing 15 customer companies. Various industries are covered by the visited companies (Table I). The maintenance personnel at the sites were interviewed in an unstructured way to determine general information about the company, the types of maintenance operations, and the observed and perceived risks within the maintenance tasks. The interviews involved the service providers' supervisors on site, representatives from the customer companies, and some maintenance crew members.

Table I. Customer companies' sites.

Cable factory	Oil refinery	Pulp mill
Dairy	Paper mill	Sawmill
Dressing plant (nickel)	Pipe mill	Smelting plant (copper)
Engineering works	Plastic product plant	Underground mill
Maintenance workshop	Power plant	Vegetable oil and protein feed factory

Selected maintenance works were next observed, and their risks were assessed at the customer companies. The works were selected by the supervising group, using criteria such as the frequency and perceived risk exposure of the operation. These works consisted mainly of planned preventive maintenance work, like changes of paper machine cylinders and maintenance of a cream tank in a dairy. The risks related to the observed maintenance works were assessed using a general risk analysis tool (Murtonen, 2000). The observations and risk assessments were supplemented by interviewing the maintenance crew members.

A tentative version of a content of the risk assessment method was subsequently compiled according to the information collected in the previous phases. The content was revised in the supervisory group.

The draft risk assessment method was in turn tested in the customer companies. Researchers used the method with the personnel at five customer sites, while at other customer sites, the maintenance crew used the method independently. The aim of testing was to chart the feasibility and usability of the method. The risk assessment method was consequently developed based on the experiences and feedback received from users and the supervisory group. The final version of the method was delivered to all three service providing companies with the aim to test the method in normal work situations at different customer sites.

Finally, a survey was carried out six months later to determine whether the method had been applied and adopted at the companies and sites, and to collect feedback on the utilization and usability of the method. The survey, conducted via phone interviews, involved 20 representatives: the four supervision group members, twelve representatives from the cooperating companies' 15 customer sites, and four representatives from customer companies.

RESULTS

Real accident data

During the period 1985-2004, 33 accident cases (four of which involved 2 victims) that led to fatalities in industrial maintenance were reported – a total of 37 victims. On average, the victims had 14 years of work experience. Typically, fatal workplace accidents have occurred during both planned operations and unscheduled repairs. Meanwhile, the number of accidents that have been reported during calibrations, testing and inspections was minor. During the years 1994-2004, there were 90 severe accidents in industrial maintenance involving full-time maintenance crew members.

Typical fatal accidents in industrial maintenance include crushing or being trapped by a component (27% of fatalities) or persons falling (27%) while performing a planned operation or repair (48%). Fatalities typically result from dangerous working methods (48%) and accidents are typically associated with inappropriate work instructions (40%).

A typical severe accident in industrial maintenance occurs during work at a process (60% of cases) where a machine or device is live or running (30%). The accident involves machinery (30% of cases) and inappropriate safety equipment (30%), resulting in crushing or trapping between components (39%). As a result, the accident causes injuries to upper limbs (39%) or to several body parts at the same time (28%).

Perceived and observed risks

Interviews in companies and at customer sites

The subcontracted workers of the two maintenance service providers are regularly on some certain site. However, during workload peaks, such as large-scale planned preventive maintenance on some other site, the workers may change sites to distribute the loads. Depending on the task, the machine manufacturer's service operations are carried out either at the various customer sites or back in the manufacturer's facilities.

The interviews revealed that, on most customer sites, the maintenance crew takes care of unplanned repairs and planned preventive maintenance. In addition, on about half of the customer sites, the tasks include regularly maintenance duty, i.e. there are one or two maintenance crew members on site around the clock in case of an urgent repair. In practice, this may lead to working alone which is a challenge for risk management. At about half of the sites (47%), the maintenance service provider had carried out risk assessments. However, the risk assessment results had typically not been utilized or followed up systematically. On most (53%) customer sites involved in this study, the service provider has its' own incident reporting system for the maintenance crew.

The freeform interviews in the companies and at the customer sites indicated that the typical problems are perceived to be related to:

- work planning (e.g. scheduling),

- ergonomic problems (e.g. due to poor maintainability of machinery and defects in the workplace planning),
- problems with occupational hygiene (i.e. lighting, noise, chemical/biological exposures), and
- worker's risk taking (conscious or unconscious exposure to accidents).

Some additional individual specifications on maintenance-related risks were also collected during the interviews (Table II).

Table II. Individual specifications on maintenance-related problems.

Group of problems	Specifications
Defects in customer cooperation	Flow of information between the service provider and customer; informing about unfinished tasks; instructing to common practices on site; scheduling maintenance operations (pressure of time); contents and specifications of maintenance requests
Site-specific safety challenges	Chemical risks in the process industry; hot and cold working environments; lack of maintenance workshops; working alone; hygienic requirements (especially in food industry)
Defects in working environment	Lack of space around machinery/process; poor maintainability of machinery and processes
Aging of skilled maintenance crew members	Ergonomic demands; difficulty to replace experienced crew members
Working on changing sites	Site-specific practices; injury risks on site; traffic accident risks when travelling to sites; instructing to work
Defects in safety attitudes	Non-use of personal protective equipment (PPE); risk-taking
Large variety of maintenance tasks	Vast amount of different tasks; skills and knowledge on performing the different tasks; task-specific risks and requirements

The findings can be further grouped to: 1) hazards in the working environment, 2) maintenance operations planning, and 3) crew members' safety performance. The findings highlight the importance of customer cooperation.

Risk analyses in companies and at customer sites

The risk analyses supported the results from interviews; most of the identified risks were related to ergonomic concerns. Also injury risks relating to tools, machinery and walking and working surfaces were common. Another common problem was conscious/unconscious risk-taking, which was identified in more than half of the risk assessments. Risk-taking related typically to non-use of PPE, inappropriate work methods, and defects in ergonomics, such as inappropriate working postures and risks in materials handling. Maintenance tasks practically always include disassembly and assembly, which appeared to double the number of risks.

The risk analyses included also discussions with the workers. The results supported other findings in companies, i.e. risk analyses and interviews concerning observed and perceived risks. It became clear that maintenance crew members consider time-pressure to be a serious concern.

The risk analyses and discussions indicated that the working environment is an important variable for safety management. According to the interviews and risk assessments, many maintenance tasks are performed outdoors. This creates certain seasonal risks – especially during wintertime – due to e.g. slippery walking and working surfaces. As well as the diverse nature of the tasks and working

environments, also changes in the working environment are peculiar to industrial maintenance.

Structure and contents of the risk assessment method

Requirements and basic structure

The requirements for the method were defined on the basis of the findings in the preceding phases. Thus, the method needed to be suitable for all working environments and take into account different situations, such as working during the night, working alone, and workers with foreign cultural background. The tool must support safety management, e.g. by identifying hazards in machinery, working methods, and working environment. It must also draw attention to safety measures. The tool should especially emphasize the significance of planning, including e.g. scheduling and risk assessments regarding new maintenance operations and sites. In full, the method must take into account the:

1. planning, management, and supervision of the work,
2. risks related to the working environment,
3. risks related to the maintenance tasks performed and the maintained object (including e.g. machinery, chemicals, and the handling of objects), and
4. choice of relevant safety measures.

Due to the necessity of unscheduled repairs and to the fact that some workers work alone, the risk assessment tool must also include a specific section for the worker. As the tool is designed for the independent use in companies, the two most important requirements are ease of use (usability) and feasibility.

The final method consists of three parts (Table III). Parts A and B focus on safety cooperation during the planning of maintenance operations. From the service provider's viewpoint, it is important to include safety already at the negotiation phase, where it is important for customers and services providers to show and see the relevant safety aspects that must be carried out at the different organizational levels. Thus, the inclusion of financial aspects and scheduling in the negotiations can form the framework for safety planning. The safety planning is then based on previous knowledge about the operations, the working environment, and on risk analysis. In the case of changing work tasks and changing work environments, the safety planning is especially challenging. The planning must be based on current good practices, on experiences from similar work and environment, and on new risk analysis. Part C then advises the workers to identify hazards on site before the execution of any tasks.

Table III. Contents of the method.

The guide for risk management in industrial maintenance		
Part	Contents	Used, for example
A	Safety planning	When receiving a new customer site or before planned maintenance operation; after changes on old sites
B	Hazard identification	When receiving a new customer site or before planned maintenance operation; after changes on old sites
C	Worker's checklist	On site, before performing a maintenance task

As the method must be easy to use, sufficiently broad, but at the same time exact, a checklist-based approach was deemed to be the most appropriate. In responding to the questions the user has three alternatives:

- yes,
- no, or
- the question is not relevant.

Moreover, most of the questions include specific examples. And throughout the entire method the questions are designed in the way that the user is directed to make further analysis and relevant actions for safety promotion for any questions to which they have responded "no".

The entire three-part checklist should be used when planning operations, for example, on a new customer site or when planning a major scheduled maintenance. Otherwise, the parts can be used when considered necessary, e.g. if changes occur on already familiar customer sites. Findings from real accident data, in addition to interviews and risk assessments in companies, indicated that the workers could benefit from having their own tool for independent hazard identification. Carrying out brief hazard identification on site provides immediate feedback and advice for the worker in their effort to avoid risks, for example, especially when working alone.

Planning of safety

The Part A includes 46 questions concerning work planning and supervision, scheduling, resource planning, etc. It is the broadest part of the method. The aim of Part A is to enable systematic safety planning. It also helps to ensure site-specific requirements by emphasizing customer cooperation. The questions apply to the management, supervision and performance of maintenance operations. Part A is divided into 10 subsections (Table IV).

Table IV. Part A, contents and examples.

Subsection	Sample content
Planning of work	Resources, work permits, responsibilities and obligations
Instructing to work	Work-related risks, re-instructing in case of changes in working environment
Task performance	Flow of information, supervision, safety if working alone, visibility and marking of unfinished work
Dangerous operations, such as working in container, hot work, and electrical work	Specific risks and work planning, work permits
Protective equipment and safety devices	Availability and need of PPE and machine safety devices
First aid and rescue planning	Instructing in case of emergency, first aid courses
Dangerous substances	Safe use, transport, and storage of substances
Environmental issues	Prevention of environmental hazards, environmental requirements on customer site
Moving on/between sites	Tidiness and appropriateness of walking and working surfaces, internal and external traffic on site
Ergonomic issues	Physical, psychological and social workability

Hazard identification

The second part of the method focuses on occupational hazards (Table V). The aim of the Part B is to point out dangers in the working environment and especially specific tasks. Part B contains a total of 10 questions, two of which include checklists concerning condition-based risks and accident risks. The other eight questions focus

mainly on technical issues in accident prevention, such as machine safety devices, prevention of unattended start-ups, and awareness of whether a machine is starting or running. The aim is to ensure that the energies, such as vapor, electricity and mechanical energy, are reliably released or disconnected from the object being maintained.

Table V. Part B, examples of questions and specifications.

Sample questions	Sample specifications
Are the hazards identified and removed?	Specifying checklist, e.g. slipping, tripping, falling objects, drowning or suffocation, etc.
Are the risks of the working environment considered?	Specifying checklist, e.g. lighting, vibration (hand, arm, whole body), noise, weather, etc.
Are the moving parts of machines guarded?	Entanglement, cutting, ejection of parts, splashing; checking of safeguards
Have energies been disconnected reliably?	Disconnection and removal of electricity, mechanical energy, compressed air, steam, chemicals, etc.; hydraulic appliances and loads
Can safety be ensured if safeguards must be bypassed while the process or engine is running?	Use during maintenance, testing, calibration, troubleshooting

Worker's checklist

During the study it became obvious that the workers need their own checklist for hazard identification. The aim of the list (Part C) is to enable a succinct hazard identification to be performed on site before performing the job. Thus, a small, pocket-fitting size was a specific requirement for the list, with only seven statements (Table VI). The list must obviously also be concise, and usable in all conditions. The contents of the list are chosen on the basis of the: 1) most typical, and 2) most severe risks identified in the preceding phases of the study.

Table VI. Part C, statements.

Sample statements	Sample specifications
Becoming entangled or crushed	Moving parts
Lifting and holding of heavy loads	Lifting accessories, lifting position
Slipping and tripping	General tidiness and orderliness
Falling of persons and falling objects	Fall protection equipment
Splashing and ejection of objects	Emptying pipelines and tanks, PPE
Eliminating unexpected start-ups	Isolating flowing substances and energy: chemicals, electricity, compressed air, gas, vapor, water, etc.; safety switch, personal locks
Touching objects	Dangerous parts of objects and tools

Among the statements, Part C includes two checklists for task-specific safety planning. The first list addresses the locations of safety measures in case of emergency (e.g. emergency showers and fire extinguishers), while the second list helps to chart the necessary PPE (e.g. helmet, face shield, pneumatic appliance).

The guide

A guide was designed to enable the successful, independent use of the method in companies. The guide covers the basics of risk management, including hazard identification and risk assessment according to the standard BS 8800:1996 (BS 8800:fi, 1997). The guide also refers to relevant Finnish legislation, and includes a

precompleted model page to advise about the use of the method. The method itself includes a one-page summary of the guide.

Utilization and usability of the method

After the method was created and elaborated with the supervision group, it was tested in practice. The tests indicated several minor shortcomings, such as the use of incorrect terms, a lack of examples, inappropriate layout, and problems with the order of the questions. The method was further developed on the basis of the feedback, and then reassessed in the supervision group. When deemed satisfactory, the final version of the method was delivered to the companies. The companies and customer sites' representatives were contacted six months later to determine if and how the method had been used. The uptake of use of the method in companies was deemed to be 56% of all respondents.

Parts A and B had been adopted at many customer sites (47%), although they were often considered to be too extensive. Work supervisors and planners had used Parts A and B during the planning of large-scale maintenance operations and changes in machinery. Three respondents had applied some parts of the method to other methods already in use.

Of the three parts of the method, Part C was clearly the most widely used in companies. It was utilized in all such companies which had applied the method as such (73% of all sites and companies). It was hoped that Part C could eventually be made available as an adhesive sticker, which could be attached to toolboxes, for example, to ensure constant availability on site.

In general, the method was considered to be easy to use, also without any specific training. Among the 20 respondents, seven were considering to use the method as such in the future. Six respondents were planning to use only Part C or use the method as a complementary tool in addition to the existing methods. Four of the respondents were not going to use the method as they considered their current risk assessment methods to be adequate.

DISCUSSION

This article examined risk assessment in subcontracted industrial services from the service provider's viewpoint. The focus of the research was on industrial maintenance services. The paper presented the requirements and content of the risk assessment method developed for maintenance services. The method adopted a task-based approach instead of the traditional work-place specific one. This type of risk assessment method has not before been presented for industrial maintenance.

The method was developed in cooperation with maintenance service companies, which enabled an extensive view to maintenance-related risk factors. A variety of different methods were used to study the notable factors influencing safety in service providing companies. In addition, real accident data was examined in order to research incidents and the underlying risk factors in maintenance work. With this kind of extensive approach the special features of subcontracted maintenance services were successfully included into the method. Also essential requirements of subcontracted maintenance work, like unfamiliar organizations and different working cultures, were taken into account. However, the method includes also well-known industrial risk factors, like hazards related to machinery and chemicals. The method can be applied to different maintenance services in industry, that is, after-sales services and subcontracted industrial maintenance.

The increasing trend towards subcontracting in industrial maintenance has highlighted the significance of safety cooperation between the customer and service provider. The developed method supports safety cooperation from the negotiation phase to the execution of work tasks. The developed method consists of three parts in order to cover all the critical safety factors relating to service production and subcontracting. This three-part method supports the different organizational levels in their efforts to manage, supervise and execute the operations to ensure safety. The structure is in line with the concept of total maintenance management, where the three major areas include maintenance management, maintenance operations and equipment management (Raouf and Ben-Daya 1995). With this structure for the risk assessment method, safety can be promoted also while working on, for example, customer sites and/or alone.

Traditionally, safety has not been an important subject of business negotiations. In networked business, where subcontracting is common, ensuring safety becomes more important than before – for two main reasons. Firstly, the organizations are dynamic rather than fixed. This creates good grounding for latent conditions (see: Reason, 1997) that may allow accidents to occur. In addition, active failures may be more probable than earlier because of new work tasks, new environments and different organizational cultures and practices. Secondly, safety may become an important issue in the pricing of subcontracted services. For example, maintenance may have affect the process safety and the customer is responsible for the total plant safety even if it has subcontracted the maintenance. Thus, maintenance is not only a matter of subcontracting work tasks, but a part of total safety of the plant and the related responsibilities. In those cases, the negotiations should also cover the resource allocation for plant safety responsibilities. To support such aims, the developed

method includes two parts, by which safety factors can be taken into account already in the negotiation and planning phases.

CONCLUSIONS

Due to the types and causes of risks, combined with increasing trend towards subcontracting, maintenance services require a specific risk assessment method. The tool must take into account the maintenance-specific risks, such as changing sites, working alone, and disassembly and reassembly. It must also advise in hazard identification and safe working. Furthermore, service providing companies must be encouraged to support systematic and continual risk management.

To manage maintenance-related risks effectively, there are certain factors that need to be taken into account. From the perspective of occupational risk management the boundary conditions in maintenance operations are as follows:

- 1) the task is constant, but the working environment changes (e.g. after-sales service)
- 2) the working environment is constant, but the maintained object changes (e.g. subcontracted industrial maintenance)
- 3) the task and working environment changes (e.g. temporary evening out of workloads between customer sites; after-sales service).

To ensure a comprehensive risk assessment in maintenance operations, all these conditions must be taken into account. Additionally, the risk management procedures must involve all the organizational levels in the service providing company. As many risks relate to the physical working environment, the method must take into account also safety cooperation with the customer.

In order to best involve the different organizational perspectives, the format of the risk assessment tool needs to address the work planning (management), the work supervision, and the worker. It must support the planning of safety and hazard identification to promote safety. The tool must also be feasible and usable in different conditions. In this case, a three-part checklist was found to be an appropriate format.

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ARTICLE IV

**Utilization of external accident
information in companies' safety
promotion – Case: Finnish metal and
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Utilization of external accident information in companies' safety promotion – Case: Finnish metal and transportation industry

Salla Lind^{a,*}, Jouni Kivistö-Rahnasto^b

^a *VTT Technical Research Centre of Finland, P.O. Box 1300, 33101 Tampere, Finland*

^b *Tampere University of Technology, Institute of Occupational Safety Engineering, P.O. Box 541, 33101 Tampere, Finland*

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Abstract

Safety management systems emphasize the role of accident information as a requirement for continuous improvement. However, it is not clear how such information is actually applied in companies. The present study was carried out in the Finnish metal and transportation industries to determine if and how companies utilize accident information provided in external reports. There are 40–50 fatal workplace accidents in Finland annually. These are investigated and reported with the aim of preventing the occurrence of similar accidents. Among other things, the study charted how reporting should be developed. Ten recently reported cases and a total of 38 companies were chosen for the study. Information was collected using interviews and surveys. Although accident information contained in reports was found to be mostly accurate and useful, such information is rarely applied in practice. Typically, reports are utilized only as support material in safety management; usually as case-examples in accident prevention and hazard identification. There are several explanations for this low degree of implementation, such as lack of time or the perception that the information is of limited relevance. The findings of this study show that accident reporting is a useful tool in promoting safety, though weaknesses in the flow and application of information hinder its effectiveness. Improvements in the way accidents are reported could promote more active utilization of such information in companies' safety promotion.

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Keywords: Accident reporting; External information; Safety promotion

1. Introduction

Safety management systems, such as BS 8800, emphasize the role of accident information as a requirement for continuous improvement (BS8800, 2004; ILO-OSH, 2001; OHSAS 18002:fi, 2003). Accident investigation and reporting set out to describe the sequence of events leading up to an accident. They also contain a summary of recommendations for use in accident prevention (Leveson, 2001). From the company standpoint, accident information can be divided into internal and external reporting. Internal reporting investigates

* Corresponding author. Tel.: +358 20 722 3004; fax: +358 20 722 3499.
E-mail address: salla.lind@vtt.fi (S. Lind).

accidents and near misses within the company and reports on these to prevent future re-occurrence (Baram, 1997). External accident reporting provides information describing accidents and incidents from outside organizations. An example of external accident information is the publication “Fatal Facts”, which has been published by OSHA since 1984 (US Department of Labor, 2005). “Fatal Facts” reports on representative case-examples from a variety of industries with the aim of preventing similar accidents elsewhere. In Finland, the investigation and reporting of fatal workplace accidents (IFWA) is a system for providing companies with information on workplace accident fatalities. The Federation of Accident Insurance Institutions (FAII) in cooperation with labor market organizations coordinates a group of experts that carry out the investigations. The guiding principle for reporting is to summarize the accident events objectively rather than apportioning blame (FAII, 2006).

Internal accident information provides important information for measuring the adequacy of a safety management system. A company’s internal accident information is rarely published or distributed to other companies for the purpose of accident prevention. According to Williamson et al. (1996), fatal accidents share common features across different industries. Hence, it is reasonable to suppose that applying accident information from different companies can, at best, generate almost the same benefits as investigating and learning from accidents internally. External accident reports can, therefore, be regarded as useful in preventing potentially fatal events. In general, external accident information and its utilization have not been studied widely. Other studies on the utilization of accident information focus mainly on internal accident information within a company or design process (e.g. Bruseberg et al., 2002; Dyreborg and Mikkelsen, 2003; Harms-Ringdahl, 2004; Kjellén, 2000; Rundmo and Hale, 2003). Though most companies nowadays have their own safety management systems and internal accident investigation procedures, accident information is seldom published or distributed to other companies.

In reporting accidents efficiently, the important questions are how the information should be presented, who will read the report, and how the information can be used to prevent the occurrence of similar accidents. According to Johnson (1999, 2000), the typical shortcomings of accident reports are a failure to present facts in logical order and the use of abstruse language that may confuse or mislead the reader. The challenge to assist and encourage the reader to initiate change is most evident in external accident reporting.

Despite a long history of external accident reporting, it is not clear if and how such external accident information is actually applied in companies. The present study, conducted between 2002 and 2004, set out to clarify this. The study was undertaken in two statistically high risk industries: the Finnish metal and transportation industries. Its aims were as follows: (1) to determine if and how external accident reports are utilized in companies’ safety promotion and (2) to determine how reporting should be developed and improved. The IFWA reporting represented external accident information. The study includes companies with specific fatal accident cases and a sample of other companies.

This paper introduces the study along with its major outcomes. The results summarize how external accident information is utilized and the suitability of the reporting. Ways to improve the reporting are discussed on the basis of the findings.

2. Materials and methods

2.1. Investigation of fatal workplace accidents

Workplace fatalities have been investigated and systematically reported since 1985. IFWA investigates 40–50 workplace fatalities annually. By the end of 2004 a total of 678 fatal workplace accidents have been investigated or are currently under investigation (FAII, 2004, 2006).

Between 50 000–60 000 copies of IFWA reports are distributed annually to companies’ safety delegates (FAII, 2006). Distribution of the reports is industry-based, so that each accident is reported to other companies in the same branch. The reports typically contain 4–5 A4 pages of text with black-and-white illustrations. They usually also include a figure giving a chronological summary of the events surrounding accident and the factors that caused it. Key data (e.g. profession of the victim, a brief accident description, and the industry in question) on the fatal accident are presented in a table on the front page of the report. In an IFWA report, the details of the events are described by means of text and pictures. A flow chart describing the chain of events

summarizes the information. Investigation and reporting of fatal workplace accidents (IFWA) are based on the Finnish accident investigation model. This is a standard model in which the causes and events leading to the accident are presented together in the form of flow chart. This helps in identifying measures to prevent the occurrence of similar accidents in the future (Hämäläinen, 2000). In each IFWA report the measures to be implemented are specified for each individual case.

2.2. Sample

For the study, FAII selected 5 IFWA cases from the metal industry and 5 from the transportation industry for the period 1999–2001. In selecting the cases, the main considerations were their scope for applicability in different companies and the high statistical prevalence of the accident type. One report, describing a typical accident, was chosen to represent each hazardous area of work. Table 1 presents the cases selected, their themes, and year of occurrence.

In each industry sector the companies were divided into two groups, A and B. Group A consisted of those companies having the fatal accidents in question. Each accident site was visited and interviews conducted. Sources for the required contact information were the following: (1) the official Register of Occupational Safety Personnel in the Centre for Occupational Safety in Finland, (2) labor market organizations, and (3) FAII (companies in Group A). In both groups interviews were held with safety personnel (typically the workers' safety representative) and the company's safety manager. In some cases other personnel such as production or environmental managers were present. Group B consisted of the companies from the same industry sectors as Group A. The sample, comprising 38 companies of different sizes, is presented in Table 2.

In Finland, companies operating in the transportation industry are generally small. Among the employers' association there are some 1000 member companies of which about 700 have 10 or fewer employees. There were also about 300 companies employing 50–100 persons, and 40 companies with more than 100 workers. The number of small companies is increasing (ALT, 2005). In 2005, there were 3430 companies in the metal industry having more than five employees and the entire metal industry employed 207200 persons (Technology Industries of Finland, 2006). The companies investigated here were mostly larger than average (Table 3).

2.3. Methods

The study was carried out in three stages. First, a half-structured questionnaire was developed containing 62 questions divided into five sections on the basis of the following topics:

Table 1
Themes of chosen IFWA cases and year of occurrence

Metal industry	Transportation industry
1. Lifting: use of cranes and other lifting equipment (1999)	1. Maintenance and repairs: defects in flow of information (1999)
2. Use of ladders (1999)	2. Loading/unloading: unexpected move of a vehicle (2000)
3. Working surfaces (2000)	3. Loading/unloading: falling of load (2000)
4. Shared sites (1999)	4. Loading/unloading: crushing (2001)
5. Risk-taking/risky behavior together with instructions for dangerous work (2000)	5. Maintenance and repairs: crushing (2001)

Table 2
Sample of companies

	Group A (companies with the chosen IFWA-cases)	Group B (other companies)	Total
Metal	5	15	20
Transportation	5	13	18
Total	10	28	38

Table 3
Size of companies in Groups A and B

	Metal		Transportation	
	Group A	Group B	Group A	Group B
Less than 10 employees	1	1	2	1
10–49 employees	0	1	2	5
50 employees or more	4	13	1	7

- (1) background information on the companies;
- (2) whether or not the company has received the IFWA reports in question;
- (3) measures taken on the basis of the IFWA case reports;
- (4) way in which IFWA reporting should be developed and improved;
- (5) respondents' opinions concerning the quality of reports and reporting procedures.

Second, the companies were contacted and the information collected. This was done in three ways: (1) interviews conducted during visits and (2) telephone interviews. In the transportation industry telephone interviews were supplemented with (3) mail inquiries. The latter were used when the company's representative was unavailable for a full-length telephone interview. Within all industries the questions were the same, irrespective of the way in which the data were collected.

Third, the interviews with both Groups A and B were analyzed qualitatively. The analysis focused on the distribution, availability and the utilization of the IFWA reports.

In addition, the major requirements for developing external accident reports and/or reporting procedures were analyzed and discussed. Discussion of the characteristics of effective reporting is based on the findings from the literature as well as the company interviews.

3. Results

3.1. Distribution of information to companies

A prerequisite for applying external accident information is that the relevant reports are made accessible to the target companies. In the metal industry, IFWA reports are delivered to companies on the basis of information contained in the official Register of Occupational Safety Personnel held at the Centre for Occupational Safety in Finland. Reports are sent in the name of individuals whose contact information is recorded on the Register, rather than to a company address. Thus reports can be sent to a recipient's home address. In most companies, it is the safety manager who receives the reports and, in larger companies, industrial safety representatives also receive a copy.

In the metal industry, all the companies in Group A received IFWA reports. However, this was not the case with Group B in the metal industry, where 5 companies out of 15 received no reports (Table 4). The companies were all selected from the official Register of Occupational Safety Personnel, and therefore all should have received copies of the reports. There are several explanations for this discrepancy. A company's personnel may change without this being recorded in the official Register of Occupational Safety Personnel. Alternatively, the report may have been sent to a home address and not reach the actual workplace. Addressing reports to a company or a specific job title in the company, instead of to an individual, could help improve the distribution and delivery of the reports. However, even reports addressed to a company may disappear and never get read, unless someone intentionally makes use of them. One solution to this problem would be to address the reports both to a specific job title and also a particular individual in the company.

In the transportation industry, the individual in receipt of the reports is usually the safety manager and/or the industrial safety representative. In small transportation companies, it is typically the general manager who receives the IFWA reports. Five out of 13 respondents were unable to say who in the company actually receives the IFWA report.

Table 4
Metal and transportation industry: delivery of reports to companies

		Metal		Transportation		Total
		Group A (N = 5)	Group B (N = 15)	Group A (N = 5)	Group B (N = 15)	
Reports are received in company	Yes	5	10	3	12	30
	No		4	2		6
	Not known by the respondent		1		1	2
Reports are received by	General manager	1		3	2	6
	Safety manager	4	10	1	4	19
	Industrial safety delegate	4	2	2	2	10
	Somebody else		2	1	2	5
	Not known by the respondent		1		5	6

The questionnaire indicated that recipients in Group A in the transportation industry were less likely to receive IFWA reports than those in Group A in the metal industry. Only 3 out of 5 companies in Group A in the transportation industry received reports, whereas all Group A companies in the metal industry did so. One reason for this difference may be that in the transportation industry, distribution is carried out through the employers' association. As a result, those companies without membership of the association do not receive reports, not even following a fatal accident. The results for the Group B companies seem to be the opposite of those for the Group A companies. Here the results show that almost all companies receive the reports. This is probably only to be expected as the companies were selected on the basis of the same information from the employers' association register used in mailing the reports. However, 5 respondents could not identify the person in the company who received the report. This is likely a reflection of how reports are utilized in such companies.

The delivery system could be improved by ensuring that the sending of reports includes all the companies, irrespective union affiliations. Another improvement would be addressing reports to a company rather than to an individual.

3.2. Flow of external information in companies

The received external safety information can influence safety only if companies have the appropriate procedures for communicating this information to management and workers. A typical practice in companies is that the recipient (safety manager, industrial safety delegate, etc.) browses the external report and decides independently whether it is useful to the company. The report is then either considered by the company's industrial safety commission or it is placed on a bulletin board or similar notice for the employee to read. The report may also be put to one side. A total of 21 companies out of 38 responded that external reports are considered by the recipient or by the safety commission. In 12 out of 38 companies reports were considered to serve as independent reading material (Table 5).

Table 5 shows that 30 out of 38 companies are in receipt of the external IFWA reports. In some companies the reports are offered to the employee as independent reading material in addition to being discussed by the safety commission. As a result, some companies are counted twice in the figures.

Table 5
Practices in internal delivery

	Group A (N = 10)	Group B (N = 28)	Total (N = 38)	Metal (N = 20)	Transportation (N = 18)
Recipient/occupational safety commission decides on actions	5	16	21	12	9
Reports are offered for independent reading	4	8	12	4	8

Companies that receive the external IFWA reports often lack any systematic approach in using the reports. Approximately one half of the companies take some action after receiving a report, whereas the other half makes no use of them at all. The recipient alone decides whether an external report is useful and worth forwarding to others in the organization. This could be misleading and possibly interrupt the flow of useful external information. During the study no evidence was found of companies sharing the reports in any systematic way with employees. It therefore remains uncertain if workers actually do receive this kind of external accident information.

3.3. Appropriateness of reporting

The findings of the study indicate that the external reporting system should be improved so that it reaches companies more effectively (see Table 4). Companies, themselves, should also be encouraged to apply and distribute information internally in more efficient ways. Other factors concerning the need for development in the external IFWA reporting system are presented in Table 6.

Only about one-third of the 38 companies considered the number of received report copies to be adequate. Delivering additional copies to companies was seen as a way of promoting the distribution of information internally. Thus, providing more copies to companies would be an important way to improve external reporting. The findings indicated that among most companies in Group B, the contents of the reports were considered to be good. Group A was more critical of the reports, which may be the result of investigation procedures following a fatal accident in the respondents' own company. Listing the right practices for accident prevention was regarded as important in 20 out of 38 companies. In general, the contents of reports were seen as good rather than unsatisfactory. Group A was more critical of the reports, whereas in Group B the contents of reports were found satisfactory.

3.4. Changes on the basis of the chosen external case reports

Despite the presumed wide-ranging applicability of the chosen cases, there were only a few companies that had implemented changes in their operations (e.g. in machinery or working instructions) on the basis of the selected IFWA reports (see Tables 7 and 8). This applied to Groups A and B in both industries.

In the metal industry, Group A appears more prepared to utilize IFWA reports than Group B (Table 7). It could, therefore, be assumed that the occurrence of an accident accelerates utilization of external accident information to some degree. The external accident investigation may also have made the companies better acquainted with the IFWA reporting system. It is significant that none of the cases was found irrelevant in Group A. Other measures in accident prevention were relatively more common in Group A than in Group B. This may also reflect a more active approach to accident prevention in Group A. None of the companies in Group B had taken any measures on the basis of the chosen case reports. In this group some of the cases were also considered irrelevant. This may reflect the reality that no such risk actually exists within the company or it may indicate an inability to apply the external information to one's own organization. Some

Table 6
Respondents' opinions on reports and reporting system

	Group A (N = 10)	Group B (N = 28)	Total (N = 38)	Metal (N = 20)	Transportation (N = 18)
Reports are received in the company	8	22	30	15	15
Number of received copies is appropriate	3	10	13	5	8
More copies are required	5	11 ^a	16	13 ^a	3
Right practices should be described explicitly	7	13	20	9	11
Contents are good	3	16	19	11	8
Contents should be improved	6	7	13	6	7

^a The numbers include the four companies within metal industry, which are not receiving reports.

Table 7
Metal industry: familiarity of cases and changes in companies' operations, layout and/or organization

Case	Mode of utilization	Group A (N = 5)	Group B (N = 15)	Total (N = 20)
Lifting: use of cranes and other lifting equipment	Report familiar, no changes	4	6	10
	Report familiar, changes			
	Other actions	2	3	5
	Case considered irrelevant		2	2
	Case not familiar		9	9
Use of ladders	Report familiar, no changes	2	4	6
	Report familiar, changes	2		2
	Other actions	2	3	5
	Case considered irrelevant		1	1
	Case not familiar		11	11
Working surfaces	Report familiar, no changes		1	1
	Report familiar, changes	2		2
	Other actions	2	3	5
	Case considered irrelevant			
	Case not familiar	1	14	15
Shared sites	Report familiar, no changes		2	2
	Report familiar, changes	2		2
	Other actions	2	3	5
	Case considered irrelevant		1	1
	Case not familiar	2	13	15
Risk-taking/risky behavior together with instructing to risky work	Report familiar, no changes	2	1	3
	Report familiar, changes	1		1
	Other actions	2	3	5
	Case considered irrelevant			
	Case not familiar	2	14	16

companies dealt with risk on some other basis than an IFWA report (e.g. company's own risk assessments). Typical explanations for not making changes to safety procedures were attributed to major differences in work practices or operations.

In Group A in the transportation industry, non-utilization of external accident information is partly explained by the fact that only 3 out of 5 companies actually receive reports (Table 8). None of the companies had taken any action on their own initiative to prevent risks similar to those described in the reports. However, some companies in both groups had taken action on the basis of the reports. In Group B, utilization is uncommon despite the fact that the reports are more familiar than to respondents in Group A. Underutilization of reports was often attributed to the fact that the case was considered as unlikely to happen or impossible to prevent. Typical explanations made reference to differences in the company's operations or work practices compared with those described in the case report. Differences between the goods or materials being handled was a very common explanation for not making use of the external reports (8 out of 13 companies in Group B). Another common reason for regarding case report material as inapplicable was the view that the victim alone caused or prevented the accident. Despite the reports' investigation results, the cause of the accident was often attributed to human error. A specific issue in the transportation industry is working alone, which is often associated with risky tasks such as loading wood, climbing/working on the load, and working in a cold and/or dark environment. Two of the five cases chosen for this study involved working alone. Despite the existence of relevant proposals for improvement in external accident investigation reports, companies' representatives often found it difficult in practice to promote the safety of unaccompanied drivers.

In both industries, the plethora of detailed report information confused many readers. The likelihood of encountering a similar accident was often dismissed by a mismatch in details. In general, an active approach to utilization was not typical of either industry and measures to achieve employees' safety in the workplace were often considered difficult to implement. Where external case reports were seen as irrelevant or inapplicable, the reasons given were that the victim alone was responsible for causing or preventing the accident.

Table 8

Transportation industry: familiarity of cases and changes in companies' operations, layout and/or organization

Case		Group A (N = 5)	Group B (N = 13)	Total (N = 18)
Maintenance and repairs: failure in flow of information	Report familiar, no changes		7	7
	Report familiar, changes	1	1	2
	Other actions			
	Case considered irrelevant		3	3
	Case not familiar	3	2	5
Loading/unloading: unexpected moving of a vehicle	Report familiar, no changes		5	5
	Report familiar, changes	1	2	3
	Other actions			
	Case considered irrelevant			
	Case not familiar	3	2	5
Loading/unloading: falling off load	Report familiar, no changes	1	5	6
	Report familiar, changes	1		1
	Other actions			
	Case considered irrelevant	2	7	9
	Case not familiar	1	3	4
Loading/unloading: crushing	Report familiar, no changes		6	6
	Report familiar, changes	2	1	3
	Other actions			
	Case considered irrelevant	1	4	5
	Case not familiar	1	3	4
Maintenance and repairs: crushing	Report familiar, no changes	1	5	6
	Report familiar, changes	1	1	2
	Other actions			
	Case considered irrelevant	1	4	5
	Case not familiar	2	3	5

In both industries, the utilization of reports appears to be more common in Group A suggesting that a fatal accident may accelerate utilization of reports. Observations made during the interviews support this finding. Furthermore, considering a similar accident impossible in one's own company is more prevalent in Group B. On the basis of the findings, typical of the changes implemented in companies are the improvement in work practices and the promotion of safety in routine operations. In addition, a number of companies had carried out additional risk assessments on the basis of the improvement proposals contained in reports. Nonetheless, the challenge for both industries lies in discovering ways to encourage companies to adopt more progressive thinking in promoting safe working methods on the basis of external accident information.

3.5. Individual suggestions for developing external accident reporting

During data collection, the companies' representatives were invited to express their own individual development ideas. Their ideas and suggestions for improving the IFWA reporting system were examined in terms of advantages and drawbacks. The results are presented in Tables 9 and 10.

The individual opinions underlined the need for changes in the distribution and layout of reports. One weakness seems to be the delay in publishing the report after the accident. The first information about an accident is normally carried by the media, such as the press, radio, or even TV. However, companies receive external IFWA reports several months after the accident, which is partly due to the time taken to complete the investigation. It was recommended that the safety authorities publish a brief notice as soon as possible after the occurrence of an accident. This could be a useful way to raise awareness of fatal accidents. It would also stimulate discussion and general interest in learning more about the incident. Such a measure would also assist other firms with similar hazards to take corrective measures immediately.

Some respondents suggested the use of electronic media as a way of improving distribution of the reports. In practice this means using e-mail and/or the Internet. Using electronic distribution has several advantages,

Table 9
Changes in reporting system – advantages and drawbacks

Change	Advantages	Drawbacks
Informing firms about an accident more quickly	<ul style="list-style-type: none"> – The accident may become commonly known within the same industry – Other companies with a similar risk may take steps to immediately reduce it 	<ul style="list-style-type: none"> – Reporting before investigation is finished – Who takes care of informing process?
Publishing reports electronically	<ul style="list-style-type: none"> – Accelerates and facilitates distribution (intra- and inter – firm) 	<ul style="list-style-type: none"> – Should electronic reporting be concurrent with printed copies? – (Firms' preferences should be taken into account)
Distributing all reports to firms irrespective of the industry	<ul style="list-style-type: none"> – Firms can utilize the reports of other industries – Frequent distribution may promote systematic application 	<ul style="list-style-type: none"> – The number of incoming reports may be considered too large in some firms – Firms should have the freedom to choose which reports they get
Addressing reports to a firm instead of an individual	<ul style="list-style-type: none"> – Reports are still received despite personnel turnover 	<ul style="list-style-type: none"> – The report may not be forwarded to the right person in the firm
Classifying accidents according to the type; not only according to industry	<ul style="list-style-type: none"> – Cases involving e.g. falls and forklifts would be useful in many industries – Frequent distribution may promote systematic application? 	<ul style="list-style-type: none"> – The number of reports increases – Should systems be used concurrently?

Table 10
Changes in reports – advantages and drawbacks

Change	Advantages	Drawbacks
Number and quality of pictures	<ul style="list-style-type: none"> – Readability of the report and visualization of the accident improve 	<ul style="list-style-type: none"> – Length of the report increases
Minimizing amount of detail in text	<ul style="list-style-type: none"> – Readability of text improves – Irrelevant facts are minimized 	<ul style="list-style-type: none"> – Keeping the accident description accurate enough
Listing keywords	<ul style="list-style-type: none"> – Summarizes the most relevant factors – Applicable in electronic distribution 	<ul style="list-style-type: none"> – Will it add any value if used along with the summary?
Determining responsible persons	<ul style="list-style-type: none"> – Helps firms to allocate responsibilities in accident prevention 	<ul style="list-style-type: none"> – Against FAII's guiding principle in accident reporting?
Adding an explanatory part to a chronological figure summarizing the accident with contributory factors	<ul style="list-style-type: none"> – Usability of the figure improves 	

such as making it easier to distribute the reports more widely within the firm. It also allows the quality of the reports to be improved by the addition of pictures, use of color, and other means of visual enhancement. Reductions in cost and time required for printing, sending and handling are other benefits. Most of the respondents interviewed considered the number of copies (typically two per firm) to be too small. This would support distribution of the reports by e-mail and/or Internet. However, it was seen as important to have a printed copy of the report as well as an electronically distributed one. The most important finding was that the respondents were unaware that IFWA reports are available on the Internet in PDF format. Nowadays, it is possible for companies to download the external IFWA reports electronically. Companies clearly need to be better informed on the scope for searching and downloading external accident information on the Internet.

Confining distribution of reports to the industry in which each accident occurred is not good policy. Several companies found the reports of other industries useful. For example, large companies in the metal industry with dense internal traffic would be likely to find reports from the transportation industry relevant and instructive. It would improve matters if companies could notify their interest in receiving all IFWA reports instead of only those for their own industry. Conversely, many companies also believed that the amount of mail received is already too big.

A commonly expressed recommendation was the need for more color illustrations. Most of the respondents found the amount of text (usually 4–5 pages) suitable. The interviewees also agreed that supporting textual information with pictures, figures and tables would be worthwhile improvements and support utilization by illustrating more clearly the chain of events. Some of the respondents found the chronological diagrams (flow diagram) describing the accident and its contributory factors difficult to interpret. On the other hand, the diagram was also widely regarded as being a useful summary since it provides an effective way to describe the chain of events. An explanatory text should, therefore, be added rather than removing the diagram.

A typical problem affecting utilization of external information is the reader's lack of time. Another common reason for not reading a report was the perception that it was not applicable to the firm. This may reflect a lack of interest in systematically utilizing the information provided in external reports. Overall, the respondents failed to see connections between the external accident described in the report and the internal operations of their own firm. Thus, leaving a report unread was both cause and effect.

The contents of the reports were considered essentially useful, though proposals for improvement were made. These included listing correct and good practices in the prevention of similar accidents. IFWA reports do, in fact, contain information about correct and good practices. Therefore it remains unclear whether the problem lies in the information content or in the way this is depicted and presented. Developing the abstract on the cover page of the report was seen as important because this is often the first and only part of an external report to be thoroughly read. Some interviewees believed that discussion of accident liability would also improve the reports.

In discussing the poor applicability of the reports examined, it became clear that respondents often paid too much attention to irrelevant or minor issues. Overly detailed information seemed to confuse readers. This kind of information should, therefore, be omitted and/or the relevant facts highlighted. The representatives of the companies did not always appreciate the underlying causes of the accident. Therefore, external accident reports should highlight root causes rather than apparent or peripheral causes.

4. Discussion

4.1. Flow of external accident information in companies

This case study indicated that there can be some essential weaknesses in the flow of external information in companies, such as the absence or shortage of reports in some companies and the delay in report publication. In the case of IFWA reporting system, the main reasons for the lack of reports in companies are inaccuracies in the address register and an industry-based distribution process, which in some cases is too limited. One important finding is that in many companies, reports are not forwarded to employees. In such cases, workers may never receive or be able to implement important safety information.

In many companies, only one individual, such as the safety manager, will receive a copy of the report; he or she alone will often decide on its relevance to the company. In such a situation, the recipient's attitude to safety promotion, including the utilization of accident information, has a significant bearing on the speed of information dispersal. There is less risk of applicable information being ignored in those companies where the external reports are routinely handled by an occupational safety committee.

Many companies provide the reports as voluntary reading for their employees. Ajzen (1991) suggests that actual behavior can be predicted when intentions to behave in a certain way are combined with perceived control over the behavior. External safety information should, therefore, impact both on the workers' intentions to adopt the new, safer working methods as well as on the organizational support that makes this possible through motivating workers to behave in the new safer way. Application of the external safety information should be carefully coordinated and not simply depend on the uncertain outcomes of voluntary reading.

Theories of organizational behavior, group learning and shared mental models (see e.g. Kim, 1997) all emphasize that unique information (i.e. information adopted by an individual) may impact on the knowledge of the group. This means that information adopted by one employee could have a favourable influence on the safety performance of others. In practice, however, this seems improbable since the idea of group learning is based on group discussion and problem solving. It is, therefore, unlikely that the mere distribution of IFWA reports would improve safety performance through group learning.

4.2. Utilization of reports in companies

On the basis of the sample, it appears that active utilization of external reports is quite rare in companies. One explanation is that this reflects the actual situation in companies, that reports – irrespective of their possible applicability – are neglected in safety promotion. Another interpretation is that the cases, chosen on the basis of their statistical significance and presumed wide applicability in companies, were actually less representative than originally believed. However, several companies do utilize external reports, at least occasionally. Fatalities at work share similarities across different industries (Williamson et al., 1996). This supports the whole notion of accident reporting and justifies its dispersal across industry sector boundaries.

The occurrence of a fatal accident (Group A) appears to promote the utilization of reports. There may be several reasons for this. For example, the accident may have made the prospect of another fatal accident more real. Additionally, the external accident investigation procedure would have at least introduced the reporting system to companies. Typical ways of utilization emphasized safety in routine operations as well as implementing changes in working procedures. In developing and improving reporting, one challenge is to encourage other companies to utilize reports in a proactive way.

Comparison of utilization between industries is difficult because of differences in companies' operations, the accident cases selected, and the delivery of reports. However, there were similarities in problems of utilization. Many respondents found it difficult to apply information to their own operations if there were even minor discrepancies between the information in the reports and in the company's operations. It would, therefore, be beneficial to highlight the real causes of an accident while limiting the amount of confusing detail.

Within the metal industry the difference in the utilization of reports between Groups A and B was clear. A comparison can be made because of equal coverage of reporting in both groups. In the metal industry it can be seen how the occurrence of an accident affects the way in which the provided external information is utilized. Due to differences in delivery within the transportation industry, a similar estimation in utilization cannot be made between Groups A and B. Moreover, in the transportation industry some companies outsource maintenance and repair services. Thus the results concerning cases 1 and 5 in the transportation industry are not entirely comparable to the results of the other cases.

4.3. Improving external accident reporting

The causes and remedies for the underutilization of reports can be divided to (1) the way information is used in companies and (2) the characteristics of reports. It emerged that the main reasons for the non-utilization of external accident information in companies are as follows:

- absence of any systematic practices (such as scheduling) for reading and applying external information;
- inability of identifying the relevant facts to be applied within one's own company;
- the believe that the victim's performance is the only cause of the accident;
- awareness raised by accidents in external companies is only short-lived;
- a plethora of detail undermines readability of reports.

Thus, there are weaknesses both in the reports themselves and in the willingness to utilize the external information. Findings and feedback from the interviews indicate that certain changes could improve the applicability of reporting. Delivery should be enlarged to cover all companies. Distribution channels should be standardized across different industry sectors to ensure that receiving IFWA reports is not dependent on particular affiliations, such as membership of an employer association. Addressing reports to a specific position in a company, instead of an individual, would be an improvement.

Respondents in some companies noted a need for more copies of reports to facilitate delivery within the company. Conversely, many companies also considered the amount of mail received as already too big. Such an explanation, however, may be only an excuse. Among other suggestions was the view that electronic distribution could be a useful option for many companies. This offers several advantages, such as easier delivery intra- and inter-firm and also the chance to include more color illustrations. It was surprising to learn that many companies were unaware that IFWA reports are available on the Internet in PDF-format. Therefore,

it might be worth giving more publicity to such Internet sources to encourage companies to make and circulate copies, or send PDF-documents or web-links. However, electronic distribution may not be suitable for all companies. Before making any changes in distribution, it is important to study carefully the best format and channel for each company.

Emphasizing the role of safety management would be important in helping companies to apply information effectively. For example, discussion of liability and responsibility for accidents and incidents was referred to frequently throughout the interviews. Some of the respondents believed that allocating responsibility would assist in accident prevention. This might have a positive effect on the beliefs and attitudes (see Ajzen, 1991) of both workers and managers in terms of their safety responsibilities and safety behavior. However, such a practice would conflict with the FAII principle of not apportioning liability for accidents.

To promote the application of information in companies, recipients should be encouraged to distribute and utilize information proactively. In addition, recipients would need practical advice on accomplishing changes in working methods. This could be supported, for example, by improving the contents and layout of reports in order to make them more user-friendly. Suggestions by interviewees underline this need. Several factors affect the readability of reports and, thus, the information obtained from them. Avoidance of too much detail is supported by Johnson's (1999) findings. The challenge lies in discovering how to place the appropriate emphasis on the most important facts.

Part of the difficulty in understanding the reports may be explained in terms of the theory of premature cognitive commitment. Here the individual makes an early decision as to the futility of the provided information before examining it in any depth (see e.g. Kim, 1997). In this situation the reader may, for example, be misled by excessive detail into interpreting the external information as inapplicable. Reports should, therefore, be made more persuasive in order to "market" the information to the reader (see e.g. Stubblefield, 1997; Pierro et al., 2005). In practice, persuasive communication aims at changing the receiver's beliefs, attitudes, and behavior. It is employed to great effect in areas such as marketing and health promotion. Persuasive communication is based on the questions "Who says what to whom with what effect?" (Stubblefield, 1997). These questions should also be considered during the writing process of IFWA reports. Since the reports are sent to companies with the aim of preventing accidents, the contents should also be tailored to this end.

Nowadays the contents of reports are highly technical and contain a wealth of detailed investigative results. Though this kind of information may be valuable to certain readers, such as safety authorities and safety managers in companies, other readers may find it complex and of little help. In order to reach a wider readership, two types of report could be published: one for employees and another for the authorities and safety experts. The employees' report should be brief, persuasive, and published soon after the fatal accident. The other report could focus in more detail on an analysis of the events.

5. Conclusions

The case analysis of utilization of external accident information in Finnish metal and transportation companies' safety promotion revealed three main lessons that should be considered when devising accident information systems. First, not all companies receive the relevant IFWA reports; the main reason being that companies were not members of a particular employer association. Industry-based distribution is often too narrow since many companies have, for example, auxiliary operations in different industrial sectors. To improve the reporting system, it is important that records are kept up to date and distribution is wide enough to include to all companies concerned. It would also be advisable to address the reports to a specific individual as well as to a specific position within a company. The IFWA reports are also available in the Internet. Companies should, therefore, be informed of the existence of the relevant Web pages and encouraged to use such resources.

Second, companies receiving reports applied external accident information in various ways. Within companies, the flow and utilization of information is determined by the report recipient and the company's own practices which may affect the pace at which information is applied. It would therefore be beneficial if the IFWA reports were to receive regular examination by the company's safety commission. The organization should provide the new information as well as the organizational support to implement recommendations for new working methods.

Third, in the companies investigated here, the selected IFWA case reports were seldom utilized. IFWA reports in general, including the selected case reports here, are employed mainly as supportive material in safety promotion. They are also used to promote safety in everyday operations as well making working procedures safer. The occurrence of a fatal accident appeared to accelerate the utilization of the reports. In general, companies found external accident information useful. However, readers often had difficulty identifying the essential points if there were discrepancies in the details between an IFWA report and their own working environment. The publication of two kinds of information is therefore recommended: a detailed technical accident investigation and a persuasively written educational safety letter for safety promotion.

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Title Accident sources in industrial maintenance operations Proposals for identification, modelling and management of accident risks		
Abstract <p>Industrial maintenance operations include a variety of risks, which should be identified and managed systematically. This thesis bases on a set of studies, which explored the safety risks in maintenance operations together with types and causes of maintenance accidents. In addition, studies were carried out to explore identification and modelling of the accident risks. As a result, the thesis gives proposals for identification, modelling and management of the accident risks in companies. The focus is on the maintenance worker's viewpoint.</p> <p>The results can be applied in machine and system design, as well as in maintenance task planning and supervision. The results can be also utilized in companies to manage and design maintenance safety.</p>		
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