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FINDING METHODS FOR RECOGNIZING AND CLASSIFYING SPARE PART CRITICALITY – CASE FULL DEPOSIT STRIPPING MACHINES

Examiners: Docent Harri Eskelinen
Professor Juha Varis

ABSTRACT

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Finding Methods for Recognizing and Classifying Spare Part Criticality – Case Full Deposit Stripping Machines

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86 pages, 16 figures, 8 tables and 4 appendices

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Keywords: spare part, criticality analysis, multi-criteria classification,
full deposit stripping machines, original equipment manufacturer

The aim of this Master's thesis is to find a method for classifying spare part criticality in the case company. Several approaches exist for criticality classification of spare parts. The practical problem in this thesis is the lack of a generic analysis method for classifying spare parts of proprietary equipment of the case company. In order to find a classification method, a literature review of various analysis methods is required. The requirements of the case company also have to be recognized. This is achieved by consulting professionals in the company.

The literature review states that the analytic hierarchy process (AHP) combined with decision tree models is a common method for classifying spare parts in academic literature. Most of the literature discusses spare part criticality in stock holding perspective. This is relevant perspective also for a customer orientated original equipment manufacturer (OEM), as the case company.

A decision tree model is developed for classifying spare parts. The decision tree classifies spare parts into five criticality classes according to five criteria. The criteria are: safety risk, availability risk, functional criticality, predictability of failure and probability of failure. The criticality classes describe the level of criticality from non-critical to highly critical. The method is verified for classifying spare parts of a full deposit stripping machine. The classification can be utilized as a generic model for recognizing critical spare parts of other similar equipment, according to which spare part recommendations can be created.

Purchase price of an item and equipment criticality were found to have no effect on spare part criticality in this context. Decision tree is recognized as the most suitable method for classifying spare part criticality in the company.

TIIVISTELMÄ

Lappeenrannan Teknillinen Yliopisto
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Simo Myrttinen

Kriittisten Varaosien Tunnistamiseen ja Luokittelemiseen Soveltuvan Menetelmän Valinta – Case Kestokatodin Strippauskoneet

Diplomityö

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Tämän diplomityön tavoitteena on kehittää menetelmä varaosakriittisyyden luokittelemiseen kohdeyrityksessä. Laitteen kannalta kriittisiä varaosia on mahdollista tunnistaa monella lähestymistavalla. Käytännön ongelmana tässä työssä on yleisen analyysimenetelmän puuttuminen kohdeyrityksen yksinoikeudella valmistamien laitteiden kriittisten varaosien tunnistamiseen. Yleisen analyysimenetelmän löytämiseksi suoritetaan kirjallisuustutkimus käytettävissä olevien analyysimenetelmien selvittämiseksi. Kohdeyrityksen asettamat vaatimukset kriittisyysanalyysille selvitetään haastattelemalla laiteasiantuntijoita yrityksessä.

Kirjallisuuskatsauksen mukaan analyyttinen hierarkiaprosessi (AHP) yhdistettynä erilaisiin päätöspuumalleihin on yleinen analyysimenetelmä. Useimmissa kirjallisuuslähteissä käsitellään kriittisyyttä laitteen omistajan näkökulmasta. Tämä on myös oikea näkökulma asiakaslähtöiselle alkuperäiselle laitevalmistajalle (OEM), kuten kohdeyritykselle.

Varaosien luokittelemiseen kehitettiin päätöspuulogiikkaan perustuva luokittelumenetelmä. Varaosat luokitellaan viiteen kriittisyysluokkaan käyttämällä viittä kriteeriä. Kriteerit ovat varaosan: turvallisuusriski, saatavuusriski, toiminnallinen kriittisyys, vikaantumisen ennakoitavuus ja vikaantumistodennäköisyys. Menetelmää testattiin kestokatodin strippauskoneen varaosien kriittisyysluokitteluun. Laitteen varaosien kriittisyysluokitusta voidaan käyttää yleisenä mallina tehtäessä varaosasuosituksia muihinkin vastaaviin laitteisiin.

Varaosan hinnalla ja laitekriittisyydellä ei havaittu olevan vaikutusta varaosakriittisyyteen tässä asiayhteydessä. Päätöspuumalli on kohdeyrityksen tarpeisiin parhaiten soveltuva kriittisyysanalyysimenetelmä.

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Simo Myrttinen

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TABLE OF CONTENTS

ABBREVATIONS AND SYMBOLS

AHP	Analytic Hierarchy Process
ER	Electrorefining
EW	Electrowinning
ETA	Event Tree Analysis
FDSM	Full Deposit Stripping Machine
FDRSM	Full Deposit Robotic Stripping Machine
FSI	Functionally Significant Item
FSN	Fast moving, slow moving, non-moving
FTA	Fault Tree Analysis
HAZOP	Hazardous Operability Studies
O&M	Operation & Maintenance
OEM	Original Equipment Manufacturer
RCM	Reliability Centered Maintenance
FMEA	Fault Mode and Effects Analysis
FMECA	Fault Mode, Effects and Criticality Analysis
PDM	Product Data Management
VED	Vital, Essential and Desirable

K	Criticality index
K_s	Criticality sub-index for safety
K_e	Criticality sub-index for environment
K_p	Criticality sub-index for production
K_q	Criticality sub-index for quality
K_r	Criticality sub-index for repair
M_s	Multiplier for safety
M_e	Multiplier for environment
M_p	Multiplier for production
M_q	Multiplier for quality
M_r	Multiplier for repair
p	Time between failures

P_1	Production unit
P_2	Production line
P_3	Process
P_4	Sub process
W_s	Weighting factor for safety
W_e	Weighting factor for environment
W_p	Weighting factor for production
W_q	Weighting factor for quality
W_r	Weighting factor for repair

1 INTRODUCTION

The aim of this thesis is to compare relevant approaches for spare part criticality analysis and create a generic method for analyzing spare part criticality at Outotec. The method will be verified for the case example and as a result generic spare part recommendations are created for this type of equipment. Applicability of the method for other proprietary equipment of Outotec will also be evaluated.

Multiple approaches are available for recognizing and classifying critical spare parts. The starting point can be ensuring process reliability, reliability of each mechanical part and continuity of production or cost optimization. In this thesis the method is focused on criticality classification of spare parts in order to understand the impact of part failure to equipment availability.

Even though criticality classification has been utilized in different fields of industry, the practical problem is the lack of a generic method for spare part criticality analysis at Outotec. As a result, no generic recommendations are available which leads to a situation that spare parts sold by Outotec need to be considered case by case.

The main research question is, what relevant criticality analysis methods are available and which is suitable for Outotec and why? Another question concerns the criticality classes of spare parts of Outotec proprietary equipment. Under which conditions, can this classification method be used for other equipment than those of the case example, will also be evaluated.

Technology discussed in this thesis is limited to electrolysis technology. Limitation is performed due to great number of technologies Outotec offers. Logistic aspects of spare part criticality are mostly limited to lead times. Even though warehousing influences greatly on availability and thus on item criticality. Equipment criticality is discussed only when it is relevant for analyzing spare parts. The focus of this thesis is not in identifying critical equipment for a process or a plant. However, the analysis methods can be similar.

2 RESEARCH METHODS

The research methods in this thesis consist of a literature review, interviews within the case company, evaluation of the results and a case study. Relevant research literature is utilized for establishing a state-of-the-art view of criticality classification of spare parts. Within the literature, basics of criticality analysis are revealed and relevant analysis methods presented. Alongside the literature review, various stakeholders requiring the analysis method are interviewed in order to establish requirements for the analysis. Various methods from literature are presented in these meetings and interviews. Feedback from the company lays the basis for choosing the method. The evaluation of results is conducted by applying evaluation criteria presented originally by Scott D. Sink. This widely recognized method for evaluation of a measurement is utilized for receiving an analytic view of the analysis method developed as a result of this thesis. The case study is described in section nine.

Research articles, mainly from Scopus, are utilized for gathering relevant literature references for this thesis. An article is considered relevant when it is published well after the millennium, it is a peer reviewed research article and has been cited by multiple researchers. The aim is to discover research articles presenting various criticality classification methods. Criticality criteria, classes and analysis methods from relevant articles are presented. Articles regarding criticality analysis in heavy equipment applications are referred to when found relevant.

The literature review aims to find methods for recognizing critical components within equipment. Stocking strategies are discussed merely as a result of functional criticality. Even though stocking has an essential role in lead time of critical parts, thus, affecting an important criticality criterion. Stocking is, however, an entirely different matter and requires a study of its own. Nevertheless, articles regarding different stocking options and logistic aspects are referred to for gathering required research results. On many occasions the analysis methods are similar.

The literature provided by the case company is mostly confidential. In order to provide a state-of-the-art view about the case example and background regarding it, some confidential material is required. Academic literature related to these subjects is also referred to when necessary. Several professionals within the company are also involved in this thesis by providing the company perspective in addition to literature results. Some of which are also providing their feedback for developing the criticality analysis method.

2.1 Evaluation Method for the Developed Criticality Analysis Method

How to evaluate a newly developed evaluation method is discussed in this section. The concept of measurement for measuring productivity was presented by Scott, D. Sink in 1985. Nine evaluation criteria intended for measuring any productivity evaluation measurement were presented. The nine criteria are also found suitable for evaluating a classification method developed for the case company. Before presenting the criteria, basics of collecting data and scaling are introduced.

Collecting data is an essential part of measuring a phenomenon. Three basic ways for data collecting exist. They are: inquiry, observation and collecting system data or documentation. Each data collecting system belongs to one of these categories. For managing collected data categorization is required. Data can be categorized by either existing scale or creating a new one. Measurement requires using one of the following scales: nominal, ordinal, interval or ratio. (Sink, 1985, pp. 65–66.)

Evaluation criteria of a newly developed evaluation method are the main subject of this section. The criteria are first presented as a list and then explained more in detail. The following nine criteria for evaluating measure or measurement system are applied in this thesis:

1. Validity
2. Accuracy and precision
3. Completeness or collective exhaustiveness
4. Uniqueness or mutual exclusiveness
5. Reliability
6. Comprehensibility
7. Quantifiability
8. Controllability
9. Cost effectiveness

(Sink, 1985, pp. 68–69.)

Validity aims to answer if the right phenomenon is actually being measured. A chance is that the measurement is not measuring what it is considered to measure. Accuracy and precision focuses to determine how accurately and precisely the phenomenon is measured. True state of the phenomenon should be measured accurately and precisely. The ability to measure statistical characteristics of the behavior accurately is evaluated. The third criterion concerns if the total set of variables is sufficient for measuring the phenomenon and is the measurement exhaustive enough. Uniqueness or mutual exclusiveness stands for, that specific measures should be unique in the measurement system. No redundancies nor overlapping measures should exist in the system. Each property of a given phenomenon should have one proper measure. The fifth criterion evaluates reliability of the measurement process. Each measurement should consistently provide valid results and errors should be consistent or minimal. (Sink, 1985, pp. 68–69.)

A measurement system should be simple and understandable, yet conveying the meaning intended to. For evaluating comprehensibility, comprehension of the person conducting the measurement is relevant. Not all persons intended to use the measurement system are equally competent, therefore, the measures are affected by competence of the intended user. Quantifying provides the maximum amount of information, in other words, measures should be quantified. By quantifying measures their behavior can be more easily understood. However, qualitative measures are not less important, they are rather a way to supplement and provide robustness to the qualitative ones. This way providing also meaningfulness to the quantitative criteria. The idea of controllability is to measure variables that can be controlled. This is important for measuring productivity where actions are required after measurement. Thus, measurement variables or criteria that are unable to control, are less attractive. The last criterion focuses on if the measurement is actually worthwhile of conducting. Labor consumption due to the measurement should not be intolerable compared to the results achieved by the measurement. (Sink, 1985, pp. 68–69.)

3 BACKGROUND

Literature part of this thesis consists of sections: three to seven. Sections four and five provide basic theory according to which various criticality analysis methods are presented in section seven. Section six presents the role of risk analysis in criticality classification and various methods for conducting the analysis. Section seven presents criticality analysis methods discovered as a result of the literature review. In section eight a criticality analysis method developed for the case company is introduced, as well as, the recognized criticality classes and the evaluation of the method. In chapter nine the developed method is verified for the case example and spare part recommendations are created accordingly.

This section begins with a brief introduction to Outotec as a company and to its technologies. The case example is full deposit stripping machines which are used in the last stages of copper production chain. Basic introduction to copper applications and markets are also covered. After which metallurgical techniques for extraction of copper are presented. The focus is in copper electrolysis and the equipment in order to understand copper production chain and the role of the case example in an industrial scale electrolysis.

3.1 About the Case Company

Outotec is a Finnish worldwide operating technology company. It is a leading provider of process, technology and service solutions for mining and metal industry. The company has wide expertise and over a long time accumulated experience in providing concentrating plants and metallurgic plants, equipment and services based on their own technologies. Outotec operates in a close co-operation with its customers in order to supply them with environmentally friendly and energy efficient solutions. The company had a turnover of 1 402, 6 million euro in 2014 and employed 4 571 persons in 27 countries. The company shares are listed in Nasdaq Helsinki since 2006. Earlier Outotec was a part of Outokumpu Oyj. (Outotec, 2015, p. 21.)

Outotec offers leading technology solutions in two business areas: minerals processing, and metals, energy and water. The business areas are briefly presented in table 1. (Outotec, 2012.)

Table 1. Business areas of the case company (Outotec, 2012).

MINERALS PROCESSING	METALS, ENERGY AND WATER
Comminution	Non-ferrous metals
Concentration	Ferrous metals and ferroalloys
Dewatering	Light metals, fluidized bed applications
Process automation and analyzers	Aluminum smelting and casting
Tailings treatment/ paste backfilling	Sulfuric acid plants
Services	Energy production
	Industrial water treatment
	Services

3.2 Copper Applications and Markets

Copper is known for its good electrical conductivity, heat conductivity and corrosion resistance. Good electric conductivity is due to small electrical resistance. For this reason copper is utilized in most electric applications, e.g. in electric wires and coils. The main applications of copper are electrical applications. Roughly half of mined copper is used for electrical wire and cable. Copper consumption in electronic devices is relatively small when measured in tonnage consumed. The significance is, however, great due to ever increasing need for electronic devices. (Davis, 2001, pp. 153–159.)

Other significant industrial applications for copper in addition to the previously mentioned are heat exchangers, condensers and plumbing goods. Corrosion resistance and heat conductivity are the main features in these applications. (Davis, 2001, pp. 161–162.)

London metal exchange, later referred as LME, is the leading forum for determination of prices for non-ferrous metals. Aluminum and copper being the most important metals according to volume. Metals are traded in LME as spot and future delivery contracts. The future contracts are for 25 tons batch of grade A copper and deliveries vary from three to 27 months to locations in Europe and USA. The most heavily traded futures are for three month deliveries. Another significant market place for copper is Shanghai Futures Exchange. (Goss & Avsar, 2013, pp. 79–80.)

3.3 Metallurgical Techniques for Extraction of Copper

Metallurgical process is a process to liberate metals and remove impurities. Valuable metals are extracted from complex ores, e.g. copper sulfides and zinc sulfides contain impurities such as iron. Mechanical separation of these metals is not possible, therefore, chemical separation is required. (Outotec, 2012a, pp. 2–6.) Copper ore contains typically from 0, 5 to 1 or 2 % copper. Pure copper is produced from these ores by pyrometallurgical process. Another way to produce copper is hydrometallurgical process that utilizes oxidized minerals containing smaller concentration of copper. Third way to produce copper is by recycling used objects. (Schlesinger et al., 2011, p. 1.) Hydrometallurgical and pyro metallurgical process technologies for copper extraction are briefly introduced next.

3.3.1 Pyrometallurgical Extraction

About 80 % of annual copper extraction in the world is produced by pyrometallurgical process. Ores containing copper, iron and sulphur are not easily dissolved by aqueous solutions, thus, requiring pyrometallurgical extraction. Prior to this process copper mineral particles are isolated to a concentrate by froth flotation, resulting a 30 % copper concentrate. The copper ores being mined nowadays are too lean in copper and have to be concentrated prior to smelting. (Schlesinger et al., 2011, pp. 2–4.)

Pyrometallurgical process for copper extraction consists of flash smelting and flash converting stages prior to fire refining and anode casting. In flash smelting stage fine concentrate particles are ignited by oxygen in order to form a molten matte and slag of the burned concentrate. The purpose of converting is to refine the smelted matte to blister copper (Outotec, 2012c, p. 2). The blister copper contains Sulphur and other harmful impurities after smelting and converting. Fire refining consists of two stages: oxidation and reduction. In the oxidation stage most of the harmful sulphur is removed. In reduction stage oxygen level of the metal is adjusted to appropriate level for anode casting. In the last stage molten metal is casted in anode shape for electrorefining (ER). (Outotec, 2013, pp. 2–14.)

3.3.2 Hydrometallurgical Extraction

Hydrometallurgical process is a process for separating valuable metals from minerals by chemical reactions in solutions. Metals are separated through series of aqueous reactions. Typically hydrometallurgical process starts by leaching mineral concentrate after which the leached solution is separated and purified from by-products and impurities. Then metals are recovered from purified solution and the outcome is pure metal product such as 99,99 % pure cathode copper. (Outotec, 2012a, pp. 2–6.)

About 20 % of annual copper extraction in the world is produced by hydrometallurgical process. Hydrometallurgical extraction of copper consists roughly of three stages: leaching, solvent extraction and electrowinning (EW). In the first stage broken or crushed copper ore is leached by sulphuric acid in order to produce impure aqueous solution containing copper. In the second stage the impure solution is transferred to pure high copper electrolyte by solvent extraction. In the third stage pure copper is electroplated on cathode plates from the pure electrolyte. This stage is later called electrowinning. (Schlesinger et al., 2011, p. 8.)

The leaching stage is conducted by dripping sulphuric acid on top of ore heaps. The acid is allowed to trickle through broken or crushed ore to collection ponds. The leaching stage requires several months in order to efficiently extract copper from ores. Leaching can also be conducted in less than 24 hours by using reactors intended for this purpose (Outotec, 2012a, 8). The leached solution is still too dilute in copper for electrowinning. Thus, copper is transferred from the leached solution in solvent extraction stage. First copper is extracted from the impure leach solution into copper specific liquid organic extractant. In the second stage copper loaded extractant is separated from copper depleted leach solution. Then copper is stripped from loaded extractant into an electrolyte. After this stage copper concentration in the electrolyte is suitable for electrowinning. (Schlesinger et al., 2011, pp. 8–9.)

Copper is nowadays produced all around the world. Most of the ore, about 40 percent of it, is mined in South America. Concentrators, leach- and solvent extraction, and electrowinning plants usually locate near the mines due to low concentration of copper in the ore. Whereas, smelters and refineries are often in coastal areas. Which makes it possible for them to receive concentrates or copper anodes worldwide. (Schlesinger et al., 2011, p. 29.)

3.4 Tankhouse Solutions

The last stage in production of pure non-ferrous metals is electrolysis which is called in industrial scale a tankhouse (Outotec, 2013, p. 17). The purpose of electrolysis is to make non spontaneous redox reactions occur. Energy is provided into the electrolytic cell in form of electricity from an external source. Electricity is passed through an electrolyte, which is an electricity conducting medium. Direct current dissolves metal from the electrolyte or anode plate and precipitates it into cathode plates. (Neuss, 2001, p. 58.) Two options are available for electrolysis: electrorefining and electrowinning (Outotec, 2013, p. 17).

In electrorefining, later referred as ER, the anode is a casted impure unrefined metal plate which is corroding into the acid electrolyte. Pure metal precipitates from the anodes on the cathode plates. The anodes are casted as a final stage of pyro metallurgical process described earlier in this section. (Outotec, 2013, pp. 17–22.)

Electrowinning process, later referred as EW, takes place in a hydrometallurgical plant. Before EW the incoming pregnant leach solution is concentrated and purified in order to result a pure electrolyte. The refined metal is in an aqueous solution called purified electrolyte. Electric current in the electrolytic cell precipitates metal from the electrolyte on the cathode plates. In the meantime oxygen or chlorine gas, depending on whether the process is sulfate or chloride process, is formed on the inert permanent anode plates. The key difference between ER and EW processes is the use of inert permanent anodes in EW and casted copper anodes in ER. Figure 1 presents the copper production chain from ore to cathode copper in an electrowinning plant. (Outotec, 2013, pp. 21–22.)

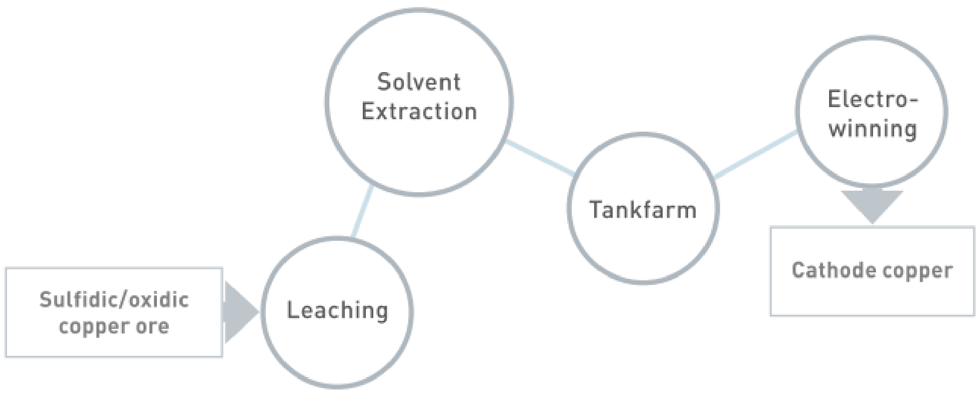

Figure 1. Copper production chain in an electrowinning (EW) plant (Outotec, 2011, p. 3).

3.5 Tankhouse Equipment

The main Outotec proprietary equipment included in a tankhouse are: permanent cathodes, cell-top busbars and insulators, full deposit stripping machines, anode handling machines in case of ER-plants, tankhouse cranes and acid mist capture systems. Anode handling machines are: anode preparation machine and anode scrap washing machine. Tankhouse machinery is briefly introduced next. The main focus is in full deposit stripping machine. Figures 2 and 3 present materials flow and key proprietary equipment in ER and EW plants.

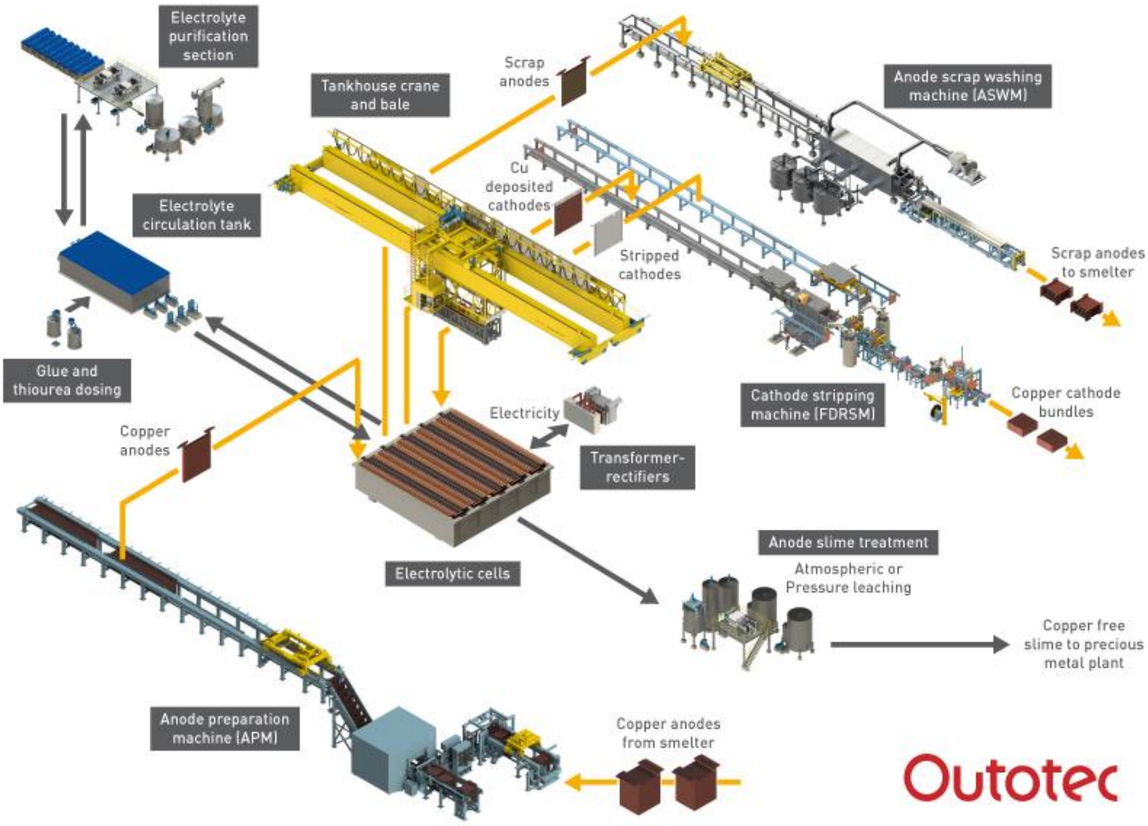

Figure 2. Key proprietary equipment of an electrorefining (ER) plant. A full deposit robotic stripping machine (FDRSM) can be seen on the right side of the figure. (Outotec, 2012d)

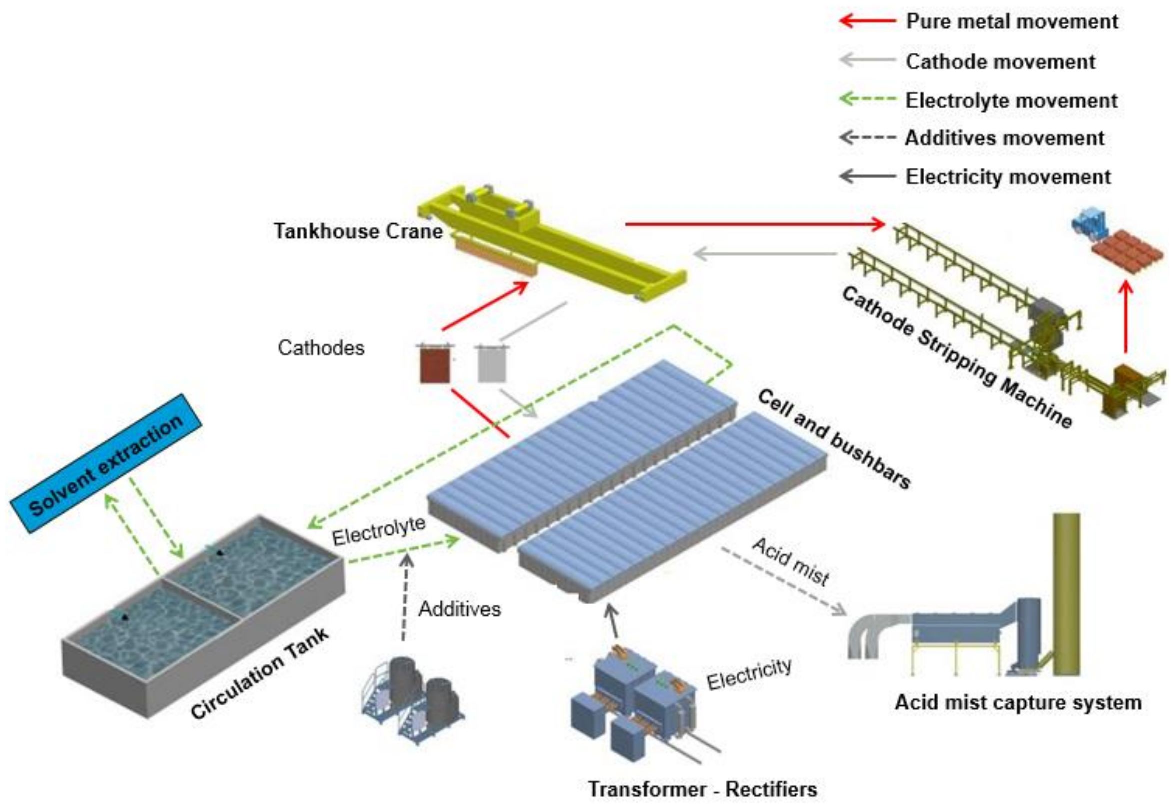

Figure 3. Key proprietary equipment of an electrowinning (EW) plant. A full deposit stripping machine can be seen in the upper right corner. (Modified from Outotec, 2013c, p. 29.)

Permanent cathodes have an important role in electrolysis since the purified metal, e g, zinc or copper, is deposited on them. The cathodes are about 1 m^2 in deposition area per side and they are made of stainless steel. An electrolysis plant requires from 5000 to 100 000 cathodes. The double contact busbar system provides even current distribution for the electrodes in the electrolysis cells which leads to even weight distribution in the produced copper cathodes. Full deposit stripping machine is intended for removing deposited metal from the cathode blanks. (Outotec, 2012b, p. 12.)

Anode preparation machine is an important part of an ER plant since it mills and presses the casted anodes in correct shape. Especially lug contact surfaces are required to be in tolerance in order to provide good conductivity and vertical hanging of the anodes. After the preparation the anodes are similar in shape and spaced correctly for tankhouse crane to collect them for the electrolysis. Anode scrap washing machine is required for washing the used anodes after the electrolysis. Slime on the surface of the anodes is, thus, removed before recycling. (Outotec, 2013c, pp. 97; 116.)

Tankhouse crane is intended for loading and unloading of the electrodes. It transfers the harvested cathodes to stripping machine and after stripping transfers cathodes back to the electrolytic cells. It also loads copper anodes to electrolytic cells and removes scrap anodes to anode scrap washing machine. This is presented more thoroughly in figures 2 and 3. Acid mist capture system is required for removing harmful gases, e.g. sulphuric acid, from the air to improve occupational health and safety. The electrolysis cells are covered with cell hoods in order to capture and recycle sulphuric acid and copper sulphate gases. (Outotec, 2012b, pp. 14; 19.)

3.6 Full Deposit Stripping Machine

Full deposit stripping machine is intended for removing pure metal blanks from cathode surfaces. After stripping the permanent cathodes are sent back to the electrolysis. Stripped metal blanks are stacked in 2 – 4 ton bundles after which they are ready for processing into various copper products, e.g. electric wire. The machines feature either linear- or robotic stripping. In a robotic machine, stripping is performed by robots. Figures 3 and 4 feature a traditional linear stripping machine (FDSM) and figure 2 a robotic stripping machine (FDRSM). Cathode stripping consists of two parts: first pre-opening knives penetrate between metal and cathode after which separating unit separate metal deposit blanks from the cathode. Figure 4 presents deposit detachment unit of the machine. The stainless steel cathode is in the middle and the stripped copper can be seen in red. (Outotec, 2013c, pp. 28; 57–67.)

Stripping machines produce either one deposited plate on each side of the cathode or a so called taco cathode in which copper is deposited round the cathode. This way the deposits are connected to each other in the bottom. Edge strips in the cathodes prevent copper from depositing on the edges of the plates (Nordlund & Virtanen, 2013, p. 91). The machines are either: manual, semi-automatic or fully automatic. Lay-out and units of stripping machine are presented in figure 5. The main functions of the machine are covered next. (Kuusisto, Pekkala & Karcas, 2005, p. 329.)

Figure 4. Cathode stripping in progress. The copper deposits can be seen in red and the stripped stainless steel cathodes on center and right side of the figure. (Kuusisto et al., 2005, 330.)

Material flow starts at the receiving end of the machine. Tankhouse crane loads cathodes on the receiving conveyor where the receiving wagon transfers the cathodes to wash chamber. Washing stage is intended for removing organics and sulphuric acid from the cathodes before stripping. After washing, the cathodes are sent one by one to stripping by transfer device 2. Deposit detachment and chiseling units remove copper deposits and stripped cathodes continue to discharge conveyor. Sampling and stacking units pile the copper deposits into bundles. After weighing and labeling the metal bundles are ready for selling or reprocessing. The stripped cathodes are collected by tankhouse crane and transferred back to the electrolysis cells. Non-strippable or damaged cathodes are removed from circulation by reject conveyor. (Outotec, 2013c, pp. 60–72.)

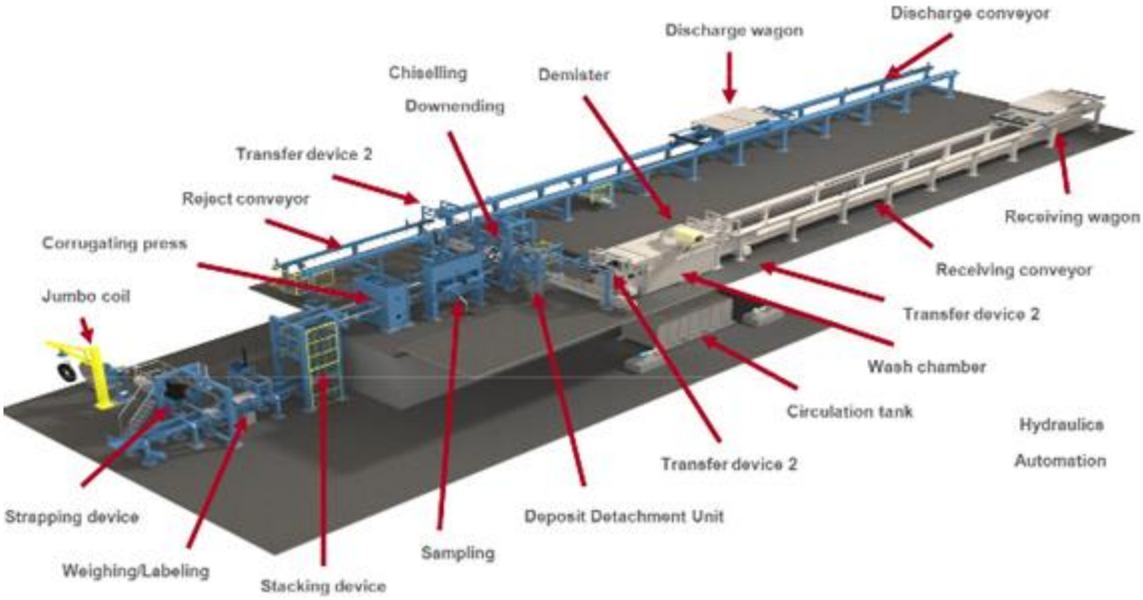

Figure 5. Units of full deposit stripping machine (FDSM) for which criticality analysis of spare parts is conducted in this thesis (modified from, Outotec, 2012b, p. 16).

4 LINKING MAINTENANCE WITH SPARE PART CRITICALITY

Basic understanding of maintenance provides a starting point for the thesis as spare parts are utilized in maintenance actions. Reliability centered maintenance is introduced first. It is a thorough analysis method for establishing a maintenance program. Some of its applications can also be utilized in spare part classification, e.g. for recognizing functionally significant items. Failure modes are introduced briefly to cover the role of failure data for maintenance purposes. Different types of spare parts are introduced in form of spare part packages the case company has to offer. The nature of service business provided by an original equipment manufacturer (OEM) is also introduced in order to understand the link between spare part criticality and spare part packages sold to the customers. In other words: the commercial potential of criticality analysis.

According to SFS-EN 13306 (2010, p. 5) : “maintenance is combination of all technical, administrative and managerial actions during life cycle of an item intended to retain it in, restore it to, a state in which it can perform the required function.” Two basic approaches for maintenance are either try to prevent a failure by conducting some maintenance tasks or run the equipment to failure. Maintenance strategies can be roughly categorized into four groups: condition based maintenance, preventive maintenance, proactive maintenance and corrective maintenance. These strategies are briefly introduced next. (Gulati, 2013, 55.)

Condition based maintenance is based on equipment monitoring. The aim is to identify and predict the coming failures in order to conduct proactive maintenance tasks when needed. Common ways to identify maintenance tasks are vibration analysis and oil analysis. The idea of preventive maintenance is to conduct maintenance tasks at certain intervals. This requires also paying regular attention to equipment and to observe indications of forthcoming failures. The key difference between predictive and preventive maintenance is that preventive maintenance is based on preliminary scheduled maintenance activities, whereas, predictive maintenance is based on condition monitoring. Proactive maintenance stands for all maintenance tasks conducted in order to avoid failures. Correcting maintenance actions are performed after the failure has a disrupting effect on the equipment or has led to a total failure. An equipment break down may cause unsafe conditions and loss of production. Corrective maintenance is also known as repair maintenance. (Gulati, 2013, 55-59.)

4.1 Reliability Centered Maintenance

Reliability centered maintenance (RCM) is a widely accepted methodology in maintenance through wide range of industries. This section does not aim to provide profound understanding of the subject but rather the definition of functionally significant items (FSI) of each system. RCM was originally established for maintenance requirements of aviation. It is a comprehensive methodology for establishing maintenance program for critical assets. (SFS-IEC 60300-3-11, 2011, p. 9.) According to SFS-IEC 60300-3-11 (2011, p. 9): "reliability centered maintenance (RCM) is a method for establishing a preventive maintenance programme which will efficiently and effectively allow the achievement of the required safety and availability levels of equipment and structures, which is intended to result in improved overall safety, availability and economy of operation."

Successful use of RCM analysis requires full understanding of the analyzed equipment and structures related to it, as well as, auxiliary systems and subsystems. This includes understanding possible failures and the consequences of those failures. This can be very labor consuming. The use of RCM should be carefully considered in advance. In case of significant environmental risks related to maintained equipment or risk of significant production losses in case of unexpected failure, the use of RCM should be considered. The result of RCM analysis is a preventive maintenance program. Development of the program consists of two stages: identification of FSIs and identification of preventive maintenance tasks. (SFS-IEC 60300-3-11, 2001, pp. 9; 23.)

Building a maintenance program starts by identifying system boundaries and system functions. Functionally orientated partitioning is the starting point. Block diagrams are a suitable way for organizing various functions. This is followed by selection of systems, their functional failures and criticality which leads to identifying FSIs. This starts by identifying candidate FSIs. Failures of candidate FSIs affect safety, are undetectable during normal operation and have significant operational or economic impact. (SFS-IEC 60300-3-11, 2001, pp. 27–28.)

Maintenance tasks are identified in RCM analysis by applying decision tree models for FSIs, which present a “yes or no” question at each node of the model. After recognizing the candidate FSIs a failure mode and effects analysis (FMEA), or similar risk analysis, is required for identifying the following information for further analysis: function of the item, functional failures of the item, failure causes and failure effects. This information is not only required for answering questions at the nodes of the decision trees at the second stage of the analysis. It is also important for identifying the actually critical items from candidate FSIs. These items have medium or high probability of failure and are functionally significant. They may also be considered as critical due to poor maintenance record. (SFS-IEC 60300-3-11, 2001, pp. 27–31.)

RCM is considered as too labor consuming for the case example. However, certain parts of it can be applicable, e. g. recognition of FSIs. Conduction of an RCM analysis prior to criticality classification or the ability to utilize already created analysis could offer significant advantage for spare part classification.

4.2 Failure Modes in Collecting Maintenance Data

Failure mode analysis is an important step in identifying failure mechanisms of various equipment and components. Identifying failure modes and reporting them is essential for maintenance planning. Data regarding failure modes and the frequency of their occurrence forms an important input for maintenance analysis, e.g. for RCM and spare part classification.

In order to utilize failure data for RCM analysis, FMEA is required. For this purpose failure modes are categorized in four groups in SFS 5438 standard. They are premature function, missing function at a specific moment, an error in stopping the function at a specific moment and failure during operation. The most common failure modes are presented in SFS 5438 standard, which is congruent to IEC 812 standard, thus, they are not covered in this section. (SFS 5438, 1988, p. 10.)

4.3 Spare Part Packages

Spare part is according to SFS-EN 13306 (2010, p. 6): “item intended to replace a corresponding item in order to retain or maintain the original required function of the item.”

Common spare part types applied in the case company are commissioning parts, operational parts, capital parts, and insurance parts. These spare parts are then categorized in three subgroups: spare parts, repairable parts and wear parts. Items that are neither wear parts nor repairable parts are categorized as spare parts. Common bulk items, e.g. bolts, nuts, screws and cables are spare parts. The definitions for each type of spare parts, except insurance parts, are retrieved from the case company and are informative only. The categorization also varies within the company.

Insurance spare parts are items that are normally not needed during the lifetime of the equipment. Unavailability of an insurance part can cause unacceptable downtime to the process. (SFS-EN 13306, 2010, p. 7.) The parts are reserved for critical equipment in case of unexpected outages. The demand of insurance parts is unpredictable and lead times are long. (Gulati, 2013, p. 120.) Capital spare parts are very similar to insurance spares. The key difference is a higher unit sales price for capital spares. They are usually manufactured and purchased simultaneously with the original equipment due to significantly higher costs when ordered separately. Capital spares are expected to have long service life and low probability of failure. They are, however, expected to cause prolonged shutdown in case of failure. (Siekkinen, 2015.)

Wear parts and operational spare parts are intended to consume during normal operation. They are replaced during scheduled maintenance, minor repair or overhaul. Operational spares encounter wear, corrosion, deterioration and erosion and are expected to be replaced in less than 2 years. Bearings, seals, hoses, valves and filters are considered as wear parts. Commissioning spare parts are expected to break, consume or damage during commissioning, start up or the initial run in period. Repairable parts are items which can be restored after failure to their original state. Repairable parts have repair kits available or they can be restored in other ways. They can be wear parts or mechanical parts. The parts can be repaired by applying spare parts, e. g. a seal kit or ball joint for a hydraulic cylinder. They can also be repaired without repair kits by other measures, e.g. welding, straightening or refabricating. (Ollonqvist, 2014, pp. 2–8; Siekkinen, 2015.)

Spare parts which should be replaced simultaneously are offered as spare part kits. They are created for predefined maintenance and repair procedures. The parts are easier for the customer to order and stock managing is also simpler. Maintenance quality is also increased when all the relevant parts are replaced together. (Ollonqvist, 2014, pp. 9–12.)

4.4 After Sales Services

After sales services provide a great business potential for equipment manufacturers. This has been recognized by more than half of manufacturing companies in the western countries. These companies provide after sales services in addition to their primary products. Providing of these services is particularly prosperous for original equipment manufacturers (OEM) who are collecting most of the profits related to them. Providing of after sales services along with primary products can generate more than half of total profits of an OEM. The profits are generated throughout the whole lifecycle of the equipment and not only with the initial provisioning. (Dombrowski & Malorny, 2014, pp. 618–619.) The main advantage in services is the constant nature of the business. Economic cycles have low impact to it. Profit margins are also generally higher with services than goods. A key driver for the business is that customer organizations tend to focus on their core competences. This leads to outsourcing of non-core functions, such as, maintenance to the OEM. (Turunen & Toivonen, 2011, p. 75)

Activities related to after sales has several advantages as mentioned. After sales services including spare part sales can generate more than three times that of the original provisioning during lifecycle of the equipment. In addition to increased revenue and profits it is also a way to keep customers satisfied and this way increase sales for new equipment and services. (Saccani, Johansson & Perona, 2007, pp. 52–53.)

First step when entering the service business for an OEM is usually provision of maintenance and repair for the installed base (Turunen & Toivonen, 2011, p. 76). Typical services provided by an OEM are spare part installations, commissioning, preventive or repairing maintenance, inspections, warranty management, modernizations and upgrades, as well as, staff trainings. In addition to the previously mentioned the case company provides also operation and maintenance (O&M) agreements (Outotec, 2012e). Challenges in OEM services relate to difficulties in standardizing products offered to customers and customization. Quality insurances related to great variety of products brings its own challenges. (Dombrowski & Malorny, 2014, pp. 618–619.) Major challenges are also managerial in OEMs offering services. The transfer from equipment manufacturer to also services provider is not necessary successful. The economic potential or the customer orientated nature of the business are not always recognized. These challenges exist regardless of beneficial business for both customer and the OEM. (Turunen & Toivonen, 2011, p. 75.)

By using services provided by an OEM the customer can add value to its operation. Smith et al. categorized customer value in three groups: reduced equipment recovery time, increased availability and increased performance. Recovery time is the time required for retaining the equipment performance after a failure. Recovery consists of repair services, spare parts and technical support. The value is in retaining the equipment as quickly as possible to usable state. Availability aspect covers e.g. equipment maintenance service, operating advice and component forecasting in order to maximize availability of the equipment. Increased performance comes in form supporting effective operation of the equipment. (Smith, Maull & Ng, 2014, p. 252.)

As mentioned, selling spare parts can be profitable business for equipment manufacturers. Sporadic nature of spare parts demand and the variety of items brings challenges to this business. A quantitative method for managing spare parts is, thus, required. Persson & Saccani (2009, pp. 128; 133) conclude in their study that classification of spare parts is a very important lever for managing after sales logistics network for a heavy equipment manufacturer. Their multi-criteria classification method takes into account: lifecycle phase of the final product, volumes, competition and spare part criticality.

5 CHARACTERISTICS OF SPARE PART CRITICALITY CLASSIFICATION

This section covers the characteristics of criticality classification of spare parts. The phenomenon of spare part criticality is introduced first beginning with the definition of criticality. The most important content of this section discusses criticality criteria of spare parts under various conditions. Variables applied in criticality classification are referred as criticality criteria. Basics for dividing items into classes according to their criticality are also introduced. This section, as well as, sections six and seven, are based on a thorough literature review in order to provide a state-of-the-art view about spare part criticality classification methods. The literature review in sections five to seven is completed by introducing the requirements and current practices of the case company for criticality classification.

5.1 The Phenomenon of Spare Part Criticality

Multiple ways define criticality. In the maintenance point of view criticality is defined according to SFS-EN 13306 (2010, p. 10) as: “numerical index of the severity of a failure or a fault combined with the probability or frequency of its occurrence.” The definition is derived further for spare part criticality in this thesis. Other aspects in addition to maintenance need to be considered. These aspects relate mainly to logistics and warehousing costs. Stoll et al. (2015, p. 225) describe criticality as risk in procurement and storage or the consequences caused by a failure due to unavailability of a spare part. In this thesis criticality is divided into multiple classes describing the consequence and frequency of a part failure and its effects to occupational safety and economical costs. Safety being the most important criterion.

Classification of spare parts consists of multiple research areas: inventory control, maintenance, reliability and supply chain management being the most relevant ones. (Molenaers et al., 2012, p. 570). A major aspect in spare parts management and classification are the inventory costs. Syntetos & Keyes (2009, p. 293) suggest that even a small effort put to spare part inventory management can have significant reductions in stocking costs. Multiple aspects to spare part management occur in literature. In many cases the aspect of the equipment owner is considered and how to manage spare part stocking on site. Understanding the customer aspect is important for a customer orientated service providing

OEM as the case company. A lot of information about logistic aspect of criticality is available. How to take all characteristics of item criticality into consideration is a different matter. Safety, functional location criticality, probability of failure and maintenance or repair costs influence on item criticality.

Roda et al. (2014, pp. 528; 531–534) conducted a literature review of spare part criticality classification methods. The review presents multiple approaches for criticality evaluation. Analysis methods focusing on the aspect of the equipment owner are presented, as well as, their advantages and disadvantages. The review reveals different aspects for spare part classification. The starting point being that critical parts in maintenance point of view are different than the ones in logistics or financial point of view. Severe consequences of an item failure in a plant point of view are important for maintenance, whereas, costs for holding an inventory are relevant for logistics. Combining these aspects into a criticality classification method is a challenge. The purpose of holding spare parts in stock is to support maintenance to ensure safe process continuity in case of failure. This needs to take place in the limits of maintenance budget. Multi-criteria classification is suggested to be the approach for criticality analysis in recent academic literature. The need for multi-criteria analysis seems evident due to several qualitative and quantitative measures having an effect on criticality. Receiving proper data for this purpose can be a challenge.

An approach for evaluating spare part criticality presented by Valmet Oyj is the use of three factors: functional location criticality, mean time between failures and lead time. By analyzing the effects of these three factors each spare part receives a criticality index. In order to take all aspects of criticality into account functional location criticality is divided further into three parts. Functional criticality index consists of production losses, environmental risks and safety risks. In case of production losses a relevant question is for how many hours will it last after equipment failure. In case of environmental and safety risks the severity of the risk need to be evaluated. The question is how to weigh these factors in order to receive correct results. This is not revealed by Valmet. The basic idea of this evaluating approach is cost efficient spare parts inventory with minimal risks for production losses. (Valmet, 2015, pp. 1–4.)

5.2 Relevant Criteria for Analyzing Criticality

Countless criteria for evaluating criticality exist. Roda et al. (2014, p. 532) categorized criticality criteria in four groups after a thorough literature review. The groups are: spare parts plant criticality, spare parts usage characteristics, spare parts inventory problems and spare parts supply characteristics. The criteria as categorized as follows:

1. Spare parts plant criticality
    - Quality problems
    - Production losses or stock out costs
    - Domino effects
    - Health safety and the environment aspects
2. Spare part usage characteristics
    - Identical spare parts usage rate
    - Probability and predictability of failure
3. Inventory problems
    - Turnover rate
    - Deterioration problems
4. Supply characteristics
    - Lead time
    - Number of potential suppliers
    - Substitution costs
    - Possibility or costs of internal repair

(Roda et al., 2014, p. 532.)

In many publications criticality itself is considered as a classification criterion, especially in stock control applications. According to a literature review by Bacchetti & Saccani (2011, p. 724) item criticality is applied as classification criterion in 15 out of 25 publications. The same conclusion is drawn by Stoll et al. (2015, p. 226). Worth looking into is that both studies discuss spare parts management from point of central warehousing.

A widely accepted approach for criticality analysis of spare parts is based on dividing criticality criteria in two categories: process and control criticality (Roda et al., 2014, p. 531; Molenaers et al., 2012, p. 573). These two approaches were presented by Huiskonen (2001,

p. 129) and have been frequently cited in academic literature since. The most relevant classification aspects recognized in this thesis are introduced next.

5.2.1 Process Criticality

Process criticality focuses on spare parts functional criticality. It is related to the consequences of part failure to a process in case that a replenishment is not immediately available. Traditional ABC analysis is not considered as useful for identifying all process critical parts due to significantly higher costs caused by process down time compared to item costs. It is suggested that process criticality can be measured by estimating downtime tolerated due to a part failure. The production losses caused by downtime are a key factor. The estimation of the downtime does not have to be specific. The main function is to point at the right direction. Therefore, the author suggests dividing process criticality into three groups according to accepted unavailability of spare parts. (Huiskonen, 2001, p. 129.)

For practical purposes criticality can be evaluated roughly according to available lead time. Huiskonen (2001) suggests principles for the use of three criticality classes. In the most critical class a failure must be corrected immediately and spares must be available immediately. Safety stocking on site is the preferred option for these parts. In the second class the failure is tolerated for a limited time by applying temporary arrangements. Short lead time of spares is, therefore, acceptable. In the third class the failure is not critical and long lead times are acceptable. The use of time as a measure for criticality is especially useful for considering material control and available time buffers. (Huiskonen, 2001, p. 129; 131.)

A similar description for process critical parts is functionally significant items. As defined earlier, they are items that affect safety, are undetectable during normal operation and have significant operational or economic impact (SFS-IEC 60300-3-11, 2001, p. 29). RCM could be applied for identifying process critical parts. Another way is to apply relevant risk analysis method. They can be utilized to some extent for providing a systematic approach for identification of process critical items.

5.2.2 Control Criticality

Control criticality is not straightforward linked to consequences of a failure. It is a way to control the situation. Control criticality includes aspects as predictability of a failure, probability of failure or mean time between failures, lead times and availability of spare part suppliers. Considering the logistics point of view it is important to know the time available to react to the situation. Whether the need for replenishment is immediate or whether there is time to react. Process criticality dictates the positioning of spare parts and works as a foundation for stocking strategy. This leads to ensuring spare part availability in the time that is available. On site or centralized stocking options need to be evaluated for control critical parts. Process criticality is the key factor for classifying spare parts according to control factors. Safety stocking on site is necessary in case of lead time is longer than the accepted stockout situation. (Huiskonen, 2001, pp. 129–131.)

The cost of a part is also an important control criterion. High cost of a spare part makes it unattractive to store on site, whereas, low cost parts have to be supplied efficiently. In the plant owner point of view expensive spare parts should be drawn back in the supply chain. (Huiskonen, 2001, p. 130.)

Paakki, Huiskonen & Pirttilä (2011, p. 167) found availability risk as a suitable criterion for describing uncertain lead times, ordering behavior and purchase order quantities. Unreliable or insufficient data related to the mentioned criteria can make evaluating them as such challenging. To overcome the challenge the authors concluded that the best way to categorize spare parts in their supply chain management method is by dividing availability into three groups: commercial parts, industry specific parts and key parts. In terms of implementation and usability of the categorization this type of simplification is required.

Commercial parts are considered to offer low risk, whereas, industry specific parts offer moderate risk and key parts high risk. Key parts are considered as made to order parts with only few suppliers, thus, possessing long lead times and greater risks in case of urgent replenishment. Industry specific parts have more manufacturers and are similar in characteristics. This reduces the availability risk. These parts are fabricated according to specific drawings. However, they are more generic compared to key parts. Commercial parts are standard items, e.g. screws, bolts and other parts that are widely used across all fields of industry. They are easily available from several sources and have short lead times. (Paakki et al., 2011, p. 167.)

Huiskonen (2001, p. 130) also suggests dividing spare parts according to their predictability of failure into at least two groups. The first group consists of parts with random failing pattern and the other of predictable failures. Predicting takes place by estimating failure patterns and rates by statistical methods.

5.2.3 Probability of Failure

SFS-IEC 60300-3-9 (2000) standard provides three ways for analyzing frequency of undesired events, such as accidents. Or as in this case, failure rate of a spare part.

1. The first way is the use of relevant historical data regarding the undesired events. The data is intended to determine frequency of these events based on the data available and predict their occurrence in the future.
2. Another way is to predict failure frequency by the use of fault tree or even tree analysis in case of unavailable or inadequate historical data. The frequencies are derived by analyzing the system and its associated failure modes.
3. The third way is to rely on expert judgement. This can be conducted by eliciting expert judgement in order to make them visible and explicit. Expert judgement should be utilized also when applying the two previously mentioned techniques.

(SFS-IEC 60300-3-9, 2000, p. 17.)

Receiving proper historical failure data can be challenging for an OEM service provider. The equipment are in possession of the customers which brings challenges in estimating failure rates and spare part consumption of the equipment. Data concerning sold spare parts can also be incomplete. Several suppliers for spare parts exist in addition to equipment manufacturers. Another challenge in estimating failure probability is that some equipment are operational only eight hours per day, whereas, other equipment are operational throughout the year. Ghodrati & Kumar (2005, p. 181) also found the challenges in operational environment significant. In their study, spare part recommendations were insufficient due to challenging environment in a mining application.

Two approaches for evaluating probability of failure are recognized in this thesis. First approach is to divide failure rate into certain intervals in which the failure can occur. Another approach is to utilize failure statistics. By analyzing failure data it is possible to evaluate failure probability of a spare part at various confidence intervals. Of these two approaches, the first one is found more suitable for the case company due to requiring less data.

5.2.4 Safety Components

Safety is recognized as an important criterion for spare part criticality. ISO 12100:2010 is a widely recognized standard for safety design. It is recognized from China to USA, as well as, in the European Union. (SFS, 2015, p. 7.) Safety components discussed in this thesis are equivalent to safeguards and protective devices defined in ISO 12100 standard. Protective measures are required when inherently safe design of the equipment has not been able to remove or minimize all the risks related to it. Safeguards and protective devices are identified as critical components and are to be recognized in the classification. They are intended for keeping persons away from danger zones, most often hazards created by moving parts. Different types of guards and protective devices are briefly introduced next. (SFS-ISO 12100, 2010, p. 75.)

According to SFS-ISO 12100 (2010) safe guards is a guard or a protective device that is a physical barrier designed as a part of the machine intending to provide protection. Guards can be fixed, movable, adjustable or interlocking. Fixed guard is affixed by screws, nuts or welding and it cannot be moved without appropriate tools, whereas a movable guard can be removed without tools. Fixed guards are utilized whenever access to a danger zone is not required during normal operation. Adjustable guard is either fixed or movable and it is adjustable as a whole or it includes adjustable parts. Interlocking guard is a guard associated with an interlocking device. Thus the guard operates with the machines control system and stops the machine from operating until the guard is closed. When opening the guard the machine stops. An interlocking device can be mechanical, electrical or other type of device intended to prevent operating hazardous machine functions generally as long as a guard is open. (SFS-ISO 12100, 2010, 17-19.)

Various protective equipment in addition to safeguards provide important safety measures. Sensitive protective equipment, e.g. light curtains, pressure sensitive mats and laser scanners. The devices can be utilized when access to the danger zone is required for machine setting, teaching or maintenance. (SFS-ISO 12100, 2010, p. 79.)

5.3 Requirements for Criticality Analysis in the Case Company

Certain requirements for criticality analysis of spare parts in the case company exist. They relate mostly to OEM nature of the company. This section is based on several meetings within the company. A list of meetings is provided in appendix I. All memorandums are in possession of the author. The focus of this section is in presenting the requirements for a criticality analysis method. The requirements concern mostly safety and functional effects in case of part failure. Other aspects concern the usability of the method and the requirements of different stakeholders.

An important aspect as an equipment manufacturer is to identify the equipment and components that are critical to safety and process. This is evident regardless of how often they fail. Identifying components that affect occupational safety in case of failure or unavailability of the equipment is essential. Especially safety components, as well as, components causing safety issues in case of failure or unavailability have to be recognized and classified to the highest criticality class. Components causing immediate and unpredictable shutdown of process should also be recognized as highly critical.

A way to sort most items by applying minimal amount of criteria is appreciated. These items are the most obvious non-critical items. Mostly the parts that are easily available or repairable, are not considered as critical. These items have to be categorized in order to avoid misunderstandings. Easily available parts are e.g. nuts and bolts. The analysis also has to be close to practice. Some spare parts can be easily repaired to the state in which they continue to perform their duty. These items are not to be considered critical even though lead time or functional location criticality can be significant.

Criticality analysis is also an important argument for selling spare parts. Pricing has to be correct and reflect criticality of the parts, yet competitive. Criticality classes provide a way of focusing spare parts sales. By comparing sold item data to critical components of the equipment, it is possible to recognize the items that the customer should have purchased to ensure safe operation and availability of the equipment.

The criteria applied in the analysis have to be unambiguous and precise. Unambiguity refers to the fact that regardless of the person conducting the analysis, same results must be achieved. The criteria cannot remain open to various interpretations. The terminology applied in the analysis should also be congruent with the terminology already applied in the company. This refers mostly to the spare part types already applied by the company.

The ability to use criticality analysis integrated to product data management (PDM) is also highly appreciated. This is important since PDM is already a global tool utilized by professionals in the company. An additional tool or user interface for criticality analysis and data storing is not convenient. An impractical method could also remain un-used and not to be implemented to the company. User friendliness is also a key factor. A single equipment can consist of hundreds of spare parts. Sub functions of entire plants are measured in thousands and spare parts are to be multiplied with that. Therefore, the analysis cannot be too labor consuming. A relevant question is how many spare parts can be classified in an hour. Too computational and difficult to understand methods are, therefore, not discussed.

Different stakeholders have somewhat different requirements for spare part classification. The main stakeholders recognized in this thesis are maintenance, logistics and the responsible product line. A challenge in the analysis process will be the availability of sufficient and accurate data. Failure rates and lead times are expected to be challenging to estimate. Environmental circumstances are also site-specific, as well as, operating hours for each equipment.

6 RISK ANALYSIS METHODS IN CRITICALITY CLASSIFICATION

Risk analysis forms the basis for criticality classification. Some of the risk analysis methods presented in this section are already utilized by the case company. All the methods are, however, common for risk identification and they can be applied as well. This section introduces first the basics of risk analysis after which the focus is in covering multiple risk analysis methods. The methods are applicable for supporting criticality analysis and for identifying risks related to operation and functioning of equipment.

Three levels of risk exist: intolerable risk, tolerable risk and negligible risk. Intolerable risks are not acceptable in any situation. This can be hazardous exposure to products that severely affect workers occupational health and safety. Tolerable risks are considered acceptable. Certain procedures have been conducted in order to obtain tolerable risk. This offers some benefit, e.g. in form of saved costs in preventing an accident or injury from occurring. Negligible risks are considered as so insignificant that no preventive actions are required. (Stapelberg, 2009, p. 530–531.) Risk levels can also be quantified in form of financial losses due to stock-out of spare parts leading to unavailability of equipment. (Hassan, Khan & Hasan, 2012, p. 347.)

According to SFS-IEC 60300-3-9 (2000, p. 7) risk analysis attempts to answer the following three questions:

- “What can go wrong (by hazard identification)?
- How likely is this to happen (by frequency analysis)?
- What are the consequences (by consequence analysis)?”

Risks cause harm to safety, environment, production or equipment. Risk management aims in identifying the risks in order to prevent their causes to health environment and property. Effective risk management requires analyzing risks. Risk analysis is useful in order to identify risks and approaches to their solution by providing systematic information for decision making. It can also be required for meeting regulatory demands. (SFS-IEC 60300-3-9, 2000, p. 11.) The following risk analysis methods are introduced in this section: hazard and operability study, event tree analysis, fault tree analysis, as well as, fault modes, effects and criticality analysis. These methods can be applied to some extent for analyzing spare parts functional criticality and for identifying hazardous situations. More detailed descriptions of these methods are available in SFS-IEC 60300-3-9 standard, due to which they are merely briefly introduced in this section.

6.1 Hazard and Operability Study

Hazard and operability study (HAZOP) is based on brainstorming sessions by multi-discipline experts. The basic idea is that a group of professionals from several disciplines can identify more potential problems in a process than individual experts. (Stapelberg, 2009, p. 575.) HAZOP is a systematic technique to identify hazards and operability problems of entire process plants. Each equipment, piping and instrumentation is analyzed by applying guide words presented in table 2, in order to identify various deviations in the process. Possible causes, consequences and required actions for the recognized deviations are then listed on a HAZOP worksheet. (SFS-IEC 60300-3-9, 2000, 37.)

Table 2. Terms and definitions of HAZOP (modified SFS-IEC 60300-3-9, 2000, p. 37).

Terms	Definitions
No or not	No part of the intended result is achieved (e.g. no flow)
More	Quantitative increase (e.g. high pressure)
Less	Quantitative decrease (e.g. low pressure)
As well as	Qualitative increase (e.g. additional material)
Part of	Qualitative decrease (e.g. only one or two components in a mixture)
Reverse	Opposite (e.g. backflow)
Other than	No part of the intention is achieved, something completely different happens (e.g. flow of wrong material)

6.2 Event Tree Analysis

Event tree analysis (ETA) is a risk analysis method for identifying various incidents and event sequences which generate from an initiating event. Construction of ETA requires six steps. The first step is to identify a relevant initiating event. This is a hazardous event caused by a failure or human error. In order to be suitable for evaluation it should also lead to multiple safety issues or incidents. If this is not the case then fault tree is more appropriate analysis method. Second step is to identify the safety functions which have an effect on safety consequences of the initiating event. These functions are such safety actions that mitigate the hazardous initiating event. The functions are presented according to the time of their occurrence. Probabilities for success or failure for each function are also required. Step three is construction of the event tree. An example of event tree is provided in figure 6. (Stapelberg, 2009, pp. 554–558.)

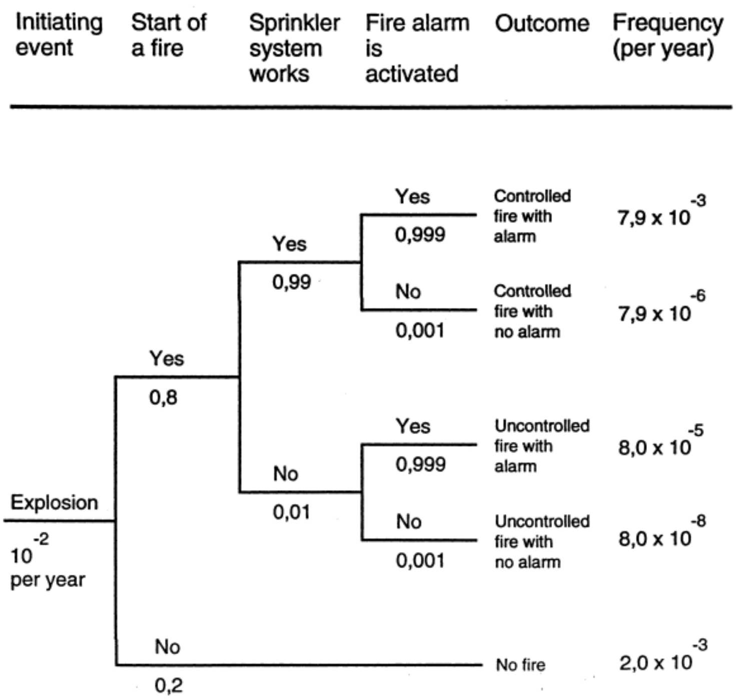

Figure 6. An example of event tree in case of a dust explosion (SFS-IEC 60300-3-9, 2000, 49).

Step four is describing the resulting hazardous sequences of events. Steps five and six include determine of probabilities for each safety consequences identified and gathering the analysis results. (Stapelberg, 2009, pp. 556; 559.) For evaluating probabilities for different events reliability and historical data or maintenance experience can be utilized (Ghodrati, Akersten & Kumar, 2007, p. 360).

A risk based classification is suggested by Ghodrati et al. (2007, pp. 358–361). Their analysis method relies on a non-standard event tree model. Safety functions in the model are presented as undesired events, e. g. inadequate spare parts estimation, spare parts shortage or loss of production. The basic idea is to analyze the risk of ignoring effects caused by the operating environment factors concerning system downtime and loss of production. The research was motivated by insufficient spare part recommendations due to challenging operating environment. The method is tested in an iron ore mine in Iran. The authors conclude that the risks caused by ignoring the operating environment are significant.

6.3 Fault Tree Analysis

Fault tree analysis (FTA) is a risk analysis method based on deductive logic. It is a logic diagram that presents the relation between an undesired event and the conditions leading to this event. The conditions are deductively identified in a tree form. The conditions derive from component failures, human errors or other relevant events leading to the undesired event. FTA is described as a highly systematic and disciplined, yet flexible approach for analyzing multiple factors leading to an undesired event. The top down approach focuses the analyst in events that directly impact to the top event. (SFS-IEC 60300-3-9, 2000, p. 39.)

Defining the top event is essential in construction of FTA. It is an accident or other type of undesired event which is recognized prior the analysis. The tree model is constructed of logical operators indicating the relation between the undesired event and conditions leading to this event. The operators are mostly OR and AND gates. OR gate indicates that one of the events is required for opening the gate, whereas, AND gate indicates that all events are required for opening the gate. (Stapelberg, 2009, p. 546.)

6.4 Failure Mode, Effects and Criticality Analysis

Failure mode and effects analysis (FMEA), as well as, failure mode, effects and criticality analysis (FMECA) are methods for analyzing reliability. The key difference between FMEA and FMECA is that the latter one completes FMEA by also considering criticality of the failure mode. FMEA is a method for analyzing reliability by considering the failures that have significant consequences to the examined system. Generally all component failures have a negative effect on systems. Both qualitative and quantitative methods are required for analyzing reliability and safety of a system. Typical quantitative measures describe availability, reliability and time between failures, whereas, qualitative measures describe failure modes and their effects. The analysis is to be conducted to the lowest component levels for which failure modes can be described. Discovering the connection between deterioration or failing of certain elements and their effects to the system basic function is a key task of the analysis. Intervals between failures can also be important. The analysis can consider different human or software errors or they can be excluded. Seriousness of the failure consequences are described with criticality. Criticality is categorized into classes that describe the level of damage according to hazards or production losses caused by failure. Probability of failure can also be considered but in such a case it should be expressed separately from criticality. (SFS-ISO 5438, 1988, p. 2.)

The first aim of FMECA is to identify every failure mode of a component and its consequences to several levels of process hierarchy. Second is to identify the significance and criticality of each failure compared to faultless operation of the system, thus, identifying effects on safety, reliability and production of the system. Third aim is to classify the identified failure modes according to their definability, testability, reparability, and maintainability. Fourth aim is to determine the significance and probability of the failure. (SFS-ISO 5438, 1988, p. 2.)

FMEA is an efficient method when applied to failure modes that cause the whole system to fail. It can, however, be very difficult and labor consuming when applied to complicated systems that consist of multiple functions and components. Another issue is that the effect of human errors to systems is often left out of the analysis. (SFS-ISO 5438, 1988, pp. 3–4.)

FMEA requires dividing system into parts in form of a schematic diagram in order to recognize functional structures of the system and to recognize necessary information. Failure mode determination is also required. Failure modes are briefly introduced in section 4.2, but the full list is presented in the standard. It is important to determine the lowest hierarchy level in which the analysis is conducted. Key factors regarding the operation and maintenance are the time the repair is allowed to last until serious consequences occur and the circumstances in which the repair takes place. The system is to be presented in a block diagram in order to receive the necessary information. (SFS-ISO 5438, 1988, pp. 4–5.)

The aim of criticality analysis in FMEA is to quantify the criticality of a failure and its probability. The aim is to support decision making for maintenance and its prioritizing. Identification of tolerable and intolerable risks is an important objective of this analysis method. Failure modes are categorized in four criticality classes in FMECA. Criticality class four stands for significant consequences to safety, environment and production. Significant safety affects are deaths and serious injuries. The difference between classes four and three is that in class three safety issues are minimal but the system can be seriously affected. In class two the function of the system has deteriorated but no significant damage is done. Class one failures may cause minor deterioration to the functions of the system or the environment but no personal injuries. Probability of failure is categorized in four groups according to its expected frequency. This is expressed alongside with criticality, allowing the analyst to identify critical failure modes with high probability. (SFS-ISO 5438, 1988, pp. 9–11)

FMECA can be considered for spare part classification as such. It also forms the basis for RCM analysis, making it possible to combine both maintenance and spare part criticality aspects. No other methods are necessarily required. This would, however be labor consuming and not necessarily ideal for the case example. The evaluation of control characteristics in FMECA is, however, limited. The following method presented by Hassan et al. is somewhat similar to FMECA.

A risk based criticality analysis method is suggested by Hassan et al. (2012, 347–359). Criticality is derived from probability of failure and its consequences. No particular risk analysis method is applied. Risk is merely evaluated by estimating the consequence of a failure and the frequency of it. The aim is to identify components potentially affecting operational target of the plant due to intolerable failure risk. Consequences are measured in financial losses due to component failure e.g. loss of production, cost of replacement and liability cost. In total the revenue loss due to unavailability of an equipment or the plant. Probabilities rely on expert judgements or historical failure data. This allows quantitative risk comparison between components due to each component having a financial loss and probability. Failure prediction is also studied in order to estimate consumption of spare parts. A holistic approach for spare parts inventory management according to the authors requires forecasting of demand, criticality classification and economical consideration.

7 METHODS FOR SPARE PART CRITICALITY ANALYSIS

This section aims to establish a state-of-the-art view of various criticality analysis methods that are applicable for analyzing spare part criticality. Some methods are intended for equipment classification and inventory control. Suitability of these methods for spare part criticality analysis is evaluated. A method for calculating criticality index for equipment can also be suitable for spare parts. After all criticality is defined in the previous chapter as a risk of failure and its consequences. Therefore, by adjusting factors impacting equipment criticality into those that imply to items, relevant analysis methods for spare part classification can be revealed.

The most common classification method in literature is the ABC-analysis. Even though multiple classification methods exist, ABC analysis is the preferred method applied in industry (Molenaers et al., 2012, p. 570). It is considered to serve well stocking of parts that are homogenous and the only variations are unit price and demand volume. It is a one dimensional method and is therefore not considered applicable for spare parts control management. (Huiskonen, 2001, p. 126.; Sarmah & Moharana, 2015, p. 462.) Several multi-criteria ABC-classification variations also exist, e. g. fuzzy logic and linear optimization based analysis methods. The principle of a Fuzzy logic method is briefly introduced at the end of this section.

This section begins with thorough coverage of PSK 6800 standard which is intended for classifying equipment criticality. The applicability of this method for spare part classification is an open question and of interest in this thesis. Next topic is introduction to a method that is being developed for the case company. The core of this section is in various criticality analysis methods studied and applied in academic literature.

7.1 PSK 6800 Criticality Classification of Equipment in Industry

PSK standards association provides a standard method for classifying equipment criticality in industry. The method is applied for analyzing criticality according to three approaches: economic impacts, personal safety and environmental impacts. The purpose of the method is to provide data required for maintenance planning. By calculating criticality index for equipment it is possible to identify and classify the criticality of the evaluated equipment. (PSK 6800, 2008, pp. 1–3.) The focus of this standard method is mainly in equipment criticality rather than spare part criticality. Then again no evident restrictions for applying the method for lower hierarchy levels such as spare parts exist. The analysis method is yet unknown for academic literature. PSK standards association provides standards for its members in Finland. An English translation does, however, exist in the standard. The basics of the standard method are introduced next.

PSK criticality analysis proceeds as follows:

1. Determine the scope of the analysis. This can be an entire plant or a process unit.
2. Determine weighting of the production loss W_p for the analyzed equipment according to formula 1. An illustration of process hierarchy is in figure 7.
3. Evaluation of the other weighting factors in table 3 and making necessary adjustments to the informative values.
4. Listing of the evaluated equipment.
5. Selecting the applicable multipliers from table 3 for the equipment listed.
6. According to the parameters given, criticality index K and five sub-indices are calculated by applying the excel sheet provided in the standard.
7. According to criticality index the equipment are sorted in order to carry out the criticality classification. (PSK 6800, 2008, p. 3)

Calculation of the production loss weighting factor proceeds according to process level hierarchy. The Plant is divided into production units P_1 which are divided into production lines P_2 and eventually into equipment as presented in figure 7. Each stage in the hierarchy receives a total weighting factor of 100 %. Thus production loss weighting factor is calculated according to formula 1,

$$W_p = P_4 * P_3 * P_2 * P_1 \tag{1}$$

where P_1 is production unit, P_2 production line, P_3 process and P_4 sub process. According to the formula, an equipment critical for the whole plant receives a weighting factor of 100 %. (PSK 6800, 2008, pp. 3–6.)

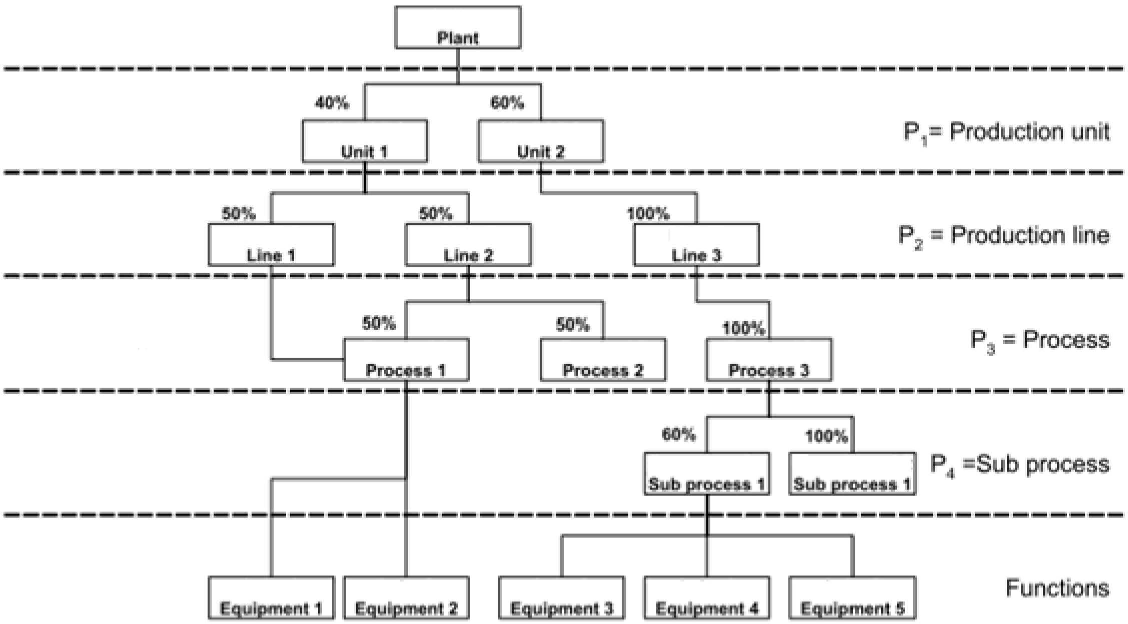

Figure 7. The basic principle to determine weighting factors of production (modified from, PSK 6800, 2008, p. 5).

Criticality index K consists of five sub-indices: safety K_s, environment K_e, production impact K_p, quality costs K_q and repair and consequential costs K_r. These sub-indices can be applied individually, e.g. for evaluating safety aspects of production. Equipment with severe safety risks can this way be revealed.

Criticality index is a sum of the sub-indices. Each sub-index consists of a weighting factor W and a multiplier M. Criticality index is calculated according to formula 2,

$$K = p * \left(W_s * M_s + W_e * M_e + W_p * M_p + W_q + M_q + W_r * M_r\right) \tag{2}$$

where p is time between failures, W provides weighting factors for safety, environment, production loss, quality costs, repair and consequential costs and repair costs, whereas M provides multipliers for these factors. Informative values for W and M are provided in table 3. Thus multiple factors of equipment criticality are taken into account. (PSK 6800, 2008, p. 8.)

Table 3. Informative values for weighting factors and multipliers for formula 2 (PSK 6800, 2008, p. 8).

Object	Weighting factor [W]	Time between failures [p]	Multiplier [M]	Selection criteria
Safety and environmental impacts	Safety risks $W_s = 30$	1 = Long time between failures, eg. over 5 years 2 = Quite long time between failures, eg. 2 to 5 years 4 = Quite short time between failures, eg. 0.5 to 2 years 8 = Short time between failures, eg. 0 to 0.5 years	$M_s = 0$	No safety risk
			$M_s = 2$	Minor safety risk
			$M_s = 4$	Moderate safety risk
			$M_s = 8$	Major safety risk
			$M_s = 16$	Serious safety risk
	Environmental risks $W_e = 20$		$M_e = 0$	No environmental risk
			$M_e = 2$	Minor environmental risk
			$M_e = 4$	Moderate environmental risk
			$M_e = 8$	Major environmental risk
			$M_e = 16$	Serious environmental risk
Production impacts	Production loss $W_p = 0 \ldots 100$		$M_p = 0$	Non-operation of equipment has no impact on the sub-process or department
			$M_p = 1$	Non-operation of equipment stops the sub-process or department momentarily (eg. ≤3 h)
			$M_p = 2$	Non-operation of equipment stops the sub-process or department for a short time (eg. ≤10 h)
			$M_p = 3$	Non-operation of equipment stops the sub-process or department for a considerable time (eg. 10 to 24 h)
			$M_p = 4$	Non-operation of equipment stops the sub-process or department for a long time (eg. >24 h)
	Quality cost $W_q = 30$		$M_q = 0$	Non-operation of equipment does not cause quality costs to the end product.
			$M_q = 1$	Non-operation of equipment causes quality costs on the end product equivalent to a momentary production loss (eg. ≤1 h)
			$M_q = 2$	Non-operation of equipment causes quality costs on the end product equivalent to a short-term production loss (eg. ≤3 h)
			$M_q = 3$	Non-operation of equipment causes quality costs on the end product equivalent to a major production loss (eg. 3 to 8 h)
			$M_q = 4$	Non-operation of equipment causes quality costs on the end product equivalent to a long-term production loss (eg. >8 h)
Repair or consequential costs	Repair or consequential cost $W_r = 20$		$M_r = 0$	Repair or consequential costs are not significant in relation to other losses.
			$M_r = 1$	Minor repair or consequential costs equivalent to a momentary production loss (eg. ≤2 h)
			$M_r = 2$	Medium repair or consequential costs equivalent to a short-term production loss (eg. ≤10 h)
			$M_r = 3$	High repair or consequential costs equivalent to a major production loss (eg. 10 to 24 h)
			$M_r = 4$	High repair or consequential costs equivalent to a long-term production loss (eg. >24 h)

Table 3 provides information for selection criteria for the multipliers. These criteria are explained more in detail in the standard and are not listed in this section. The multipliers for time between failures are also only informative and have to be evaluated case specific. (PSK 6800, 2008, pp. 9–11.)

Advantage of this method is the ability to use the sub-indices. It is important to recognize not only the equipment likely to fail but also the ones that are the most hazardous when they fail. A disadvantage is labor consumption. High professional skills and uniform multipliers are also required in order to receive unambiguous results. Another disadvantage with the

PSK standard is the lack of academic publications. Since it is a Finnish standard it is absent in academic articles and has to be evaluated other ways. It is, however, well known in the case company and has also been applied to multiple purposes. A challenge has been lack of common practices for the analysis. Common practices for applying the method are necessary in order to overcome challenges regarding subjective analysis.

Not many similar methods have been found from academic literature. Gómez & Hijes (2006, pp. 446–448; 450) propose also a criticality analysis method based on calculating a criticality index. Their method is also based on applying different weights to each criterion in the index. Each of the 12 criterion receives a value from zero to four according its criticality, as in the PSK 6800. Their article is frequently cited in Scopus (35 times), however, the analysis method itself is not applied by any other than the authors. They applied it to determine suitable maintenance actions for a wastewater treatment plant according to criticality of the equipment.

7.2 Methods Already Applied by the Case Company

The lack of a systematic method for spare part classification is a challenge in the case company. Criticality classification of process equipment according to PSK 6800 standard is common. Whereas, spare part classification is based on expertise of the responsible product line. A challenge is the lack of systematic method for conducting the analysis. The applicability of PSK 6800 standard for classifying spare parts is also being studied. A challenge is that the method is intended for classifying equipment criticality. Classifying criticality of spare parts requires somewhat different approach. The focus in PSK standard is in weighing production loss caused by failed equipment. A method for recognizing critical equipment for a plant is labor consuming for classifying spare parts. Some relevant control criteria for classifying spare parts are also not evaluated in the method. (Siekkinen, 2015.)

In order to overcome the mentioned challenges the standard method is developed further to consider spare part characteristics as well. The aim has been to create a comprehensive spare part classification method. A method that serves both maintenance and logistics aspects, as well as, the responsible product line. This way combining the requirements of services and product development for spare parts in a single analysis. Construction of plant hierarchy, analyzing equipment criticality and conducting failure analysis form the basis of this classification. Spare parts of an entire plant can be classified according to their criticality to the process. This requires also risk identification at each process and sub process level. Spare parts are classified in four groups by calculating a criticality index similarly to PSK standard. Ranges in the criticality index receive a corresponding criticality class. Production loss is evaluated by the significance of the failed function to the availability of the equipment. Spare parts affecting safety always receive the highest criticality class regardless of production impact. (Siekkinen, 2015.)

7.3 Multi-Criteria Classification Methods Studied in the Academic Literature

Various methods for classifying spare part criticality are presented next. They are often combined with one another. Some of the methods are intended for criticality analysis, whereas, others for inventory control. The key difference is that inventory control usually evaluates item criticality in a plant perspective, whereas, the aim of the thesis is to evaluate criticality in equipment perspective. The classification methods are, however, similar.

VED-analysis is covered first. It is a frequently applied method in academic literature. Many ways of applying this analysis method also exist and they are presented throughout this section. Storage turnover rate is applied alongside criticality classification and it is thus briefly mentioned. Decision tree models are frequently applied for criticality classification by various researchers. Analytic hierarchy process (AHP) is applied for solving decision making challenges related to the previously mentioned methods. It can be said that VED-analysis, decision tree models and the AHP form the core of this section. On many occasions they should be considered as one method fulfilling one another.

7.3.1 Vital, Essential and Desirable Spare Parts

VED Analysis is a qualitative method for spare part classification. It is widely applied method for classifying criticality. Criticality criteria and classes are divided into three groups: vital (V) essential (E) and desirable (D). The classification is based on expertise of the analyst, usually maintenance experts in this context. (Roda et al. 2014, p. 533.) In this method different aspects of criticality can be evaluated one at a time. E.g. a spare part can have a long lead time and is categorized as vital, whereas, an easily available part is considered as desirable. Classification is always based on expert judgment. The challenge in constructing VED analysis is to overcome the risk of subjective analysis. A common solution is to apply a systematic decision making method such as AHP and multiple criteria. (Cavalieri et al., 2008, 383-384.)

Cavalieri et al. (2008, p. 383) combined VED with storage turnover and ABC analysis in their analysis method. Storage turnover is evaluated by dividing items into three groups, fast moving, slow moving and non-moving (FSN). FSN is useful e. g. for identifying non-moving obsolescent spare parts. A rough classification is conducted first by applying VED and FSN for recognizing the items that require more attention from the maintenance management. Then a more specific ABC analysis is carried out by applying two attributes: unit purchasing costs and the number of installations. (Cavalieri et al., 2008, p. 392.)

According to a survey conducted by Roda et al. (2014, pp. 539–540) VED is the second used classification method in Chilean copper mining companies. The most common methods still being various “rules of thumb” The results were achieved by first explaining the methods and then conducting a survey.

7.3.2 Decision Tree

Decision tree is a decision supporting method. A multistage decision making process is illustrated in form of a decision tree. The graph is constructed of nodes and edges. The nodes present the criteria for decision making and edges present the alternatives. Figure 8 presents a decision making process in which the alternatives are categorized according to VED scale. After passing through the decision making process a VED overall criticality class is achieved. (Stoll et al., 2015, p. 230.) An advantages of decision making in a tree form is the ability to justify how a decision or classification is made. The path leading to a classification is well traceable. The decision making process and the decisions are more understandable when compared to statistical classifiers. Each criteria affecting the overall classification is well visible. (Quinlan, 1990, pp. 343–344.)

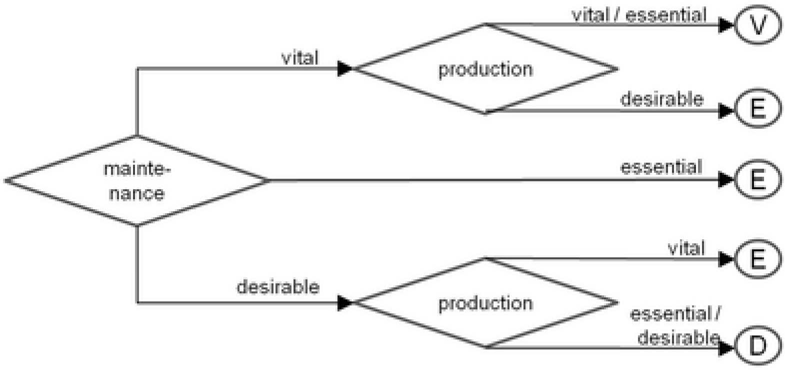

Figure 8. Multi-criteria decision making applying VED analysis in a decision tree (modified from Stoll et al., 2015, p. 232).

Similar decision trees to the ones utilized in RCM methodology are also presented by Carpentieri et al. (2007, pp. 475–476). The classification method consists of two stages. First of which focuses on functional criticality of the equipment. The criteria consider severity of failure, the effects on quality and loss of production, as well as, frequency of failure. The tree model is considered also applicable on item level. The second decision tree is intended to determine criticality by taking also control factors into account. The criteria are: level of criticality for the system, usage rate, availability on the market and failure monitoring. Criticality is divided into four groups. The method was not tested to spare parts of any actual equipment or a plant. Therefore no results regarding the applicability of the decision logic exist. (Carpentieri, Guglielmini & Mangione, 2007, pp. 475–476.)

7.3.3 Analytic Hierarchy Process

Analytic hierarchy process (AHP) is considered as a powerful method for multi-criteria and complex decision making. Both quantitative and qualitative criteria can be evaluated by AHP. By applying AHP, critical aspects are organized into a hierarchical structure. The use of AHP reduces complex decision making into simple comparisons and rankings. Most importantly the analysis provides a rationale for decision making. (Braglia et al., 2004, 63 – 64.) According to a thorough literature review by Subramanian & Ramanathan (2012, p. 228) AHP applications regarding stock control are still low. VED is found very common with the use of AHP. The review focused on mapping different applications of AHP from nearly 300 peer reviewed articles.

The basic principles of AHP are introduced first. After which three criticality analysis methods utilizing AHP are presented. Clarifying illustrations of stages of the process are provided in figures 11 and 14. AHP consists of the following four stages:

1. First stage is to decide decision criteria. This takes place in a form of hierarchy of objectives. The structuring of hierarchy begins from the top level, overall objective, and continues through various criteria and sub-criteria to the lowest level, being different alternatives.
2. In the second stage criteria and sub-criteria are weighed as a function of their importance. This is conducted through pair wise comparisons. The analyst may focus on only one comparison at a time and score them from 1 to 9 according to how close the compared criteria are from one another. 1 being equal, 3 moderately the same, 5 strongly different, 7 very strongly different and 9 extremely different. This results a judgment matrix as in table 5.
3. According to the judgment matrix a normalized eigenvector is calculated for the matrix. This weighs the elements of the matrix as presented in table 5.
4. Last stage is inconsistency evaluation. Goodness of the judgments is evaluated by using inconsistency ratio. This peculiarity of AHP allows the analyst to evaluate the judgment itself. In case of inconsistency the evaluation should be re-conducted.

(Braglia et al., 2004, pp. 63–64.)

Molenaers et al. (2012, pp. 570–572) presented a criticality classification method based on AHP and a decision tree model. In this method multi-criteria classification problem is solved by a logic decision tree where AHP is applied for solving the multi-criteria decision sub problems at various nodes of the tree. Criticality criteria are divided in three groups according to VED analysis. They are categorized to cover both process and control aspects of criticality. Process criticality is also extended to take safety and environmental issues in consideration in the analysis.

Criticality criteria are listed according to expert judgments of a case study. A list of six criteria resulted: equipment criticality, probability of failure, lead time, the amount of potential suppliers, availability of technical specifications and maintenance type. Equipment criticality is classified in six classes prior to spare part classification. Multiple quantitative and qualitative outcomes of the criticality criterion are categorized in three groups according to VED scale as presented in table 4. Both qualitative and quantitative information are gathered in one table and boundaries are provided for all three categories. (Molenaers et al., 2012, pp. 570–572.)

Table 4. Criticality criteria categorized in VED scale (modified from Molenaers et al., 2012, p. 573).

Criticality criteria	Categories		
	Vital	Essential	Desireable
Equipment criticality class	A and B	C and D	E and F
Probability of failure	≥ 1 /year	1 ≤ /year and ≤ 5 /year	< 5 /year
Lead Time	> 1 month	> 2 days and ≤ 1 month	≤ 2 days
Number of potential suppliers	1	> 1 and ≤ 2	> 3
Availability of technical specifications	unavailable	General specifications	Detailed specifications

Figure 9 presents item criticality in a cubic form according to VED scale. The cubic form features different outcomes of the criticality analysis. E.g. an item desirable from all points of view receives a criticality class four. The figure also indicates that an item likely to fail reaches criticality level three when equipment criticality and logistics characteristics are desirable. Criticality is classified in four classes, one being the most critical and four not critical. The classification is similar as presented earlier by Huiskonen in chapter 5.2. Critical items are expected to cause unacceptable conditions to safety or production in case of unavailability. For medium critical items in class two the unavailability of an item can be tolerated for a short time period. In class three longer lead time is accepted due to low risks in operation and safety. The unavailability of class four non-critical parts poses no threat to production and safety. Long lead times are accepted for these items. (Molenaers et al., 2012, p. 575.)

Figure 10 presents the decision tree in classifying criticality of spare parts. The diagram starts by equipment criticality. This is considered as the most important factor in classifying item criticality. AHP is applied for decision making at the levels where multi-criteria decision making occurs. In this case logistics present a multi-criteria problem. (Molenaers et al., 2012, p. 573.)

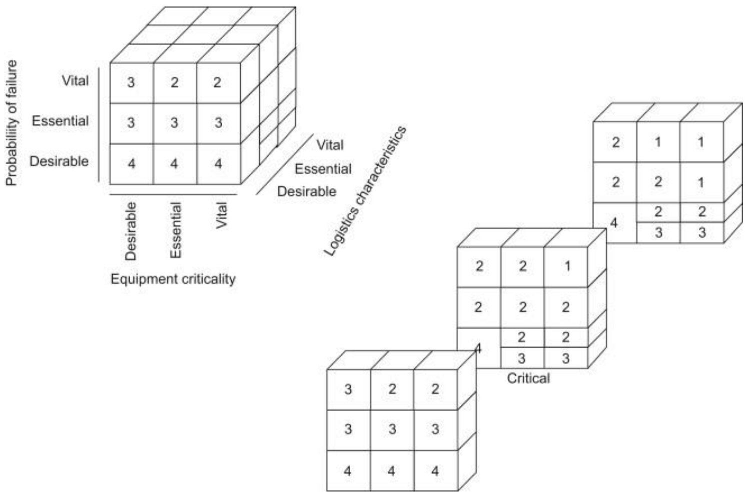

Figure 9. Three variables of the criticality analysis presented in cubic form by Molenaers et al. (2012, p. 575). Criticality classes are presented as a function of the variables in the decision tree.

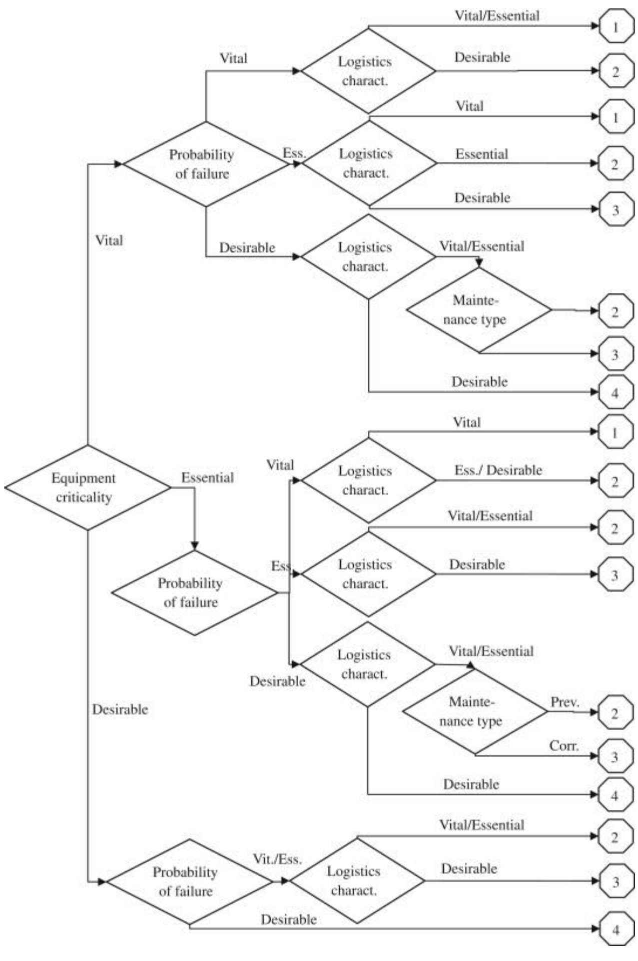

Figure 10. A four-stage decision tree model for criticality classification. AHP is applied for solving logistics characteristics according to relative weights of multiple criteria, presented in table 5. (Molenaers et al., 2012, p. 577.)

Lead time, number of potential suppliers and availability of technical specifications are presented as logistics characteristics in the decision tree. AHP is applied to provide an overall score for the three criteria, resulting a decision whether logistics characteristics is vital, essential or desirable. The decision making process is based on expert judgments. Pair-wise comparisons are conducted in order to assign relative weights to the criteria evaluated. The aim is to determine the most important criteria and how important they are compared to one another. This results a judgment matrix featuring the relative weights of different alternatives. As presented in table 5. This judgment matrix is then converted into mathematical matrix in order to calculate the normalized eigenvectors of the matrix. (Molenaers et al., 2012, p. 574.)

Table 5. Based on pair-wise comparisons lead time is considered 9 times more important than the number of potential suppliers in AHP judgement matrix, modified from Molenaers et al. (2012, p. 574).

	Lead time	No. of potential suppliers	Technical specifications	Normalized eigenvector
Lead time	1	9	3	0,669
No. of potential suppliers	0,111	1	0,2	0,064
Technical specifications	0,333	5	1	0,267

The method was tested in a case study in an industrial plant of a petrochemical company. The aim of the case study was to improve stock control at the plant. The results obtained with the analysis are proven to be accurate in the case study. 95 % of the parts were classified correctly. The authors conclude that the method can be applied as a generic decision making method. They also suggest that probability of failure could be analyzed more thoroughly by applying FMEA. Accurate information regarding failure data is necessarily not available in the case organization. Failure probability is, however, an important criterion for accurate analysis. (Molenaers et al., 2012, pp. 571; 575–576.)

Braglia et al. (2004, pp. 56–58) presented a spare part criticality analysis method based on AHP decision making and multiple decision trees in 2004. The method is called multi attribute spare tree analysis. A total of 17 criticality criteria are applied in this method. The criteria are divided in four groups according to which node of the decision tree they belong to. The four AHP models for categorizing the criteria are presented in figure 11. The criteria are categorized somewhat similarly as in chapter 5.2. Each criterion is divided into three groups: critical, essential and desirable, similar to VED scale. The analysis is conducted through series of decision making steps guided by a logic decision tree. The idea of utilizing decision trees is from the RCM methodology. The idea of decision tree is to guide the analyst through the whole process towards the correct criticality classification. Similar to the RCM methodology, finding correct answers to each decision is crucial. To overcome the decision making challenge AHP is utilized to solve the multi-criteria decisions at each node of the decision tree.

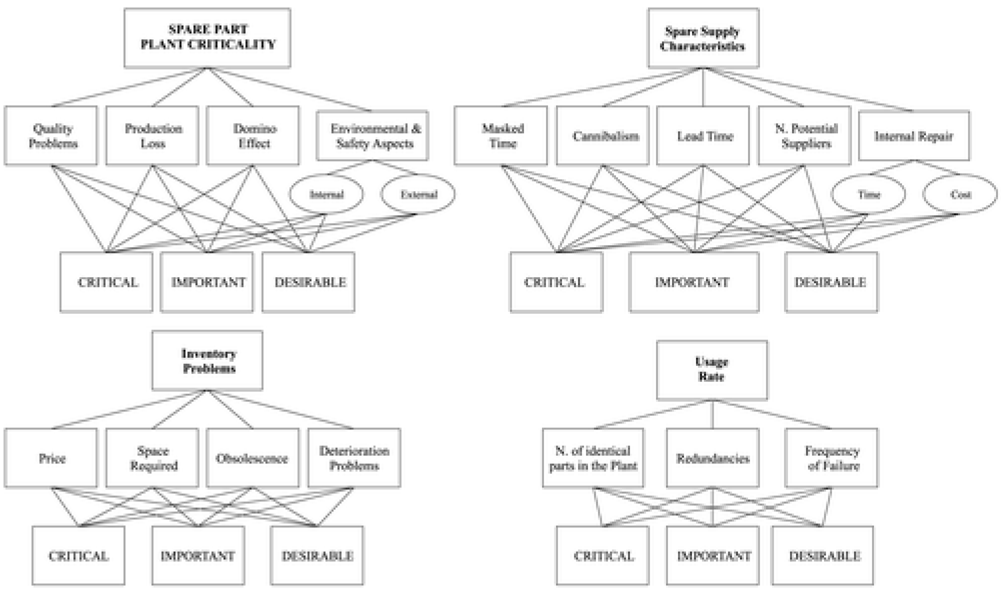

Figure 11. A total of four AHP models are applied in the decision tree by Braglia et al. (2004, p. 60). Each criticality criterion, e.g. quality problem, is categorized in one of these models.

Figure 12 presents the decision tree model for plant critical equipment. Similar tree models are also configured for equipment identified as important and desirable. Class A represents the most critical spare parts, whereas, class D the least critical ones. Criticality class is utilized in the last stage of the analysis to determine a correct inventory management policy for each spare part. For critical parts a multi item inventory is suggested, whereas, for classes

B and C either single item inventory or just in time policy are found more suitable. Stocking of non-critical items is not found desirable. (Braglia et al., 2004, p. 61.)

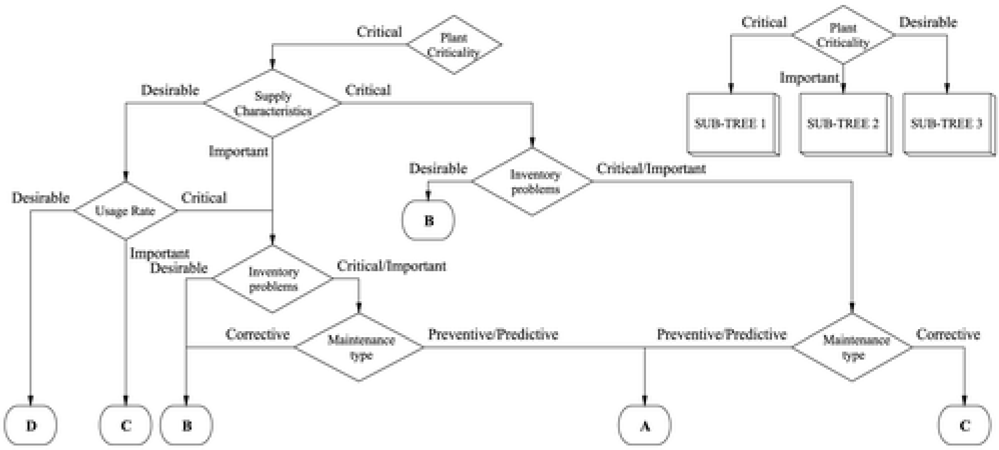

Figure 12. A decision tree for classifying spare part criticality of plant critical equipment by Braglia et al. (2014, p. 58).

Another multi-criteria VED analysis is also presented by Stoll et al. (2015, pp. 225–235). Spare parts are divided into three criticality classes according to VED scale. The criticality criteria are presented in a decision tree and the classification is based on AHP. The aim of this study is to recognize suitability of spare parts for central warehousing.

Figure 13 presents the outcomes of three-dimensional analysis method for warehouse management. The method utilizes ABC-classification, predictability of demand and criticality. ABC-classification is applied for analyzing items according to their purchase price in A, B and C classes. The accuracy of demand predictability is determined by coefficient of variation according to which it is divided into three classes X, Y and Z. X representing constant course of demand, Y average prediction accuracy and Z random demand. Item criticality is evaluated by applying AHP and VED. As a result the three-dimensional approach provides recommendations for spare part warehousing. (Stoll et al., 2015, pp. 227–229.)

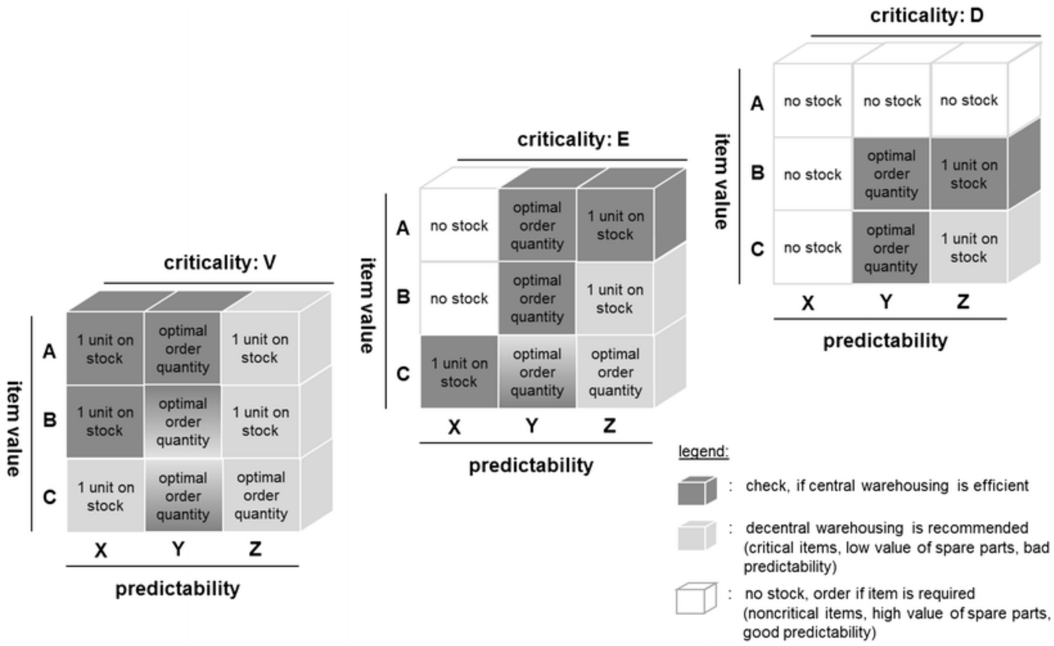

Figure 13. Suggested warehousing methods according to the three-dimensional analysis presented by Stoll et al. (2015, p. 229).

Criticality criteria are divided in two groups: maintenance and production. In maintenance point of view the criteria are: failure frequency, lead time and installation time. In production point of view: machine priority, equipment availability and shift plan. The criteria are then classified according to VED scale. E. g. failure frequency is considered as “vital” when a failure is expected to occur more than six times per year. (Stoll et al., 2015, p. 230.)

A relevant issue for the thesis is the criticality classification not inventory management. However, figure 13 provides an approach for combining predictability and item value with criticality. Thus all three attributes can be evaluated as such, when necessary. Figure 14 presents the hierarchy applied in the AHP process. Weighting of the criteria is solved according to AHP decision making process. In this case maintenance is considered twice the weight as production.

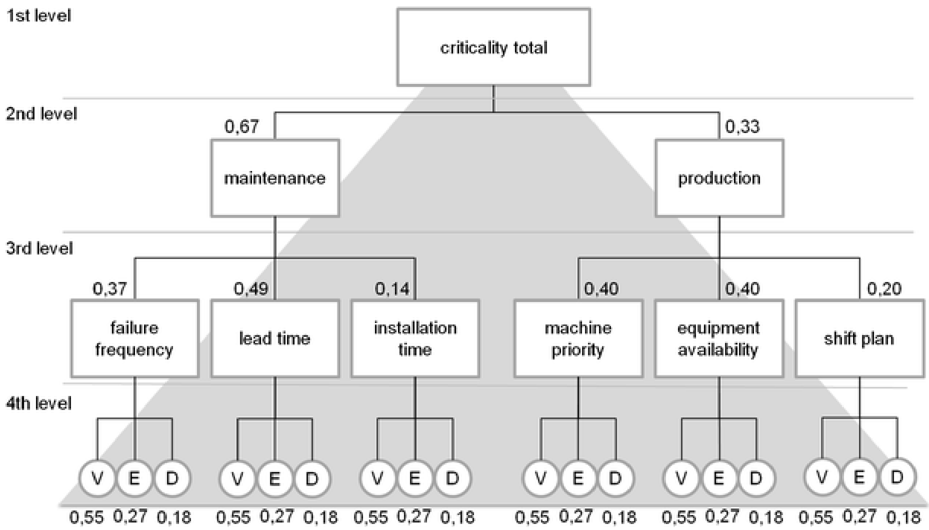

Figure 14. Hierarchy and determined weights of various criteria in the AHP model by Stoll et al. (2015, 233.) Lead time represents the highest weight in the model.

AHP is also successfully applied in a Chilean copper mining company for analyzing spare parts of a belt conveyer (Roda et al., 2014, pp. 543–545). Several attempts have been made to create a criticality analysis method based on AHP during this thesis. This was not, however, found convenient. Important criteria such as safety risk and functional criticality are found challenging for pair-vice comparisons. However, for weighing certain criteria, e.g. logistic aspects, AHP is applicable.

7.3.4 Fuzzy Logic Methods for Criticality Analysis

Fuzzy logic methods are also applied for criticality analysis and stock control of spare parts. Sarmah & Moharana (2015, pp. 456; 459) developed a fuzzy rule based method for classifying spare part inventories. The basic structure of a fuzzy inference system consists of three components: fuzzy rule base containing a selection of fuzzy rules, a database containing the definitions of membership functions applied in the fuzzy rules and a reasoning mechanism for performing the inference procedure according to the rules and created facts to derive a reasonable output as a result. Each five criteria are given the same weight in the analysis. The method is applied for inventory management and criticality is merely a criterion. The rest criteria relate to stock management. The method is incapable for identifying critical spare parts. By applying relevant criteria it could be utilized for criticality analysis, though, it has yet to been tested.

7.4 Summary of Criticality Analysis Methods

A literature review about spare part criticality analysis methods is also conducted by Roda et al. (2014, pp. 535–536.) In the review some of the methods are found too complicated or computational in practice. Fuzzy logic methods in ABC- or AHP-analysis are found complicated, whereas linear optimization is found too computational. AHP is considered to face the challenge of human error. Subjective criteria evaluated and compared in the AHP model are highly dependent on the persons making the judgment. The problem of traditional ABC-analysis is the lack of a multi-criteria application. In this thesis, complicated or computational methods are mainly ruled out. A challenge is, nevertheless, to reveal the methods actually classifying criticality and not spare part stocking. In many classification methods criticality is merely a criterion, instead of the result. However, no restrictions emerge for applying these methods for criticality analysis by selecting relevant criteria, as presented in section 5.2.

The methods presented in this section are mainly retrieved from Scopus. Thus aiming to provide a state-of-the-art view of various criticality analysis methods. However, several computational and complex methods are ruled out. Regardless of computer software enabling complicated analysis methods, they are not considered desirable. Most managers are reluctant to apply methods of which they are uncertain what the results are based on. (Huiskonen, 2001, pp. 132–133.) The basic principles of a fuzzy logic approach are, however, presented. A summarizing table of criticality analysis methods is provided in appendix II. The table aims to conclude the advantages and disadvantages of criticality analysis methods covered in this thesis. The methods are evaluated by considering the requirements of the case company.

8 CRITICALITY ANALYSIS METHOD FOR THE CASE COMPANY

In the previous three sections the characteristics of spare part classification, risk analysis methods and various methods intended for recognizing and classifying spare part criticality are covered. According to these sections a criticality analysis method suitable for the case company is developed and presented next. This section begins with a decision tree model for classifying spare parts. In order to interpret the model, criticality criteria and classes applied in the tree model are also covered. At the end of this section the analysis method is evaluated.

8.1 Generic Model for Analyzing Spare Parts

A decision tree model suitable for the requirements of the case company is introduced next. Each criticality criterion is categorized in groups of three or two. The construction of the decision tree began by recognizing definitions of each criticality class and the amount of classes. According to the classes recognized, applicable criteria were selected. According to the classes and criteria a decision logic was constructed. The decision tree is presented in figure 15. Criticality criteria and classes for interpretation of the decision tree are provided in tables 6 and 7.

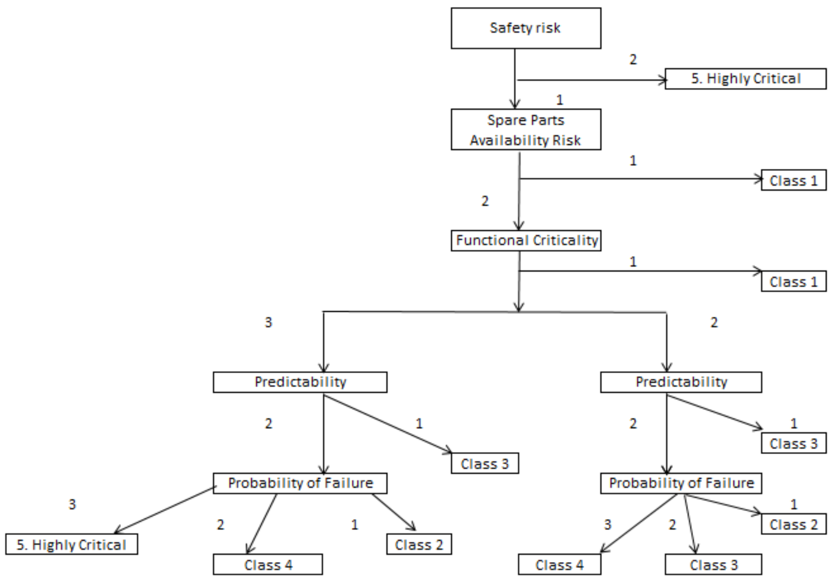

Figure 15. Decision tree model for classifying spare part criticality, developed for the case company.

Identification of critical functions, their sub-functions and hazardous situations is the initial stage of the analysis. This step is required in order to provide necessary data for the spare part analysis. Three ways of conducting the initial stage are recognized: a relevant risk analysis method, identification of functionally significant items or expertise of the analyst. An already conducted risk estimation can also be utilized at this point. The knowledge of equipment experts is essential even with relevant risk analysis methods. After the initial step, each spare part is analyzed starting from top of the decision tree according to the criteria presented next.

8.2 Criticality Criteria in the Analysis Method

Criticality criteria of Outotec proprietary equipment are provided in table 6. Safety is the first criterion in the decision tree presented in figure 15. Safety critical components are recognized by identifying components that affect safety in case of failure or unavailability. These components are to be recognized in the initial stage of the analysis as described earlier. In addition to the identified components, safety components according to ISO 12100 are also classified as highly critical. This well-known standard does not, however, replace the safety risks identified in the initial stage of the analysis. Many safety risks may emerge in addition to safety components.

The purpose of availability risk is to rule out the easily available components at an early stage. This leads to cost efficient analysis process which is especially useful for long spare part lists or bill of materials (BOM). Functional criticality aims to categorize components that affect function of the equipment. Components posing no threat to the function of the equipment are categorized as non-critical at this point and no further analysis is required for them.

Predictability aims to categorize the components with predictable and unpredictable failure pattern. Unpredictable failure pattern of functionally significant components leads to higher criticality classes, whereas, components with predictable failure pattern can be considered as less critical. A failure pattern is considered as predictable when deterioration of an item can be recognized well before failure, corresponding at least the lead time of the item. Probability of failure categorizes components according to their expected operating life. Components not expected to fail during the lifetime of the equipment or should run longer than five years are categorized as less critical. Components expected to be replaced within few years are recommended for the customer to be held in their own stocks, thus, classified as more critical. When estimating failure probability the operating environment, should also be considered.

Table 6. Recognized criticality criteria of Outotec proprietary equipment based on sections five and seven.

	1	2	3
Functional Criticality	No effect to the equipment or the environment	Causes malfunction	immediate shut down
Probability of Failure	Not expected to fail	Between 2 and 5 years	< 2 year
Predictability	Predictable well before failure	Unpredictable	
Spare Parts Availability Risk	Commercial Parts, e.g. Standard nuts and bolts/ Available or repairable < 2 days	Proprietary Parts. Industry parts. E.g. standard bearings and seals	
Safety Risk	no effect	Has an effect on safety. E.g. safety components according to ISO 12100	

Multiple criteria commonly found relevant in the academic literature are ruled out of the method presented in this section. The most important ones are: production loss, equipment criticality and lead time. Production loss is found as somewhat complex criterion. Production loss per time or in percentages are better approaches. For constructing a user friendly method, with low risk of interpretations, the criterion is not found suitable. Equipment criticality is also a challenging criterion. It is useful for stock control in a plant perspective. Receiving proper data of the local circumstances regarding equipment criticality can, however, be problematic. Since stock control perspective is limited out of this thesis, equipment criticality is not considered as criticality criterion. For this purpose item criticality, equipment criticality and item cost are suggested to be applied for decision making. Lead times are on many occasions several weeks and for insurance parts even longer. Thus, lead time is categorized either into few days or longer. The effect of e.g. five weeks lead time compared to ten is not considered to affect criticality classification. Lead time is, however, important evaluating predictability of failure.

8.3 Recognized Criticality Classes of Spare Parts of the Case Company

The following criticality classification is partially based on the classes presented by Huiskonen (2001, p. 129) in section 5.2. Criticality is first categorized in three classes according to available lead time in case of a part failure. Class five is added in order to take the safety aspects more profoundly in consideration. The aim is to identify parts that cause great risks to safety of the operating personnel. Class two is added for identifying the components that are critical but unlikely to fail. The criticality classes are presented in table 7.

Class five items are classified as highly critical due to high functional significance and frequent failure pattern or safety risk. These items, as well as, class four items are considered as suitable for stocking on site. The items in class three feature either predictable failure pattern or lower functional significance and less frequent failure pattern. They are not necessarily suitable to be held on site. Central warehousing can be more appropriate for these items. Class two items are functionally critical but not expected to fail. They are comparable to insurance parts. Stocking of these items can be considered case specifically. Class one items are not critical and long lead times are acceptable.

Table 7. Criticality classes of Outotec proprietary equipment based on sections five and seven.

Class	**Description**
1.	Non-critical, long lead time accepted Items that are not functionally critical or are easily available
2.	Functionally critical, Not expected to fail but critical for the equipment
3.	Certain lead time is accepted Predictable failure pattern (e.g. wear parts and electric motors) or functionally less critical
4.	Critical, spares should be stocked on site Moderate or high probability of failure Unpredictable failure pattern Lead time unacceptable due to functional criticality Recommended spare part packages e.g. wear parts with long lead times or high functional criticality
5.	Highly critical, severe effects on safety and/or immediate shut down Required spares, including safety components Safety is the major aspect

8.4 Evaluation of the Criticality Analysis Method

In order to verify the usability of the developed analysis method a thorough evaluation is conducted. The decision tree model, criticality criteria and classes are evaluated according to the nine criteria, presented in section 2.1. The evaluation according to each criterion is described in table 8. The evaluation is conducted in co-operation with two maintenance experts.

Based on the evaluation the analysis method is suitable for classifying spare part criticality in the case company. Disadvantages of the method are high competence required from the analyst and the lack of quantifiable variables. Advantages are the ability to guide the analyst to the correct criticality class with a minimum amount of variables. The validity of the results is also an advantage. The decision tree can also be extended or modified if necessary. A logical way to extend it would be by adding more options to availability risk. By separating proprietary parts from industrial parts as Paakki et al. (2011, p. 167) suggested, the availability and especially lead time can be taken better into account.

Table 8. Results of the evaluation of the analysis method according to Sink`s criteria to verify the usability of the developed analysis method.

Criterion	**Evaluation**
Validity	Item criticality is measured from several approaches by applying relevant criteria. The analysis method focuses on item criticality by considering both process and control criticality, as well as, safety risk. A higher weight is, however, given for process and maintenance aspects of criticality. The analysis is considered as valid.
Accuracy and precision	Available data has an effect on accuracy, as well as, competence of the person responsible for conducting the analysis. Criteria are relevant and guide the analyst to the right direction. The accuracy could be improved for the most critical components. Certain criteria can be added in the decision logic in order to improve accuracy.
Completeness or collective exhaustiveness	The method is complete with the current criteria in order to describe the phenomenon. Each criterion evaluates a certain aspect of criticality in order to provide a complete view of the phenomenon.
Uniqueness or mutual exclusiveness	Each criterion applied in the analysis method describes different aspects of the phenomenon. No redundant or overlapping criteria exist.
Reliability	Accuracy has an effect on reliability. Competence of the person conducting the analysis has an effect on reliability. Especially functional criticality and failure probability rely on competence of the analyst.
Comprehensibility	The method is simple yet conveying the meaning intended. Each criterion has a minimum amount of different variables in order to evaluate the phenomenon comprehensively.

Table 8 continues. Results of the evaluation of the analysis method according to Sink`s criteria to verify the usability of the developed analysis method.

Criterion	**Evaluation**
Quantifiability	Most of the criteria are qualitative and difficult to quantify yet describing the phenomenon accurately. Many of the criteria present two options according to which proceed. Qualitative criteria are, thus, considered more suitable.
Controllability	Not all criteria can be controlled. Probability of failure and predictability can be controlled to some extent by applying condition monitoring and preventive or predictive maintenance. For the availability risk, only minimal corrective actions are possible. Controlling other criteria would require redesign of the equipment.
Cost of effectiveness	For new and unfamiliar equipment the analysis is especially cost effective. For older equipment the critical components can be familiar already. However, a systematic approach, as presented in this section provides unambiguous results for both new and old equipment. The analysis method also focuses on critical components instead of clearly non-critical ones, thus, improving cost of effectiveness.

9 CASE EXAMPLE OF SPARE PART CRITICALITY ANALYSIS OF FULL DEPOSIT STRIPPING MACHINES

The analysis method presented in the previous section was verified for classifying spare parts of a full deposit stripping machine. The analysis was conducted in weekly meetings with equipment experts. Relevant data required for the analysis relied on expertise of the analysts. Spare parts of the machine were analyzed one unit at a time beginning with the most critical ones. Due to profound understanding of functioning of the machine, a risk identification was not required prior to the analysis. The classification method was constructed on an Excel sheet. Brief instructions of constructing an excel sheet are provided in appendix III. Some important findings in the analysis process are introduced in this section, as well as, results of the analysis. The findings concern mainly usability of the method and the results.

After analyzing all spare parts of the machine, an attempt was made to build a generic model of critical spare parts for this type of equipment. Each machine is different from one another but similarities exist. Most of the functions of each machine are the same, thus, functional location approach was chosen to identify similar parts. Another way is to compare identical item codes between equipment. The analysis method is, however, designed to classify items according to their functional locations. Applicability of the developed analysis for other proprietary equipment is also evaluated in this section.

9.1 Findings in the Analysis

The analysis was conducted for items in the bill of material (BOM) already identified as spare parts. Most of the items in the BOM were thus excluded of the analysis, e.g. common bulk items. The classification results are presented in figure 16. Approximately one third of spare parts were recognized as easily available or low in functional criticality and categorized in criticality class one. Most of the items recognized as spare parts are expected to be replaced at some point. Thus, the amount of class two spare parts was low. Most class five items are safety critical. According to the equipment experts, the classification results reflect criticality of the items correctly. The amount of critical spare parts can also be reduced significantly by identifying identical items within the equipment. This is worth considering while planning stocking of these items.

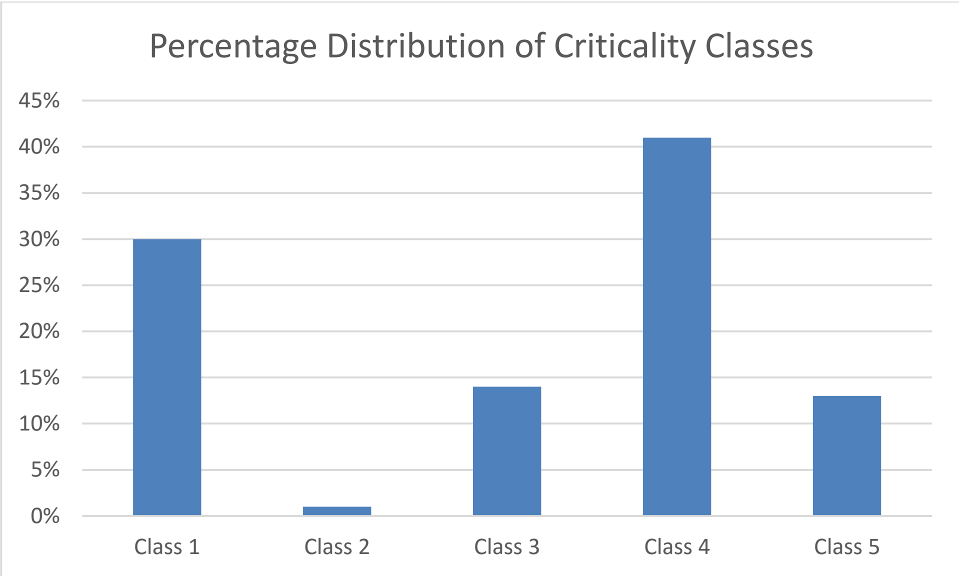

Figure 16. Ratio of spare part criticality classes of a full deposit stripping machine (FDSM).

Predictability proved to be a problematic criterion in the analysis method. No failure pattern was recognized as predictable. For site-specific criticality analysis, with an already existing predictive maintenance plan, failure predictability could cut stocking costs by lowering criticality of certain items. By conducting criticality classification in co-operation with the customer more accurate results could be reached.

The analysis method proved to be user friendly. All spare parts were analyzed in five meetings, each of them lasting about an hour. This was mostly due to well-prepared participants in the meetings. No time was consumed for finding relevant data regarding spare parts, nor for constructing excel sheets. The analysis method was also functioning as planned. However, construction of excel sheets prior to meetings somewhat doubled the total time consumed. Thus, user interface of the analysis method requires some development. Integration with PDM is expected to solve this challenge. A lot of time was, however, saved due to expertise of the analysts.

9.2 About Generic Applicability of the Analysis Results

The practical aim of this thesis is to construct a generic model of critical spare parts of linear type full deposit stripping machines. According to criticality classification, spare part recommendations can be created. Most of the machines consist of the units presented in section 3.6. An exception is the corrugating press which is optional and installed roughly on half of the machines. In addition to the mechanical units a significant amount of spare parts can be found from hydraulic, electric and pneumatic systems. The analysis method is considered also as capable for classifying these items.

An attempt was made to construct a generic model of critical spare parts. The model was constructed by first analyzing all spare parts of a single stripping machine. The machine was considered as suitable for creating generic analysis for this type of equipment. In the analysis process described earlier in this section, some units of the machine were found more critical than others. Thus, functionally critical spare parts within these units received higher criticality classes. The units are somewhat comparable between various machines. Even though not many identical item codes were found between different machines, functional locations of the parts had only little variation. For linear type of machines, representing the most of the installed base, the units are mostly similar. Technical variations exist depending on the year of commissioning.

Each unit of the machine consists of multiple assemblies and sub-assemblies. Most of the units are critical for the machine, but not all assemblies nor items within these units. Variations exists between similar units in different machines. By comparing assemblies and sub-assemblies of the units a decision can be made whether to apply the already created model or to conduct a machine-specific criticality analysis.

Linear and robotic type stripping machines are comparable to some extent. The key difference is deposit removal which can be entirely different. Both types of stripping machines feature conveyors for receiving, discharging and washing of cathodes, as well as, material handling after removal of copper deposits. The function of these units is roughly similar regardless of the machine. Most spare parts are also recognized similar in these assemblies, e.g. chain and bearings in the conveyors. The advantage of a robotic type machine, compared to linear type, is speed. Higher speed leads to higher wear. Regardless of similar construction, failure probability can be higher for mechanical parts of a robotic type machine. The financial consequences of unavailability of the machine are also higher. These factors should be considered when applying the spare part classification for robotic type machines.

A challenge in creating a generic model is the variation of maintenance practices of each machine. Depending on the level of maintenance failure probability can vary. Geographical location of the machine may also cause challenges. Some countries are more difficult to export than others. Some locations are in industrial areas where spare parts are easily available and the basic infrastructure is in good condition, whereas, in other locations these aspects are challenging, leading to more profound safety stocking.

Under the exceptions provided, the criticality classification conducted in this section can be utilized as a generic model. Items in criticality classes four and five are suitable for spare part recommendations in order to ensure safe operation and availability of the machine. The classification is only available within the case company. A modified example of the classification is provided in appendix IV.

9.3 Applicability of the Analysis Method for Other Proprietary Equipment

The method has also been tested to another similar equipment in the development stage of the analysis method. The results are, however limited and no conclusions of this can be drawn. The method is not developed only for the case example. It is designed for large amount of items, even entire BOMs. It is also intended for items with relatively long lead times.

No apparent restrictions for applying the method for other equipment have emerged. The method is not specifically designed for stripping machines. It is also generic in nature and could provide correct results for many types of equipment. A restriction is the ability to recognize a difference in criticality whether the lead time is e.g. a week or eight weeks. The ability of the method to recognize differences in availability risk of these items is low. In such a case, additional tree models are required to consider more variables in the availability risk.

10 DISCUSSION

This section begins with discussion regarding the references utilized in the literature parts of this thesis. Reliability and validity of the study leading to classification methods presented in sections seven and eight are also discussed. Generalization of the results presented in section eight are discussed next. Objectivity of the study is also evaluated. At the end of this section future research suggestions are laid out, in addition to which, key findings and conclusions are presented.

10.1 About the References

Literature references can be divided roughly in three groups: research articles, material provided by the case company and standards. About half of the references are research articles. Especially regarding articles cited in section seven, it is worth mentioning that many of the authors refer to articles published by each other. All of the articles also refer to Huiskonen (2001). Braglia et al. (2004) is also very common reference in these articles. Even though several authors refer to the same articles it can be concluded that their results are reliable because they have been evaluated and accepted by multiple researchers. Frequent citations in these few articles increases, thus, their validity. Each research is based on previous work of other researchers.

A common criticality classification method in academic literature is VED analysis which does not seem to be an analysis method. It is rather a way of categorizing outcomes of a criterion in three groups. Similar categorization can be conducted disregarding the amount of categories and it does not have to be called an analysis method. Other than that the contents of the references are still valid. Even though the categories vital, essential and desirable well describe the criticality of an item, it is difficult to see VED as an analysis method.

In academic literature, specifically weighing of criteria in reaching a decision was found as one of the greatest challenges. This challenge is solved in this study by creating a decision path instead of weighing the criteria. By beginning with the desired results, in this case defining criticality classes, the decision making process leading to these results is fairly unambiguous to construct. Weighing of criteria is, thus, not found challenging.

An important aim of this thesis was to refer articles that are published well after the millennium. Few articles published before this, were also referred due to frequent citations in Scopus. When referring to articles published before or around the millennium they had to be frequently cited to this day in academic literature. For some standards such as SFS 5438 the valid version dates back to 1988. Valid information regarding criticality analysis methods and their characteristics can be found from older publications. In articles published around the millennium a challenge encountered by researchers was computational performance. Computers have without a doubt increased their performance since then. The basic characteristics of classification have, however, remained similar. Relevant references in section seven were published in 2012 and 2015, as well as, the literature review referred in section five which was published in 2014. Thus, the key references are fairly new. References published earlier than that are mainly cited by the three previous articles. In section four the references covering after sales services are also fairly new.

A great number of references are also produced by the case company. Some of them are confidential, especially in section three. The basic theory of electrolysis technology is, however, available in academic literature. Receiving a state-of-the-art understanding of these technologies is more reliable by utilizing material provided by the case company. Especially for a person, previously unfamiliar with these technologies. The range of Outotec proprietary equipment in tankhouse technologies is also described in an understandable way in educational material of the company. No confidential material is presented at this point. This applies also to the case example. Some references are, however, inaccessible without a permit which can be noticed in the reference list.

10.2 Reliability and Validity of the Thesis

Reliability and validity of this thesis are discussed next. Sections seven and eight aim to answer the research questions presented in the introduction. The results have been obtained after a thorough literature review and interviews. The results were also verified for the case example. The results of the case study proved accurate.

The results obtained are valid. Criticality analysis methods studied in the academic literature are presented. The results are evaluated according to nine criteria by Sink (1985) which is a widely accepted method for evaluating a measurement. This increases the overall validity of the study. A thorough literature review has been conducted and to overcome subjective decision making the results are also evaluated.

Variations in reliability can occur. The methods described in section two rely to human judgement to some extent. Even though an objective mindset is maintained throughout the thesis, repeatability can suffer in various contexts. However, for the case company, similar results are expected with these research methods. The requirements of the case company are also fulfilled. The classification method is verified to provide accurate results in early testing stages, as well as, for the case example.

A decision tree model is recognized as suitable method after a literature review and several meetings. The main reason is the ability to classify safety and availability risks at an early stage of the analysis. Multiple overriding criteria makes weighing of criteria unattractive. The most overriding criterion being safety risk. This rules out the methods relying on weighting. These methods were, however, evaluated as well in this context, e.g. pair-wise comparisons as in AHP. Decision tree was still recognized as the most suitable method.

10.3 About Generalization of the Results

The criticality analysis method developed as a result of this thesis is designed for the requirements of the case company. It is well generalizable for the case company for recognizing and classifying critical spare parts. One aim being to support spare part sales and the other to recognize the components causing the greatest risk for production and safety. For any other closely related purposes, e.g. stock control or logistics management, it cannot be applied as such. The method does, however, support decision making in these areas. A stocking suggestion is presented in section eight. The suggestion is informative only and is not thoroughly studied. Site specific stocking strategies can be developed according to criticality class of an item, price of the item and criticality of the equipment.

The criticality classes from one to five are necessarily not in a logical order. An important factor in the classification is probability of failure. Item criticality can also be considered more as the cause of unavailability, rather than the risk of it. The classification is based on classifying failure risk. For some stake holders the criticality of an item does not concern the probability of it. Thus, sorting items according to criticality class does not provide correct results due to class two items being functionally more critical than some of class three items. By altering the classification in a way that class two items are class three and vice versa, criticality classes five to three can be considered as the functionally most critical items. Another way is to filter the classification results, as presented in appendix IV, by considering the criticality criteria case specifically.

The analysis method is designed for the case company. It does not necessarily provide valid results for other companies, even in the same fields of industry. However, the method developed as a result of this thesis could be tested in other circumstances. No obvious restrictions exist for this method to be inapplicable in other fields of industry. As already mentioned in section 9.3 the method is well generalizable for other equipment with long spare part lead times. For items with shorter lead times it may not be applicable as such.

10.4 Objectivity of the Thesis and Further Research Suggestions

Objectivity of this thesis and further research suggestions are discussed next. The focus is in objectivity of the thesis, not in objectivity of the analysis method in section eight. Weighing of certain elements in the literature part, in this case different analysis methods, can vary depending on the author. Variations can occur depending on technical background of the author. Mathematical methods are more desirable for some, whereas, others are less familiar with them. In this case the author does not have the resources for evaluating all of these methods. Decision trees and the AHP are more understandable. However not including decision trees and AHP in the thesis would be unacceptable since they are applied in multiple relevant research articles. The reason for not including statistical or complex methods is still obvious. It came evident already at an early stages of the study that too computational, labor consuming or complex methods are not discussed.

In section seven more classification methods could have been presented. The amount of optimization methods relying either on fuzzy logic or linear optimization is significant. However, they are usually intended for stock optimization rather than criticality classification. Case studies regarding these methods are also still low. The analysis method should, however, be understandable for persons who are unfamiliar with them. Thus, the methods in section seven represent methods, possibly suitable for the case company more than state-of-the-art view of spare part criticality classification.

Some of the methods presented in section seven have been tested for the case company. Especially a method relying on AHP, VED and decision tree was designed and feedback from the company was received. A simplified method was requested with fewer outcomes for the criteria. Each classification method presented in this thesis were provided with an equal chance to be applied in section eight. However, a decision tree gained more advantages than any of the other methods.

The usability of the analysis method presented in section eight should be studied for other proprietary equipment of the case company. Even though no restrictions for applying the method for other equipment were found, further case studies are required. In further case studies the accuracy of the results should be evaluated more thoroughly than in this thesis. The usability of the method in identifying critical spare parts of entire process plants and creating stocking recommendations accordingly is an important area of research. By evaluating the effect of item criticality, item price and equipment criticality, spare part recommendations for an entire process plant could be created.

10.5 Key Findings and Conclusions

Study for finding methods for identifying and classifying spare part criticality has led to the following key findings and conclusions:

1. Even though equipment criticality is an important criterion for classifying spare part criticality, it is not convenient to consider both plant and equipment perspectives simultaneously. Thus, equipment criticality is excluded from the analysis method presented in section eight. For managing spare part stocks in a plant perspective, equipment criticality is a relevant criterion in addition to item criticality.

2. Price of the spare part is a common classification criterion, especially in the traditional ABC-analysis. It has, however, no direct effect on the criticality of an item, regardless of being widely applied in stock control. According to criticality of an item, price of the spare parts should be considered alongside equipment criticality,

item criticality and the amount of identical items, while planning spare part recommendations.

3. A decision tree is the most suitable method for identifying critical spare parts in the case company. It allows the analyst to focus on the most critical items by ruling out the obviously not critical ones, or including the most critical, at an early stage. Accurate results are achieved with only little chance for interpretation. Decision tree is also easy to understand for persons less familiar with multi-criteria decision making methods.

4. Five criticality classes are recognized suitable for the case company. A total of five criticality criteria are also found sufficient for classifying spare part criticality. The classification method is also verified to the case example, as a result spare part recommendations according to criticality for this type of equipment can be created.

5. The method in section eight is not yet capable for creating stocking recommendations. However, it points out that classes four and five are worth considering to be stocked on site. Whereas, central stocking is recommended for class three items. Class one spare parts are not recommended for any type of stocking. Class two parts are similar to insurance parts and stocking is to be considered case specifically.

6. A decision making method does not have to be complex, nor does it have to consider countless number of criteria. Subjective decision making of the analyst can be overcome by an understandable and uniform decision making process. By evaluating the outcomes of each criterion and accordingly continuing to the next one in the decision tree, challenges related to human judgement can be overcome. By documenting each step of the analysis, the basis for the criticality classification can be later reviewed.

7. Criticality can be presented either as a decision making process, leading to classes or as a numerical index. The index can also be categorized in ranges, each of them representing a class. By applying a numerical index, items can be sorted in order of

magnitude according to their criticality, whereas, decision based methods can only produce a certain amount of classes as a result. The aim of this thesis is to classify items into criticality classes, for which a decision tree is found as suitable analysis method, thus, numerical index is not applied.

8. In general criticality classification does not seem to be affected by the analysis method itself. By applying relevant criteria, most multi-criteria decision making methods, presented in this thesis, can be applied. Thus, analysis methods intended for stocking purposes can be applicable also for criticality analysis.

9. The method presented in section eight is suitable for analyzing spare parts that have relatively long lead times. The method does not recognize a difference in criticality, whether, the lead time is a week or ten weeks. Other than that, it can be considered suitable for other equipment than the case example.

11 SUMMARY

Multiple approaches exist for classifying spare part criticality. The aim of this thesis was to find a suitable analysis method for classifying spare part criticality in the case company. An important way to utilize spare part criticality is to identify the items risking safety or production in case of failure or unavailability. According to which spare part recommendations can be created.

In order to find a suitable method, a literature review was conducted. The analytic hierarchy process (AHP) is gaining interest in classifying spare parts in the academic literature. AHP is often combined with decision trees or the tree models are applied as such. Another common method is to categorize spare parts as vital, essential and desirable (VED). By categorizing multiple criteria according to these classes, the overall criticality class can be solved by applying decision trees and AHP. The aim of AHP is to overcome subjective judgement in the analysis process. A standard method for criticality classification is provided in PSK 6800 standard. The method is, however, intended for classifying equipment criticality. Classifying spare parts is also possible to some extent, but labor consuming.

A decision tree for classifying spare part criticality was developed for the case company. The decision tree consists of five criteria and it classifies spare parts into five criticality classes. The criteria applied in the classification are: safety risk, the risk of availability for spare part, functional criticality, predictability of failure and probability of failure. The criteria are applied for each item in the bill of material recognized as a spare part. The method is verified for classifying spare parts of a full deposit stripping machine. According to which critical spare parts of other similar equipment can be recognized.

No evident restrictions of applicability of the method for other proprietary equipment of the case company are recognized, nor for equipment of other manufacturers. Further case studies are, however, required for this purpose. It can be concluded that equipment criticality and purchase price of a spare part have no effect on spare part criticality in this context. Criticality analysis of spare parts offers valuable input data for developing stocking strategies.

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Appendix I

List of interviews and meetings

All memorandums are in possession of the author.

Meetings and interviews regarding section 5

Title	Date
Manager - Commercial Product Management, Service	23.10.2015 4.12.2015
Shutdown Planner	23.10.2015
Product Manager, Tankhouse Machines	26.10.2015 12.11.2015 4.12.2015
Product Manager, Tankhouse Machines	12.11.2015 4.12.2015
Pricing Specialist, Global Services Function	18.11.2015
Electrical and Instrumentation Engineer	23.10.2015 30.10.2015 9.11.2015

Meetings regarding section 9

<table>
<tr><th>Title</th><th>Dates</th></tr>
<tr><td>Assembly Coordinator, Stripping Machines</td><td rowspan="4">22.12.2015
13.1.2016
21.1.2016
28.1.2016
10.2.2016
17.2.2016</td></tr>
<tr><td>Service Admin</td></tr>
<tr><td>Manager, Spare Parts, Stripping Machines</td></tr>
<tr><td>Manager - Commercial Product Management, Service</td></tr>
</table>

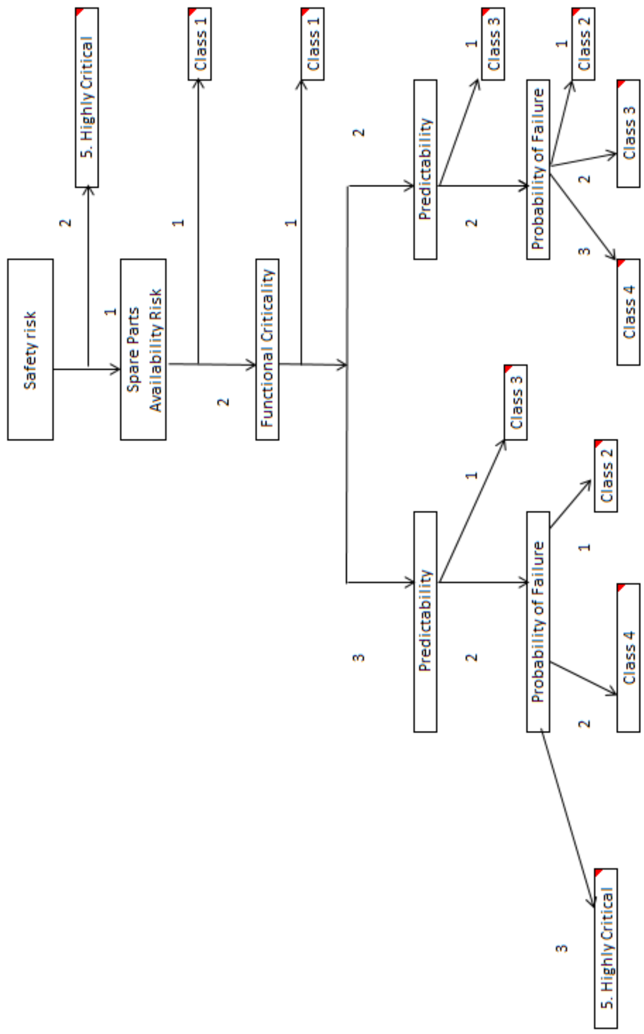
Summary of criticality analysis methods

Method	**Advantages**	**Disadvantages**
FMECA	Standard method applicable with RCM. Enables creating maintenance programs simultaneously with spare part classification.	Labor consuming. Does not consider logistics/ supply aspect of criticality
Current methods applied in the company	The classification is based on numerical index. Safety components are identified and given the highest criticality class	Labor consuming. The number of criteria and values for each criterion are great.
PSK 6800	Sub-indices e.g. for safety and production indicates why an item is critical. Already familiar method in the case company	Labor consumption for spare part analysis. Describes better equipment criticality than spare part criticality due to production loss estimation.
VED and ABC by Cavalieri et al	The ability to combine multiple approaches for classification, FSN, VED and ABC.	Several stages are required in the analysis process. Too complicated for spare part analysis. The method is not described in detail by the authors.
Decision tree by Carpentieri et al.	Considers both equipment and spare part criticality. Low amount of criticality criteria.	No case study results. The amount of criteria can be too low.
Decision tree and AHP by Molenaers et al.	Relevant amount of criteria. With slight changes in the decision logic the method could suit for the case company. Promising case study results.	The decision logic is constructed for stock control. AHP complicates the analysis.

Summary of criticality analysis methods

Method	**Advantages**	**Disadvantages**
Decision tree and AHP by Braglia et al.	The amount of criteria reduces the effect of inaccurate data of a single criterion.	The amount of criteria is significant.
AHP by Stoll et al.	The amount of criteria. AHP is suitable for weighing criteria that are nearly as important to each other.	Not all relevant aspects of criticality are considered, e.g. safety.
Fuzzy Logic approach by Sarmah & Moharana	Provides a quantified approach.	Complexity and no case study nor practical experiments
The decision tree presented in section 8	Relevant amount of criticality criteria and classes. Tested in a case study. Provides valid results.	The effect of lead time is limited in the analysis.

Instructions for constructing an analysis sheet



CRITICALITY CRITERIA

Safety Risk	Availability Risk	Functional Criticality	Predictability	Failure Probability	Criticality Class	Class 5	Class 4	Class 2	Class 3	Class 4	Class 2	Class 3	class 5	Class 1	Class 1	Class 3
1	2	2	2	3	4	0	0	0	0	1	0	0	0	0	0	0

Instructions for constructing an analysis sheet

Brief instruction for applying the excel sheet

The criticality analysis method is constructed on a single excel row as presented in the figure above. Each outcome of the decision tree has a corresponding cell on the right side of the “criticality class” cell. The cells are numbered in the comment box. In these cells a conditional statement is created. If the condition in the cell is fulfilled the cell receives a value 1, if not, the cell value is 0. Only one cell at a time can receive value 1. “Criticality class” cell recognizes which of the cells receives value 1 and presents the corresponding criticality class. Until sufficient amount of criteria in the analysis are provided, the outcome of the “criticality class” cell is “false.”

In order to function the entire row has to be copied to spare part list after which it can be copied to each row in order to easily classify each row of the spare part list. In annex IV the columns containing outcomes of the analysis, the “ones” and “zeros”, are hidden. These columns are, however, vital for the method to function because the correct outcome of the analysis is in one of these cells. The analysis method is in an Excel file that contains also the criticality criteria and classes as presented in section eight of this thesis.

Appendix IV

Modified example of criticality analysis sheet

Assembly	Part number	Code	Item	Quantity	Spare part type	Safety Risk	Availability Risk	Functional Criticality	Predictability	Failure Probability	Criticality Class
Unit 1, assembly 1											
			GUIDE LIST, ROBALON	6	S	1	2	2	2	3	4
			SCREW JACK	4	I	1	2	3	2	1	2
			SHAFT	4	I	1	2	3	2	1	2
			SHAFT COUPLING	1	I	1	2	3	2	1	2
			WHEEL BLOCK	1	I	1	2	3	2	2	4
			WHEEL BLOCK, DRIVEN	1	I	1	2	3	2	2	4
			DAMPER	4	I	1	2	3	2	2	4
			DRIVE UNIT, DESIGN LEFT	1	I	1	2	3	2	2	4
			BUMP STOP	2	I	1	1	1	1	1	1
Unit 1, assembly 2											
			ROLLER BEARING	2	S	1	2	1	1	1	1
Unit 2, assembly 1											
			GUIDE LIST, ROBALON	6	S	1	2	2	2	3	4
			SCREW JACK	4	I	1	2	3	2	1	2
			SHAFT	4	I	1	2	3	2	1	2
			SHAFT	2	I	1	2	3	2	1	2
			BRAKE MOTOR	1	I	1	2	3	2	2	4
			WHEEL BLOCK	1	I	1	2	3	2	2	4