Tampere University

Jancarlo Rodriguez

SPARE PARTS CRITICALITY ANALYSIS IN BIOGAS PLANTS

Master of Science Thesis
Faculty of Engineering and Natural Sciences
Examiner: University Lecturer, Henrik Tolvanen
Examiner: University Instructor, Hasse Nylund
April 2021

ABSTRACT

Jancarlo Rodriguez: Spare parts criticality analysis in biogas plants
Master of Science Thesis
Tampere University
Environmental and Energy Engineering, M.Sc
April 2021

The heterogenous nature of spare parts pose a great challenge for internal spare parts management in industrial companies. Therefore, it is important for asset-intensive industrial plants to categorise their spare parts assortment into relevant categories to control different items with varying characteristics. However, prior literature lacks implementation of spare parts multi-criteria classification methods in an industrial context and the use of such methods among practitioners is still limited. This thesis is conducted as a single case study, providing a method for spare parts criticality classification which can be used as a management tool in the case company.

The thesis is conducted with a constructive research approach with an intention to solve a real-life managerial problem by developing a problem-solving construction and to test its practical applicability by implementing it. The research was conducted as mixed-model research by combining quantitative and qualitative data collection techniques and analysis procedures. The collected qualitative data were analysed using an inductive approach by summarising as well as restructuring meanings into narratives to help the creation of the classification method. The classification method quantifies the qualitative judgements of spare parts characteristics into numerical codes so that the classification results can be analysed statistically. The developed classification method was used to categorise the spare parts assortment into relevant categories in three biogas plants of the case company. Each of these plants represents a mesophilic wet digestion technique in which biogas is produced through anaerobic treatment by adding organic matter into continuously stirred tank reactors (CSTR) using pumps.

In this thesis, multi-criteria approach for spare parts classification is presented. The method is based on a decision tree approach which classifies spare parts into different classes based on their criticality. Five criticality criteria are considered in the method: functional criticality, alternative production, availability, value, and demand pattern. However, many of these criteria include several other aspects as well. A spare parts management matrix is also provided to support managers in their decision-making and to give recommendations for spare parts management according to the criticality class derived from the criticality analysis. The conducted criticality analyses found that current safety stocks are partially deficient: each of the three biogas plants examined stored less than 40 % of the spare parts for which stock keeping is recommended.

The developed criticality classification method was evaluated as applicable for spare parts management in the case company. The method can be used to assess spare parts criticality in a transparent and systematic manner by considering several criteria affecting criticality, thus providing the means to support maintenance and plant managers in their decision-making. However, the greatest disadvantage of the method is that it requires expert judgement which exposes to a high level of subjectivity.

The results of the criticality analyses conducted during the thesis provide a comprehensive overview of spare parts criticality classification in biogas plants, and thus they can provide insights for other practitioners in similar industrial settings. In that respect, this thesis can be seen as a contribution towards bridging the gap between spare parts management research and practice.

Keywords: spare part, biogas, multi-criteria classification, criticality analysis

TIIVISTELMÄ

Jancarlo Rodriguez: Biokaasulaitoksen varaosien kriittisyysanalyysi
Diplomityö
Tampereen yliopisto
Ympäristö- ja energiatekniikan DI-tutkinto-ohjelma
Huhtikuu 2021

Varaosien heterogeenisuus luo haasteita teollisuusyritysten varaosien hallintaan. Tämän vuoksi pääomaintensiivisten tuotantolaitosten on tärkeää jakaa varaosat eri luokkiin niiden ominaisuuksien perusteella helpottaakseen niiden hallintaa. Varaosien luokittelua käsittelevässä kirjallisuudessa on kuitenkin kiinnitetty varsin vähän huomiota varaosien monikriteeristen luokittelumenetelmien implementointiin teollisessa ympäristössä, ja tällaisten menetelmien käyttö on edelleen rajallista käytännössä. Tämä diplomityö toteutetaan tapaustutkimuksena, jossa kehitetään kriittisyysluokittelumenetelmä kohdeyrityksen varaosien hallinnan tueksi.

Tämä tutkimus toteutettiin konstruktiivisella tutkimusotteella, jonka tavoitteena on ratkaista tosielämän ongelma kehittämällä ratkaisu ja testata sen käytännön toimivuutta implementoinnin kautta. Tutkimus toteutettiin sekamallitutkimuksena yhdistämällä kvalitatiivisia ja kvantitatiivisia tiedonkeruu- sekä analysointimenetelmiä. Kerätty kvalitatiivinen aineisto analysoitiin käyttämällä induktiivista päättelylogiikkaa, jossa aineisto tiivistettiin ja muotoiltiin narratiiveiksi. Analysoitua aineistoa hyödynnettiin varaosien luokittelumenetelmän kehittämisessä. Luokittelumenetelmässä kvantifioitiin varaosien ominaisuuksia kuvaavat kvalitatiiviset väittämät numeerisiksi koodeiksi tulosten tilastollisen analyysin mahdollistamiseksi. Kehitettyä luokittelumenetelmää käytettiin varaosien luokitteluun kolmessa kohdeyrityksen biokaasulaitoksessa. Kukin näistä biokaasulaitoksista edustaa mesofiilista märkämädätystekniikkaa, jossa biokaasua tuotetaan anaerobisen käsittelyn avulla pumppaamalla orgaanista aineitta täyssekoitteiseen reaktoriin.

Tässä diplomityössä esitetään päätöspuulogiikkaan perustuva varaosien monikriteerinen luokittelumenetelmä, jossa varaosat luokitellaan niiden kriittisyyden mukaan. Luokittelumenetelmä ottaa huomioon viisi eri kriittisyyskriteeriä: funktionaalinen kriittisyys, vaihtoehtoiset toimintatavat, saatavuus, hinta ja kysynnän luonne. Monet näistä kriteereistä huomioi myös muita näkökohtia. Työssä esitetään myös varaosien hallintamatriisi, jossa annetaan suosituksia varaosien hallintaan kriittisyysanalyysistä johdetuille eri kriittisyysluokkien osille. Näin ollen varaosien hallintamatriisia voidaan käyttää päätöksenteon tukena. Toteutettujen kriittisyysanalyysien pohjalta havaittiin nykyisten varmuusvarastojen olevan osittain puutteellisia: kukin tarkastelluista kolmesta biokaasulaitoksesta varastoi alle 40 % sellaisista varaosista, joille varmuusvarastointia suositellaan.

Kehitetty kriittisyysluokittelumenetelmä todettiin varaosien hallintaan soveltuvaksi työkaluksi kohdeyrityksessä. Menetelmää voidaan käyttää varaosien kriittisyyden läpinäkyvään ja systemaattiseen arviointiin ottamalla huomioon useita kriittisyyteen vaikuttavia kriteereitä. Näin ollen sekä laitos- että kunnossapitopäälliköt voivat käyttää menetelmää päätöksenteon tukena varaosien hallinnassa. Menetelmän huonona puolena voidaan pitää sen riskiä muuttua subjektiiviseksi, sillä analyysin suorittaminen perustuu asiantuntijan arvostelukykyyn.

Diplomityössä suoritettujen kriittisyysanalyysien tulokset antavat kattavan yleiskuvan biokaasulaitosten varaosien kriittisyysluokittelusta, ja siten ne voivat tarjota hyödyllistä tietoa myös muille vastaavan teollisuudenalan toimijoille. Tältä osin tämän työn voidaan nähdä kurovan varaosien hallinnan tutkimuksen ja käytännön välistä kuilua.

Avainsanat: varaosa, biokaasu, monikriteeriluokittelu, kriittisyysanalyysi

PREFACE

This Master of Science thesis was written for the Biogas business unit in Gasum Oy. First of all, I want to thank Erkka Laine from Gasum, for offering me the possibility to write a thesis on such an interesting topic and providing guidance and expertise throughout the thesis project. His prior research within this area was also highly valuable for my research process. I also want to thank Markku Pesonen from Gasum for his support. I want to give special thanks to all the plant managers that contributed to this thesis. I would not have been able to complete this project without their valuable input.

When reflecting on my time as a student, I can’t help but notice how much good teachers have influenced me. My upper secondary school biology teacher put a lot of emphasis on the urgency of mitigating climate change and reducing emissions. I soon found myself studying energy engineering in courses given by Henrik Tolvanen at Tampere University. During my studies, Henrik has inspired me to think about the big picture, and his enthusiasm for the energy engineering has motivated me a lot. Henrik has been a great supervisor for this thesis, and I am sincerely grateful for that. I would also like to thank my second thesis supervisor from Tampere University, Hasse Nylund. With his guidance and support, I felt confident to write a thesis about a topic that was beyond my previous field of expertise.

Finally, I want to give my thanks to my friends for their support and encouragement throughout my studies. I also want to thank my family for the endless and unconditional love and encouragement. Most importantly, I want to express my gratitude to my beautiful and supportive other half, Neea. Thank you for believing in me and for always being there for me.

Helsinki, 25th April 2021

Jancarlo Rodriguez

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

AHP	Analytic hierarchy process
CHP	Combined heat and power
CSTR	Continuously stirred tank reactor
FMECA	Failure mode, effect, and criticality analysis
LCFA	Long chain fatty acids
MDT	Mean down time
MTTF	Mean time to failure
OEM	Original equipment manufacturer
RCM	Reliability centred maintenance
SKU	Stock keeping unit
SRCM	Streamlined reliability centred maintenance
TPM	Total productive maintenance
VED	Vital, essential, and desirable
VFA	Volatile fatty acids

1. INTRODUCTION

1.1 Research background

Protecting production capacity is important for any manufacturing or service organization. To this end, maintaining fixed assets such as production machinery and materials handling equipment becomes crucial. A principal means to ensure maintenance actions such as repairs is to have the right spare parts available at the right time, in the right quantity. (Bhat., 2008, p.182) Also Braglia et al. (2004, p. 55) emphasise the importance of the availability of spare parts in reducing the long and unproductive downtimes of the equipment when a breakdown occurs. Thus, practitioners tend to solve this problem by holding an abundant number of spare parts in inventory to minimise the potential production losses. (Bhat, 2008, pp. 181–182). However, holding high inventories of spare parts may tie significant amount of capital, which drives manufacturing companies to balance between inventory holding and stock-out costs. Spare parts management is particularly challenging as "the parts can be expensive, their demand is highly erratic and intermittent, yet their shortage costs can be very large", as summed up by Dekker et al. (2013, p. 536). The aforementioned challenges in spare parts management make the issue worth studying thoroughly.

In addition to their peculiarities compared to other inventory items, spare parts differ significantly from each other in terms of item value, stock-out effects, and demand pattern. It is important for asset-intensive industrial plants to categorise their spare parts assortment into relevant categories in order to control different items with varying characteristics. (Molenaers et al., 2011, p. 570) As a result, spare parts classification enables managers to focus on the most "important" parts (Fortuin & Martin, 1999, p. 968; Syntetos et al., 2009, p. 292). Regarding spare parts classification, literature recognises individual item criticality as the principal ruling criterion. However, there is no clear definition for item criticality nor guidelines for measuring it due to its many facets.

There is a distinct gap between scientific research and practice in spare parts management. Various spare parts classification schemes can be found from literature but very few studies consider solution implementation. Also, the use of spare parts multi-criteria classification methods among practitioners is still limited. (Syntetos et al., 2009; Bacchetti & Saccani, 2012; Molenaers et al., 2011; Roda et al., 2013, p. 540) Kennedy et al. (2002) as well as Bounou et al. (2017) provide comprehensive overviews of spares provisioning models based on mathematical models. However, Wagner (2002, p. 223), for instance, argues that incremental mathematical inventory research is of little use to practice. This thesis will focus on bridging the gap between theory and practice by developing and implementing a multi-criteria classification method based on item criticality in a biogas production industry.

1.2 Research questions and objectives

This research is conducted within the Biogas business unit of a Nordic energy company that offers energy and raw materials for industry and combined heat and power (CHP) production in Finland, Sweden, and Norway. The case company also helps its customers to operate in the energy market and provides services and consultancy throughout the market chain. The company owns a nationwide network of nine biogas plants in Finland, in addition to which it has six biogas plants in Sweden. In recent years, the company has expanded its biogas production capacity with new acquisitions and several ongoing investment projects.

The case company has made a few acquisitions in recent years, which have brought the company several new employees and biogas plants. However, the company does not have a clear organization-wide strategy nor policies for spare parts management. The purpose of this thesis is to provide a blueprint for pragmatic spare parts management in the case company's biogas plants and the means to support maintenance and plant managers in their decision-making.

Based on the case company's needs, the objective of this thesis is written out as follows:

> *Design a spare parts multi-criteria criticality classification method and provide a blueprint for spare part stock keeping.*

In order to answer to the needs and objective of this research, this thesis answers the following research question:

> *How a biogas plant should manage its spare parts with varying characteristics?*

Due to its broad nature, the main research question is specified with additional sub-questions. To answer to the main research question, the following sub-questions are to be answered:

1. What are the criticality criteria to consider when managing spare parts?
2. How to classify spare parts based on the criteria in sub-question 1?
3. What is the criticality classification in the examined biogas plants?

4. How to manage different spare part classes: where to stock parts and what kind of stocking policies should be applied to them?

From a research methodological perspective, this thesis follows a case study strategy as the purpose of the research is to study a problem and to develop a solution related to the assignment given by the case company, using multiple sources of evidence (Robson, 2002, p. 178). The use of a case study methodology as a research strategy is also justified by the research questions defined for the research. According to Saunders et al. (2009, p. 149), the strategy has great ability to generate answers to the “Why?”, “What?” and “How?” questions.

According to Yin (2003, p. 14), a case study cannot be seen as a mere research method, but as a holistic research strategy in which the actual phenomenon being studied guides the design of the entire research framework. Lukka (2003, p. 83) notes that there are several divergent sub-methods under the umbrella notion of the case study method. One of such methods is a constructive research approach which focuses on real-world problems by producing constructions, intended to solve those problems. The research also intends to implement the developed construction and thus test its practical applicability. As this thesis aims to design a solution (a spare parts criticality classification method) and to assess its practical applicability by implementing the method in biogas plants, this case study follows the approach of constructive research. Close cooperation between the researcher and the case company is one of the core features of the constructive research approach. The approach also incorporates linking the research to prior theoretical knowledge as well as reflecting the empirical findings back to theory. (Lukka, 2003, pp. 83–84)

1.3 Research scope

Regarding spare parts management, the perspective of the equipment owner is considered in this thesis. This thesis examines seven biogas plants of the case company located in Finland. However, the case company expects the results of this study to be utilised in its other plants as well.

Regarding the development of spare parts management method, the focus is on classification approaches. Thus, it is beyond the scope of this thesis to study other approaches such as mathematical models based on linear programming, dynamic programming, or simulation, to name a few. Kennedy et al. (2002) as well as Bounou et al. (2017) provide comprehensive overviews of such inventory models. In cooperation with the case company, it was decided that this part of the thesis would focus on investigating practical and realistic approaches for spare parts criticality classification which can be used as a management tool in the company. However, there is no warehouse management system adopted in the case company which is why there is no comprehensive data available on spare parts such as historical demand or failure data. Thus, there are some obstacles related to the practical applicability of the classification methods presented in literature, and spare parts criticality analysis needs to be performed without leaning on history data.

1.4 Research structure

Chapter 1 provides the basis for this research as well as identifies the primary objectives for the thesis. The following two chapters review relevant literature. Chapter 2 provides a brief overview of biogas production and thus describes the industrial context within the research. The focus is on different biogas production technologies and production process stages. Chapter 3, on the other hand, describes the characteristics of spare parts as well as spare parts management. Later, different spare parts classification approaches presented in literature are reviewed. Then, the concept of criticality is discussed in terms of using it as a ruling criterion in spare parts classification.

After the literature review, Chapter 4 describes the research methodology of the thesis through a constructive research process. Also, the data collection methods and their processes are described in detail. Further, the criticality classification method development as well as the actual method and its components are described in detail. After this the implementation of the developed method is discussed and the method is evaluated based on the insights gained from the implementation phase.

Chapter 5 highlights the key findings of the spare parts criticality analysis conducted in the case company. The chapter also provides recommendations for spare parts management and explains the rationale behind them. The limitations of the research work are also considered. Finally, Chapter 6 evaluates the practical realisation of the research work according to the objectives and research questions. The contribution the thesis is also considered in addition to which recommendations for further research within the research area are provided.

2. BIOGAS PRODUCTION OVERVIEW

2.1 Anaerobic production of biogas

Biogas can be produced in a biogas reactor from almost any organic material through anaerobic digestion. Organic materials suitable for biogas production include, for example, wood and wood residue, field biomass from agriculture, sewage sludge from water treatment plants, municipal organic biowaste, and animal residues such as manure (Hellgrén, 1999, pp. 30–31).

Biogas consists mainly of carbon dioxide and methane and is formed by the decomposition of organic matter under anaerobic, i.e. oxygen-free, conditions as a result of bacterial activity. (Latvala, 2009, pp. 29–30) The anaerobic digestion can be divided into four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Wellinger et al., 2013, p. 123). The simplified anaerobic production process as well as its stages and their order are illustrated in Figure 1**.**

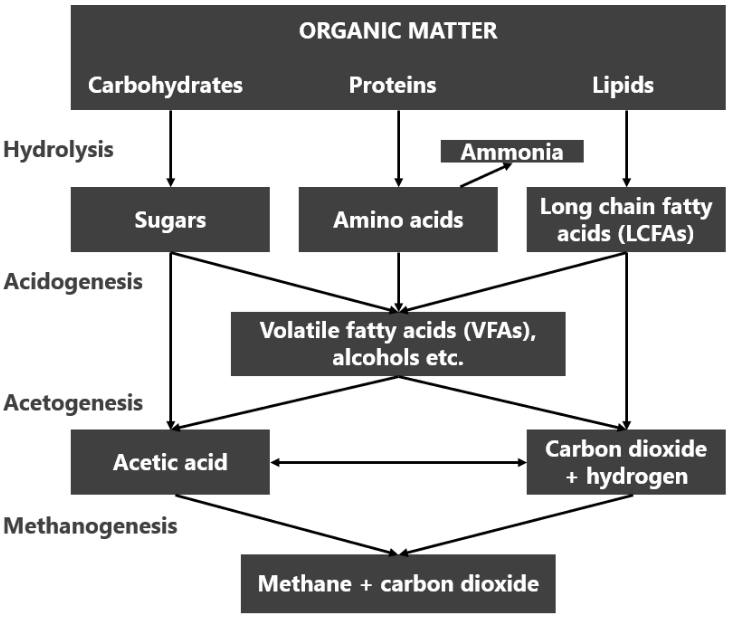


Figure 1. *Methane formation through anaerobic digestion process (Adapted from Dolfing, 1988; Madigan et al., 1997; Latvala, 2009, p. 30; Wellinger et al., 2013, p. 106).*

The first stage of the anaerobic digestion process is called hydrolysis in which organic polymers, i.e. carbohydrates, proteins, and lipids, are broken down and liquefied into more simple compounds such as sugars, amino acids, ammonia, and long chain fatty acids (LCFA) by enzymes produced by hydrolytic bacteria. (Deublein & Steinhauser 2011, p. 94; Wellinger et al., 2013, pp. 106–107; Kymäläinen & Pakarinen, 2015, p. 61) The second stage of the anaerobic digestion process is acidogenesis. Here, the carbohydrates, amino acids, LCFAs and other compounds are broken down into volatile fatty acids (VFA) and alcohols by acidogenic (fermentative) bacteria. These are further broken down into acetic acid, carbon dioxide, and hydrogen in the acetogenesis. In the final stage (methanogenesis), methanogenic bacteria produce methane and carbon dioxide, i.e. biogas, from acetate or hydrogen and carbon dioxide. Approximately 70 % of the methane produced comes from acetate and aceticlastic. (Deublin & Steinhauser, 2011, p. 99; Wellinger et al., 2013, p. 107; Kymäläinen & Pakarinen, 2015, pp. 61–63)

2.2 Biogas production configurations

Depending on the source, biogas production processes can be divided in many different, and sometimes overlapping, ways. The division can be made according to, for example, process temperature, feedstock used, plant location, moisture content, number of stages, reactor type, or continuity of raw material feed. Some different biogas production configurations are briefly examined next.

The feedstock and feed mixtures to be processed in a biogas plant determine the suitable process technologies (Latvala, 2009, p. 83). According to scale and used feedstock, three main biogas plant types can be distinguished:

- Farm-based plants
- Wastewater treatment plants
- Co-digestion plants

The main elements of a farm-based biogas plant are depicted in Figure 2. Farm-based biogas plants are relatively small, and they typically process only farm's own or contract farm's manure and plant biomass. Liquid manure is typically transferred from the barn into a pre-tank from which it is pumped to a biogas reactor. The pre-tank often contains a mixer and a preheater to make the sludge uniform. For agrobiomass, the plant may have a separate crusher that feeds crushed biomass directly to the pre-tank. Plant biomass can also be pre-treated with a shredder and fed directly to the reactor by a separate feeder. (Latvala, 2009, p. 19) If off-farm materials are processed, the equipment may also include a storage space, a sanitation unit, and a feed tank (Lehtomäki et al., 2007). Odor-inducing compounds decompose in the process and reduce barn emissions significantly due to which odor gas treatment is typically not needed. (Latvala, 2009, p. 19) Feedstock that requires laborious separation should not be processed in farm-based plants. Instead, Wellinger (1999) recommends using so-called clean waste such as food industry waste or garden waste. In farm-based biogas plants, the digestate from anaerobic treatment is usually utilised as fertiliser as such in the farm's own fields. The formed biogas is most commonly utilised for on-farm heat and power generation. (Lehtomäki et al., 2007, p. 18; Latvala, 2009, p. 12)

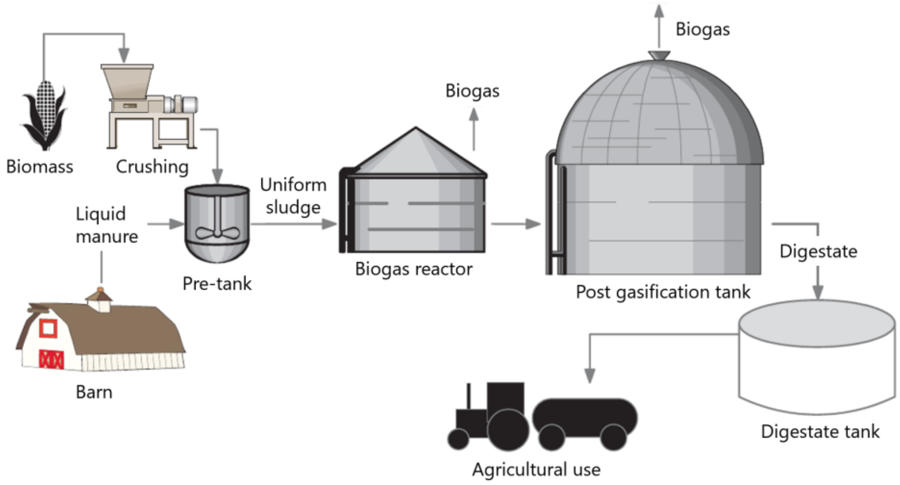


Figure 2. *Farm-based biogas plant overview (Adapted from Latvala, 2009, p. 26).*

The main elements of a water treatment biogas plant are depicted in Figure 3 below. These plants typically process sewage sludge from water treatment plants that is passed through a transfer pipe to a thickening tank. In thickening, the dry solids content is increased to a level of 2 – 8 % after which it is fed to a biogas reactor. Other suitable feedstocks include industrial effluents and septic well sludges. The digestate can be further treated, for example, by composting, granulating, or thermal drying. (Latvala, 2009, pp. 20, 27; Kymäläinen & Pakarinen, 2015, pp. 41)

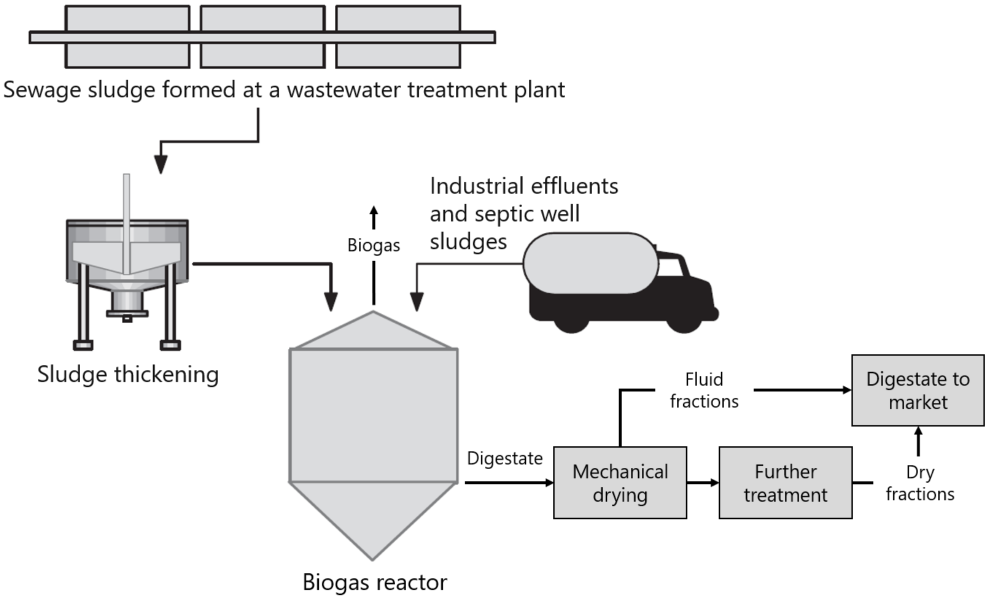


Figure 3. *Wastewater treatment plant overview (Adapted from Latvala, 2009, pp. 20, 27).*

The final biogas plant type based on scale and used with feedstock is a co-digestion plant whose main elements are illustrated in Figure 4 below. In a typical situation, a co-digestion plant can process agricultural sludges, plant biomass, separately collected bio-waste, sewage sludge, as well as industrial wastewater and side streams. Because of diverse feeds, pre-treatment requirements are rather high for co-digestion plants. There are several pre-treatment methods such as crushing, sieving, thickening, and sanitation. Due to uneven availability of feeds, co-digestion plants have to be prepared for variations in the storage space. There may also be several tanks before the biogas reactor that serve as a pre-storage. (Latvala, 2009, p. 28; Kymäläinen & Pakarinen, 2015, p. 22)

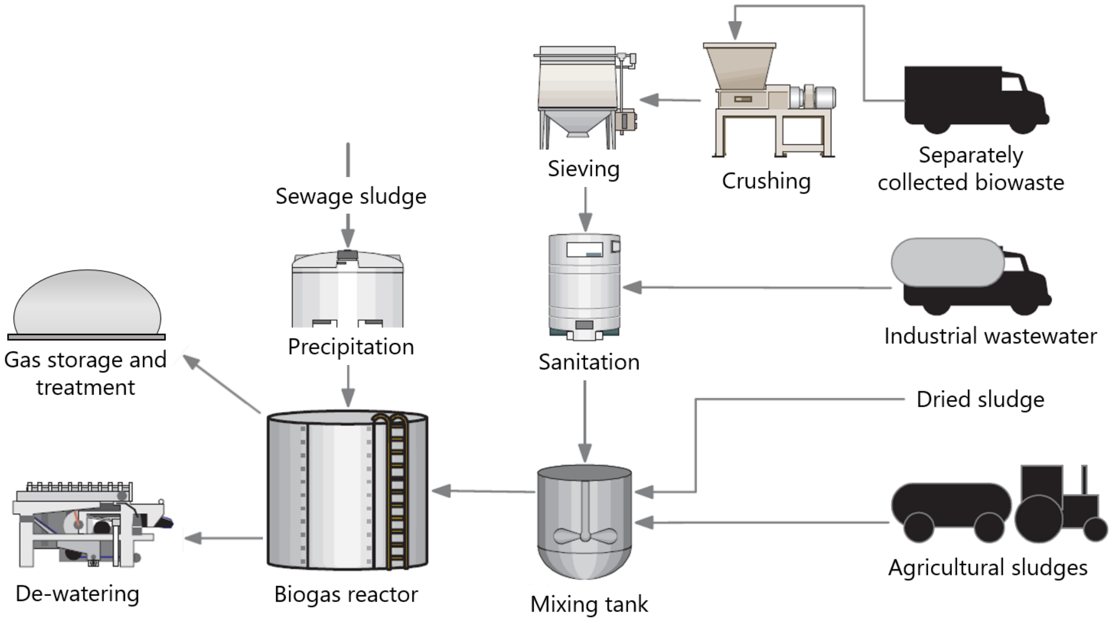


Figure 4. *Co-digestion plant overview (Adapted from Latvala, 2009, p. 21, 28).*

Biogas plants can operate as wet or dry processes. For biogas plants operating in a wet process, the dry solids content of the feed mixture is about 5 to 15 %. Dry feeds can also be added to the wet process with a separate feed device or by mixing the dry material with the slurry material prior feeding. The wet process can also be implemented by diluting the dry feed material with an available liquid, such as liquid fraction separated from the digestate or process water purified therefrom. However, the dry solids content of the feed inside the reactor must remain below 15 % so it can be pumped and mixed. (Lehtomäki et al., 2007, p. 32; Kymäläinen & Pakarinen, 2015, pp. 82–83) Mixing can be performed mechanically using either mixers or gas bubbles, as depicted in Figure 5 below. Mixing can also be performed by sludge recycling. Mixing is an important part of the biogas reactor operation as it enables a uniform temperature distribution and prevents phase separation and floating layers. (Wellinger, 1999) The wet process often uses continuously stirred tank reactors (CSTR) in which the reactor contents are uniformly mixed using a vertical mixer (Wellinger et al., 2013; Kymäläinen & Pakarinen, 2015, p. 82). This is also the most common reactor type used in farm-based biogas plants (Wellinger, 1999).

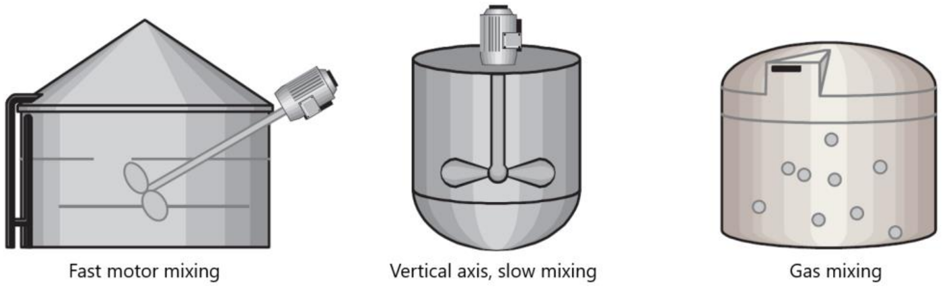


Figure 5. *Different mixing approaches (Adapted from Latvala, 2009, p. 31).*

A dry process, on the other hand, is a process in which the dry matter content of a feed is between 20 and 50 %. In this case, the feed cannot be pumped, but is moved and mixed in another way. (Latvala, 2009, p. 29; Kymäläinen & Pakarinen, 2015, pp. 83–84)

The biogas production process can be operated either continuously or batchwise. Wet processes are usually continuous, and this is the most common configuration in all biogas plant types (farm-based, wastewater treatment and co-digestion) in Finland (Latvala, 2009, p. 30). In a continuous digestion processes, the feed is continuously pumped into the reactor in addition to which the digestate from the reactor is continuously removed, resulting in constant biogas production. The dry processes can be operated both continuous and batchwise. In a batch system, feedstock is fed into the reactor once, and removed at the end of the process. Batch processes commonly use existing agricultural machinery to insert and remove the feedstock. (Wellinger, 2013, p. 116) In literature, biogas processes are commonly classified by combining moisture content and continuity of raw-material feed. These processes and their typical configurations are compared in Table 1.

Biogas production processes can be either single-stage or multi-stage. According to Luostarinen (2015, p. 88) and Wellinger et al. (2013, p. 196), most biogas plants are single-stage, meaning that the plant has a single biogas reactor where most of the raw material decomposition and biogas production takes place. Such a single-stage process is easy to operate and to build. (Wellinger et al., 2013, p. 196) However, the downside is slow gas removal, low load rate, relatively small gas yield, and variability in the quantity and quality of output digestate. (Vertes, 2009) It is open to interpretation whether a possible post gasification tank is considered as the second stage or not. Nonetheless, a post gasification tank is recommended for continuous digestion processes so that the biogas from the reactor digestate is recovered in a controlled manner and utilised together with the reactor gas. (Kymäläinen & Pakarinen, 2015, p. 88) A two-stage process, on the other hand, has two separate and sequential reactors in which the hydrolysis stage and the methane production stage are separated. (Wellinger et al., 2013, p. 196) Higher methane yield and stability can be achieved with two-stages, but advanced operational and process expertise is required to ensure process efficiency (Luostarinen, 2015, p. 89).

Table 1. *Comparison of biogas process technologies (Adapted from Latvala, 2009, p. 33).*

Criteria	**Dry continuous digestion**	**Dry batch digestion**	**Wet digestion**
Typical feedstocks	Solid biowaste, solid manure, energy crops	Solid biowaste, solid manure, energy crops	Liquid manure, industrial and municipal sludge
Feedstock requirements	Dry solids content (TS) 20 – 40 %	Dry solids content (TS) max. 50 %	Dry solids content (TS) max. 13 %
Feedstock treatment	Sanitation	Premixing, rotation technology	Sanitation
Plant	Continuous, can be expanded by adding modules	Modular, batch	Single-stage or multi-stage, continuous
Typical faults	Crusher clogging	Clogging of sprinkler mouths, sieves, and screens	Foaming, phase separation, floating layers
Failure effect	No major impact on the whole process	Affect only one batch	Affect the whole process
Energy required for the process	More	Less	More
Emissions	Less	Less	More
Hygiene	Not problematic	Not problematic	More problematic

Finally, biogas production processes are commonly operated according to the following temperature ranges:

- Thermophilic, 50 – 60 ˚C
- Mesophilic, 35 – 40 ˚C
- Psychrophilic, < 20 ˚C

The most conventional temperature ranges used for anaerobic digesters are thermophilic and mesophilic. Biogas production process within mesophilic temperature range requires less energy than in the thermophilic process. However, thermophilic process is more efficient as the matter digests approximately twice as fast in a thermophilic process than in a mesophilic process. A disadvantage of the thermophilic process is its sensitivity to various disturbances. Temperature is one of the most significant factors influencing biogas production. More important than absolute temperature is to have temperature of uniform quality: temperature variation should be kept to a minimum, preferably +/- 0.5 and a maximum of +/- 2 ˚C. (Mackie & Bryant, 1995; Lehtomäki et al., 2007, pp. 31–32; Latvala, 2009, p. 34; Wellinger et al., 2013, p. 115; Kymäläinen & Pakarinen, 2015, pp. 63–64)

2.3 Biogas production main process steps

Biogas processes have certain main process steps regardless of the process size or the feedstock used. Feedstocks are pre-treated and pre-stored after which they are fed into the biogas reactor. The digestate from the reactor is collected in a digester tank, for example, from where it is transported either directly for further use or treatment. Figure 6 illustrates a simplified process scheme of a co-digestion biogas plant and its main process steps. Biogas production main process steps are briefly examined next.

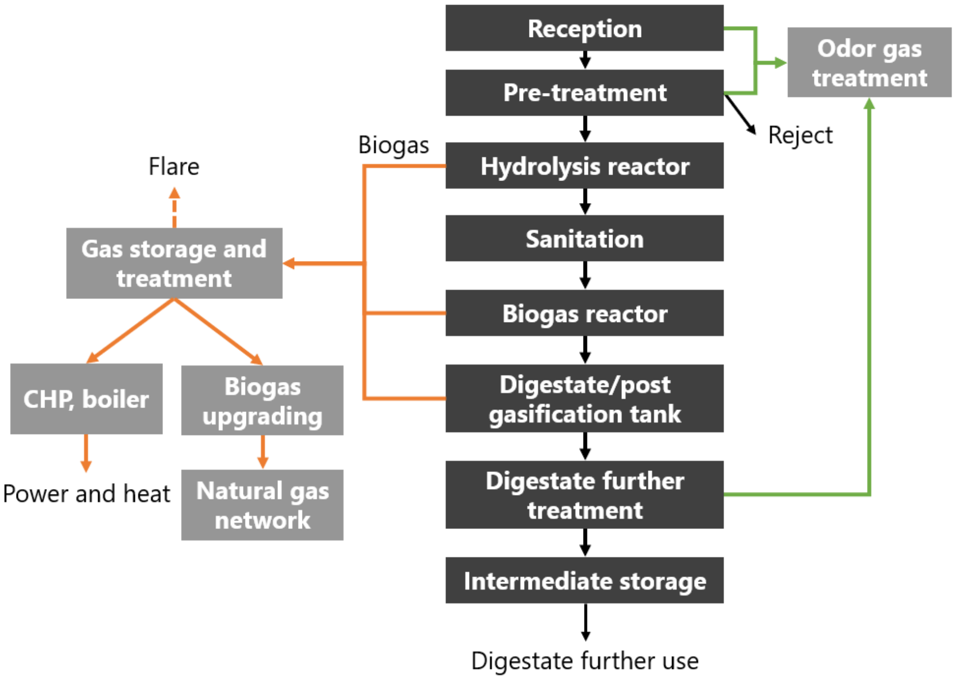


Figure 6. *Example of biogas production process at co-digestion plant.*

Reception and pre-treatment. Feedstocks processed at the biogas plant determine the used reception and pre-treatment technologies. These, in turn, are essential for plant operation as well as for environmental aspects. Biowaste is typically collected in a receiver funnel or a tank. (Kymäläinen & Pakarinen, 2015, p. 51) The purpose of the pre-treatment is to remove the impurities, crush the material to a suitable particle size, and homogenise the feed mixture into a uniform quality. Slurry-like feeds are easier to process and do not require such large investments compared to the pre-treatment of solid raw materials. Typical pre-treatment technologies for sludges are thickening and screening. In thickening, the dry matter content of the feed, such as sewage sludge, is adjusted higher. Screening is used to separate solid impurities from the feed by passing the slurry through a sieve. (Latvala, 2009, p. 23; Kymäläinen & Pakarinen, 2015, pp. 53–54)

Hydrolysis. After feedstock pre-treatment, the material can be led by pumping to hydrolysis tanks, where the first stage of the anaerobic digestion process, i.e. hydrolysis (see Section 2.1), is initiated. Hydrolysis tanks also act as pre-digesters from which the formed biogas is collected. Furthermore, hydrolysis tanks can also be used as buffer tanks to balance the daily feed flow (Latvala, 2009, p. 28).

Sanitation. The feedstock processed at a biogas plant may contain risks related to the utilisation of the final product, such as plant and animal diseases, harmful metals, or other harmful compounds such as organic contaminants, drugs, and hormone residues. The feedstocks used in the plant must therefore be known and the potential risks must be eliminated either during processing or at least their effect on the usability of the end product in the various uses must be understood. Prescribed by Side product law (1069/2009), biogas plants using animal-based waste products need to implement thermal hygienisation, also called sanitation, in which the material is treated in 70 ˚C for a minimum of one hour. The maximum permissible particle size to be treated is 12 mm, which in turn sets requirements for the pre-treatment phase. The thermophilic biogas process as such is a distinctly better sanitiser than the mesophilic process. However, thermophilic process complies with hygienisation requirements in cases where only food waste, sewage sludge, manure, or a mixture of these are processed. Regarding hygiene, properly treated and hygienised end products from biogas plants can be considered as safe organic fertilising products and soil amendments. If the end product is landfilled or incinerated, it does not need to be sanitised. (Latvala, 2009, p. 38; Kymäläinen & Pakarinen, 2015, pp. 96–97)

Anaerobic treatment. In anaerobic digestion, organic matter is converted into biogas, i.e. methane and carbon dioxide as a result of bacterial activity (see Section 2.1). Anaerobic process usually takes place in a thermally insulated and gas-tight concrete tank, which includes sludge feed, recycling, discharge, mixing, heating, and gas collection equipment. Digestion can take place in one or more reactors. The reactors may be divided so that, for example, the first reactor provides optimal conditions for hydrolysis and acid fermentation and the second reactor for methane fermentation. Such a process is called a two-stage reactor system. Alternatively, two reactors may be used to ensure high gas yield. Several reactors can also be used to process different materials, for example one for sewage sludge and another for biowaste. (Lohiniva et al., 2001, pp. 40–42) Retention time in anaerobic digestion is typically 20 – 30 days (Kymäläinen & Pakarinen, 2015, p. 74; Rolamo et al., 2017, p. 7).

Gas storage and treatment. Low pressure storage (less than 10 bar) is always a part of the biogas production process. Biogas is stored in biogas plants at low pressure in biogas reactors and post-gasification tanks. This is necessary because biogas is generated continuously and regardless of its consumption. (Kymäläinen & Pakarinen, 2015, p. 169) In addition to traditional steel tanks, there are biogas storage technologies in which the tank volume may vary according to needs. Such technologies include gas holder and gas tanks based on membrane technology. A gas holder is a large ball-shaped gas tank (Figure 7) designed to store gas at a pressure slightly above atmospheric pressure. A gas holder is typically intended to act as a buffer, especially between fluctuating production and consumption, rather than as a long-term storage of gas. (Söderena et al., 2019, p. 22) Biogas used for power and heat generation, transport fuel production, and other purposes must be purified (Kymäläinen & Pakarinen, 2015, p. 131).

Figure 7. *Gas holder at co-digestion plant. (Photo: Jancarlo Rodriguez)*

Digestate further treatment. In farm-based biogas plants, the digestate from anaerobic treatment can usually be utilised as fertiliser as such, but especially as the plant size increases, further treatment is necessary to control the mass and nutrient flows. (Kymäläinen & Pakarinen, 2015, p. 99). In wastewater treatment plants and co-digestion plants, digestate is typically dried mechanically, after which it can be, for example, composted or dried thermally. Thermally dried digestate can be incinerated or used as soil amendment. Without exceptions, separate reject water is required in co-digestion plants. (Latvala, 2009, p. 51)

3. SPARE PARTS MANAGEMENT

3.1 Spare parts definition

Since protecting production capacity is important for any manufacturing or service organization, maintaining fixed assets such as machinery and materials handling equipment becomes crucial (Bhat, 2008, p. 181). For this reason, they are subject to preventive maintenance. Kennedy et al. (2002, p. 201) note that the need for spare parts is greatly influenced by how equipment is used and how it is maintained. Regardless of the preventive maintenance, some parts of the equipment may also fail, and thus repair is required. Whatever the case, maintenance actions often require replacing defective parts such as bolts, filters, engines, and gearboxes. (Fortuin & Martin, 1999, p. 950; Gopalakrishnan & Benerji, 2004, p. 232) In literature, these parts are often referred to as service parts or spare parts, from which the latter is used in this thesis.

As mentioned above, spare parts can be defined as parts that are needed in case of equipment failure or when a component must be replaced (Syntetos et al., 2009, p. 292). Thus, it can be concluded that the most significant difference between spare parts and other stock keeping units (SKUs) is their purpose. Spare parts and their inventory are intended to serve the maintenance operations, and therefore will not become part of the final product to be sold to a customer (Kennedy et al., 2002, p. 201). Therefore, as defined by Bhat (2008, p. 181), spare parts should be available in stock when needed, in the right quantity.

Fortuin and Martin (1999, p. 950) divide spare parts into two main groups according to whether they can be repaired or not, and thus these groups are called repairables and non-repairables. Repairables are spare parts that can be removed from the process equipment and, after repair, returned as equivalent. When malfunction occurs, a repairable part will be sent to a repair centre and a new part will be installed into the process equipment. When this new part breaks down, the earlier repaired one will be available in stock and thus it can be replaced with the broken one. (Louit et al., 2011, p. 993) Botter and Fortuin (2000, p. 658) define that repairables are spare parts that are technically and economically repairable. According to Bhat (2008, p. 185), repairables are commonly characterised with high stock-out costs and unit price due to which inventory carrying costs are also high. It is also common that repairables may not be available from the supplier and hence may have to be fabricated as made-to-order due to which procurement lead times can be rather long. Repairables are also called recoverables and rotables.

Non-repairables, on the other hand, are spare parts that are very difficult or uneconomical to repair, i.e. repair costs exceed the cost of acquiring a new part. Thus, if such a part becomes defective, it must be discarded and replaced by a new part. These parts are also called consumables, expendables, and disposables. (Fortuin & Martin 1999, p. 950; Botter & Fortuin, 2000, p. 657; Louit et al., 2011, p. 993) When it comes to spare part usage, Suomala et al. (2002, p. 59) note that volumes are commonly higher for non-repairables. To add to this, Bhat (2008, p. 183) proposes a spare parts classification based on usage to regularly used and irregularly used spare parts. Within this thesis both repairables and non-repairables are considered, but the emphasis is more on repairables such as pumps and electric motors. The biogas plants examined in this thesis are co-digestion plants representing continuous wet digestion technique. Figure 8 illustrates a simplified process scheme of such a biogas plant type as well as the typical spare parts used in the plant and their location in the production process.

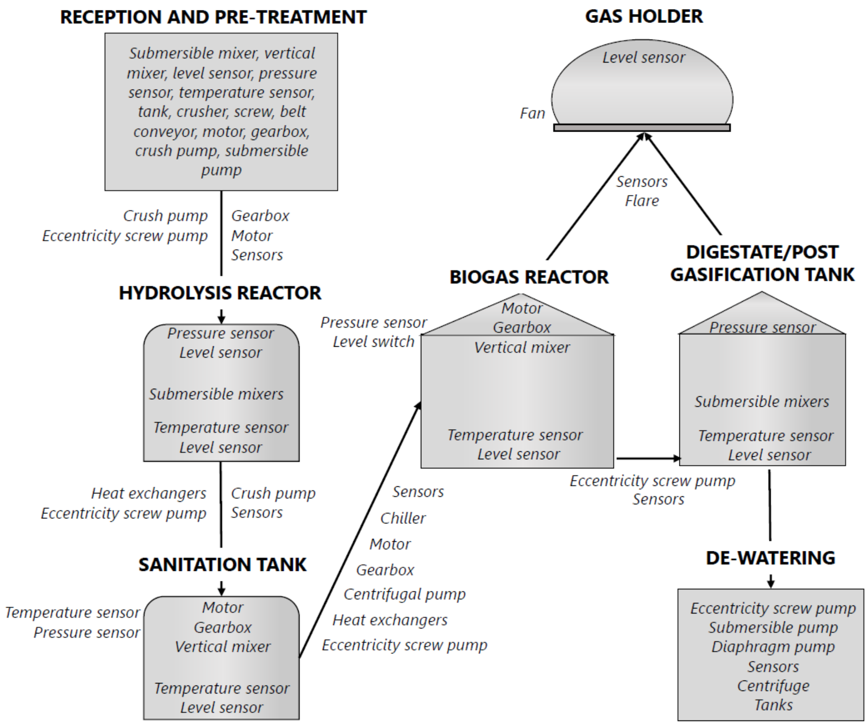


Figure 8. *Typical spare parts used in a co-digestion plant operated as wet continuous process.*

3.2 Spare parts characteristics

The main purpose of spare part inventories is to assist in maintaining the equipment in operating condition so that the necessary maintenance actions can be executed when needed in a timely and cost-efficient manner. Thus, managing MRO (maintenance, repair, and operating materials) inventories is a crucial task to any capital-intensive company. These inventories are characterised by independent demands since their requirements are not dependent on the demand of the final product (Bhat, 2008, p. 181). Therefore, spare part inventory management policies differ from other types of inventories such as work-in-process (WIP), raw material, and finished goods inventories (Roda et al., 2014, p. 532). In order to understand why spare part inventories differ from WIP and other inventories, the varying conditions that characterise spare parts inventory management are briefly reviewed below.

As stated above, managing spare parts is different from managing demand-dependent items such as raw materials and WIP parts. The main difference here is that the demand of demand- dependent items is well known whereas plant or equipment breakdown cannot always be predicted reliably and thus there is great uncertainty when spare parts are needed. (Bhat, 2008, p. 182) In addition to demand cycles and frequencies, spare parts are characterised by varied usage volumes (Roda et al., 2014, p. 531). Happonen (2011, p. 27) defines that in the field of materials management, spare parts are perhaps the most obvious single product type for which uneven demand is a rule rather than an exception. Happonen also adds that spare parts are, to a large extent, characterised by completely random demand. Partly for this reason, maintenance personnel often tend to order and stock too many spare parts to avoid potential equipment downtime and the consequent production losses (Bhat, 2008, pp. 181–182). This may be justified in case stock-out costs exceed the costs of holding spare parts. However, Cavalieri et al. (2008, p. 379) point out that stocking spare parts for uneven demand can carry, in the case of high value and low demand parts, high inventory holding costs.

Regarding spare parts sourcing, it is common that there are only few possible suppliers (Cavalieri et al., 2008, p. 381). It is also common that lead times vary between spare parts and even for the same part between different orders. This is often due to a typical operating model of spare part suppliers in which some of the spare parts are manufactured in-house as own production and some of the spare parts are purchased from subcontractors or other third parties. In addition, many original equipment manufacturers (OEMs) use the same components sold as spare parts in parallel in their own production. Companies tend to prioritise the continuity of their own production at the expense of spare part deliveries which, on the other hand, accounts to the so-called random deviations of spare part deliveries. (Happonen, 2011, pp. 27–28) Also Bhat (2008, p. 182) notes that it is common that long lead times are required for spare parts procurement from OEMs. To add to this, Cavalieri et al. (2008, p. 381) state that procurement lead times may be rather long regarding specific or make-to-order parts.

Finally, obsolescence risk of machines and equipment is one special characteristic of spare parts inventory management (Bhat, 2008, p. 182). When it comes to obsolete machines, Kennedy et al. (2002, p. 202) note that it is challenging to determine spare part inventory levels. From another perspective, spare parts may also become obsolete in case new items displace them or when there is no use for them anymore. If spare parts are not in production anymore, sourcing may also become challenging. (Boone et al., 2009, p. 34)

3.3 Spare parts inventory management

Spare parts have many special characteristics (see Section 3.2) that differentiate them from other inventories such as WIP, raw material, and finished goods inventories (Roda et al., 2014, p. 532). Nevertheless, Stoll et al. (2015, p. 225) argue that up until now intuitive assessment has been emphasised in spare parts management, according to which procurement, stocking, and provisioning decisions have been made. According to Syntetos et al. (2009, p. 293), even small improvement efforts in spare parts inventory management can bring significant cost savings for the practitioner. Literature examines spare parts management from many different aspects. Regarding different parties in the supply chain, three main operating environments in which spare parts are used can be distinguished:

1. Spare parts to maintain technical systems such as production machinery under own control
2. Spare parts to service systems installed at customer premises
3. Spare parts to repair consumer products at service workshops (Fortuin & Martin, 1999, p. 953).

The perspective of a production plant equipment owner (1.) is considered in this thesis. Regardless of the operating environment, the following aspects must be considered:

- Which spare parts have to be stocked?
- Where are the spare parts to be stocked?
- How many units have to be kept in stock for each item? (Botter & Fortuin 2000, p. 656; Bhat, 2008, p. 181).

Botter and Fortuin (2000, p. 657) note that answering to these questions is a difficult task as standard inventory control methods are not suitable for spare parts management. However, some approaches recur in literature.

Botter and Fortuin (2000, p. 664) use criticality as a ruling criterion to answer the question “Which spare parts have to be stocked?”. They use two dimensions to reflect criticality: functionality and consumption. Functionality evaluates the effect of an item failure on the system’s availability whereas consumption considers total demand for an item. From the logistics point of view, the control situation is different depending on the urgency of the replenishment need. Huiskonen (2001, p. 131) recommends safety stocking for any part with lead times longer that the time to tolerate a stockout situation when a breakdown occurs. In case there is more time to react, centralised stocking could be a viable option (Huiskonen, 2001, p. 129).

Item value, lead time, and usage are typically considered when deciding where and how many parts to stock. However, spare parts are commonly characterised with low usage, which makes central stocking an attractive solution to decrease inventory costs. (Botter & Fortuin, 2000, p. 665) In case of extremely low usage, a co-operative stock pool may become feasible. In this approach, several relatively closely located users of a high value item can create a co-operative stock pool by holding the necessary safety stock in one user’s premises for common purposes. This kind of arrangement may justify safety stocking by consolidating low and sporadic demands of several users into steadier and uniform requirements, thus reducing demand variability between users. (Huiskonen, 2001, p. 131) Spare parts management approaches considering item value, lead time, and usage are studied in more detail by Botter and Fortuin (2000).

High item value makes stocking unattractive for any party in the logistics chain, and it drives to pursue alternative solutions for stock keeping. In his paper, Huiskonen (2001, p. 130–131) considers how to utilise supply chain relationships to this end. For example, parts that are ordered on a make-to-order basis are typically characterised with long lead times, high value, and low demand. Thus, holding these kinds of parts on site can be found unattractive, regardless of item criticality. Therefore, premise suppliers are not keen to hold such items in their premises for the specific needs of a single customer. However, in case stock-out costs would be significant, it is recommended to look for a supplier that could fabricate these types of parts with shorter lead times when required. This kind of approach could be possible between a bigger customer company and a smaller machine shop, especially if the machine shop receives a large share of its orders from this particular customer. Regarding more standard parts that are widely used in different industries, it is recommended to push stocks of high value items towards suppliers. The rationale here is that with parts that are used by several prospective customers, suppliers are more willing to hold stocks and offer fast deliveries to gain clients. (Huiskonen, 2001, p. 131)

Bacchetti and Saccani (2012) propose an integrated approach for spare parts management. The approach integrates spare parts classification, demand management and forecasting, inventory management, and performance measurement, as depicted in Figure 9.

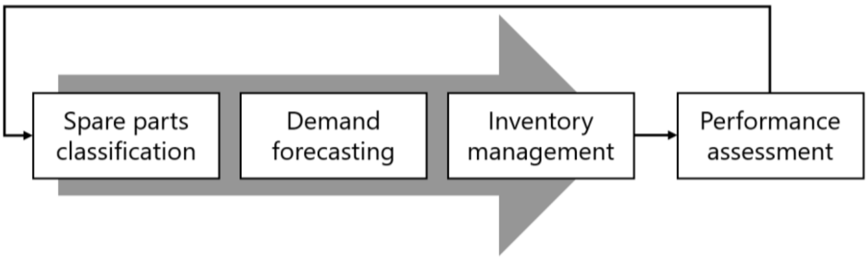


Figure 9. *An integrated approach to spare parts management (Adapted from Bacchetti & Saccani, 2012, p. 773).*

The approach presented in Figure 9 above implies that spare parts management decisions should be made with a systemic perspective. Also, different demand and inventory management approaches should be applied case-by-case according to spare parts characteristics. Thus, spare parts should be classified into relevant categories so that appropriate forecasting and stock control methods can be applied to them (Syntetos et al., 2009, p. 292).

3.4 Spare parts classification

Manufacturing companies tend to have a vast number of spare parts that need to be managed. However, some spare parts may be more critical than others, which is why these parts require more attention. (Fortuin & Martin, 1999, p. 966; Sarmah & Moharana, 2015, p. 456) For this reason, categorising spare parts into relevant classes is crucial for spare parts management as it supports decision-making, i.e. applying relevant stocking policies or using different forecasting methods. Furthermore, classification enables managers to focus on the most “critical” spare parts. (Fortuin & Martin, 1999, p. 968). Literature on classification methods recognises several different approaches. For instance, van Kampen et al. (2012, p. 863) distinguish two approaches based on the source of knowledge: judgemental methods and statistical methods. Judgemental methods, also called qualitative methods, are based on expert knowledge and judgement whereas statistical methods are based on quantitative analysis on different item characteristics. Sarmah and Moharana (2014, pp. 457–459), on the other hand, divide spare parts classification into methods using either a single criterion or multiple criteria. In the following, different approaches proposed for spare parts classification are discussed.

In literature, ABC analysis is the most common method to classify spare parts, and according to Molenaers et al. (2012, p. 570) it is widely applied in industry as well. ABC analysis is a statistical method commonly considering one criterion such as demand volume. Thus, it divides inventory items into three classes (A, B, and C) based on their importance in relation to, for example, annual inventory holding costs (unit cost x annual usage). (Vollmann, 2018) Figure 10 presents a typical ABC classification.

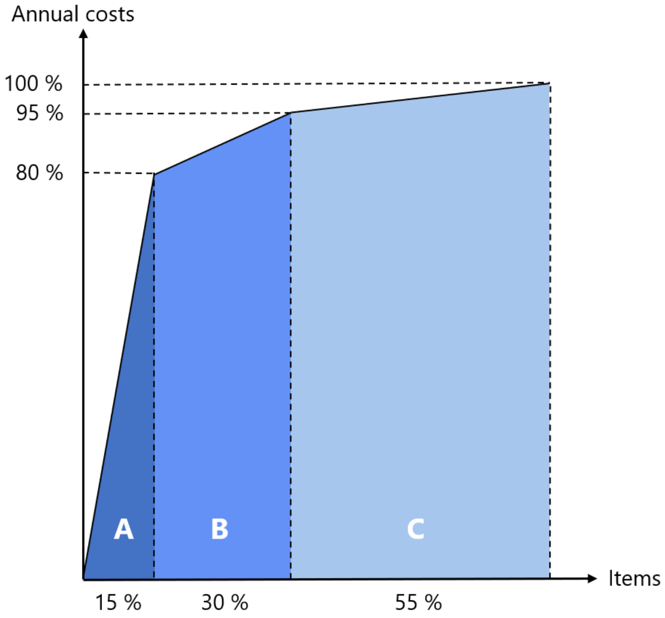


Figure 10. *ABC analysis (adapted from Haverila et al., 2009, p. 457).*

In this analysis, 15 % of the items are A items that account for a large proportion, 80 %, of the annual costs. Thus, these items are very important and require the most attention. C items, on the other hand, constitute 55 % of the items but only 5 % of the annual costs, which is why they are considered as less important. (Haverila et al., 2009, p. 457–458) Even though ABC classification originates from the Pareto principle, the classification breakdown may vary based on objectives and criteria. For example, Sakki (2014, p. 63) has extended the classification and uses the following breakdown:

- A items account 50 % of cumulative sales
- B items account 30 % of cumulative sales

- C items account 18 % of cumulative sales
- D items account 2 % of cumulative sales
- E items do not have any demand

The ABC analysis provides a means for identifying spare parts that have the most impact on overall inventory costs (Vollmann, 2018). Therefore, by focusing on appropriate and relatively small number of items one can obtain rather large reductions in inventory holding costs (van Kampen et al., 2012, p. 852). Conducting ABC analysis is simple, and it is recommended to be applied for parts that are rather homogenous in nature and differ from each other only by unit price and demand volume. For this reason, Flores and Whybark (1986) as well as Huiskonen (2001, p.126) argue that ABC analysis has maintained its popularity in the field of inventory management as no item-specific analysis is needed. However, ABC analysis has been criticised as too rough for spare parts classification as it considers only one item characteristic (Huiskonen, 2001, p. 126). Thus, by considering the varying spare parts characteristics covered in Section 3.2, it is clear why ABC analysis has generally been recognised as an insufficient approach for spare parts classification (Altay Guvenir & Erel, 1998, p. 30; Partovi & Anandarajan, 2001, p. 390; Sarmah & Moharana 2015, p. 457).

Huiskonen (2001, p. 129) argues that another dilemma with using ABC analysis for spare parts classification is that it does not consider, for example, financial impacts caused by part failure, which can be multiple in relation of the commercial value of the part. To assess spare parts criticality regarding the production process, other approaches for ABC classification are recommended in literature. For instance, Schultz (2000) considers technical aspects such as MTTF (mean time to failure) and MDT (mean down time) to assess spare part criticality. The above-mentioned technical aspects are applied to ABC analysis, which thus provides means for identifying spare parts that cause either frequent failures, long down time periods, or both.

The rationale in using qualitative classification methods is to assess spare parts criticality using expert judgement. An advantage of using such methods is that also implicit knowledge regarding spare parts criticality held by managers can be obtained. (van Kampen et al., 2012, p. 863) A widely adopted qualitative method to assess criticality is the VED approach in which spare parts are classified as vital, essential, and desirable based on the selected criterion (Mukhopadhyay et al. 2003). It is common that practitioners reduce this classification into two classes: Vital + Essential, and Desirable (see Stoll et al. 2015). Botter and Fortuin (2000, p. 662), for example, consider production losses caused by equipment failure by classifying spare parts according to VED method as follows:

- ***Vital parts*** cause high losses if not available when needed
- ***Essential parts*** cause moderate losses if not available when needed
- ***Desirable parts*** cause minor disruptions if not available when needed

An advantage of the VED approach is that the classification reflects the importance of parts from the equipment owner's perspective (Roda et al. 2014, p. 536). Thus, the VED approach provides better means to assess the criticality of parts intended to maintain own production rather than parts intended for service systems installed at customer premises. However, expert knowledge and judgement needed to conduct the VED analysis exposes to a high level of subjectivity (Roda et al. 2014, p. 536). To overcome this challenge concerning qualitative classification methods, several researchers have adopted the AHP approach (Analytic Hierarchy Process).

AHP is a multi-criteria decision-making model developed by Saaty (1980) which considers the most important criteria and alternatives influencing decision-making by determining their relative priorities or weights. Consequently, the criteria weights can be used to calculate an overall criticality score for spare parts, and thus to determine which of the alternatives would be the best judgement considering all the criteria affecting criticality. The AHP method is particularly useful in decision-making situations where it is difficult to assess the mutual importance of the criteria influencing a decision. In AHP, this is conducted by pairwise comparisons in which the expert, i.e. the decision maker, focuses on two factors at a time and scores them using a discrete nine-point scale. First, pairwise comparison is used to determine numerical values that reflect how well each of the alternatives fulfil each decision criterion. After this, the relationships between the criteria are examined. Here, pairwise comparison is used to determine the significance of each criterion in the decision-making. (Saaty & Vargas, 2012) A major advantage of using AHP is that multiple criteria, both qualitative and quantitative, can be included in the classification. However, subjectivity involved in pairwise comparisons may limit the use of the method. In their case study, Botter and Fortuin (2000) proposed AHP for spare parts classification but the method was considered as too theoretical by management, and thus it was modified to a simplified VED approach.

Another method used for spare parts classification is based on a decision diagram called a decision tree. The name originates from its tree-like structure which consists of decision nodes presenting different decisions to be made as well as edges, also called branches, that represent different alternatives for each decision. By going through the full decision path, the final outcome, i.e. the leaves of the tree, can be established. (Quinlan, 1990, p. 340) An advantage of using the decision tree method in spare parts classification is the ability to trace the decision logic used for classification. The decision-making process can be understood more easily compared to classification methods based on mathematical models. (Quinlan, 1990, pp. 343–344) Braglia et al. (2004, p. 56) also argue that mathematical models may not serve their purpose for a maintenance manager due to their complex, abstract, or oversimplified nature.

By incorporating different spare parts characteristics into a decision tree as decision nodes, the method can be used as an approach for multi-criteria classification. For example, Braglia et al. (2004) use a decision tree including 17 different criteria to classify spare parts based on their criticality. Due to the rather large number of characteristics to be considered, the decision tree is integrated with several AHP models used to solve the various multi-criteria decision problems at the nodes of the decision tree. Furthermore, Braglia et al. propose different approaches for inventory management based on the determined criticality classes. The work of Braglia et al. (2004) represents the first such integrated spare parts classification method.

Molenaers et al. (2012) also present a multi-criteria classification approach in the decision tree form with an integrated AHP approach. In their method, spare parts are classified into four criticality classes. Six criteria influencing spare parts criticality are considered: equipment criticality, probability of item failure, replenishment time, number of potential suppliers, availability of technical specifications, and maintenance type. For each criterion, spare parts are classified according to the VED scale as summarised in Table 2.

Table 2. *Example of VED classification of different criticality criteria (adapted from Molenaers et al., 2012, p. 573).*

Criticality criteria	**Categories**		
	Vital	**Essential**	**Desirable**
Equipment criticality class	A, B	C, D	E, F
Probability of item failure	≥ 1/year	≥ 1/5year - <1/year	< 1/5 year
Replenishment time	> 1 month	> 2 days - ≤ 1 month	≤ 2 days
Number of potential suppliers	1	> 1 - ≤ 2	> 3
Availability of technical specifications	Not available	General specifications available	Detailed specifications available

Figure 11 presents the classification scheme in which different criticality criteria are presented as decision nodes in a decision tree. Spare parts receive a criticality class (1–4) according to the followed decision path which, in turn, is based on the selected alternatives (vital, essential, or desirable) of each decision node. Since decision node "logistics characteristics" combines three criticality criteria (the ones without their own decision node), AHP is used to solve the multi-criteria decision problem.

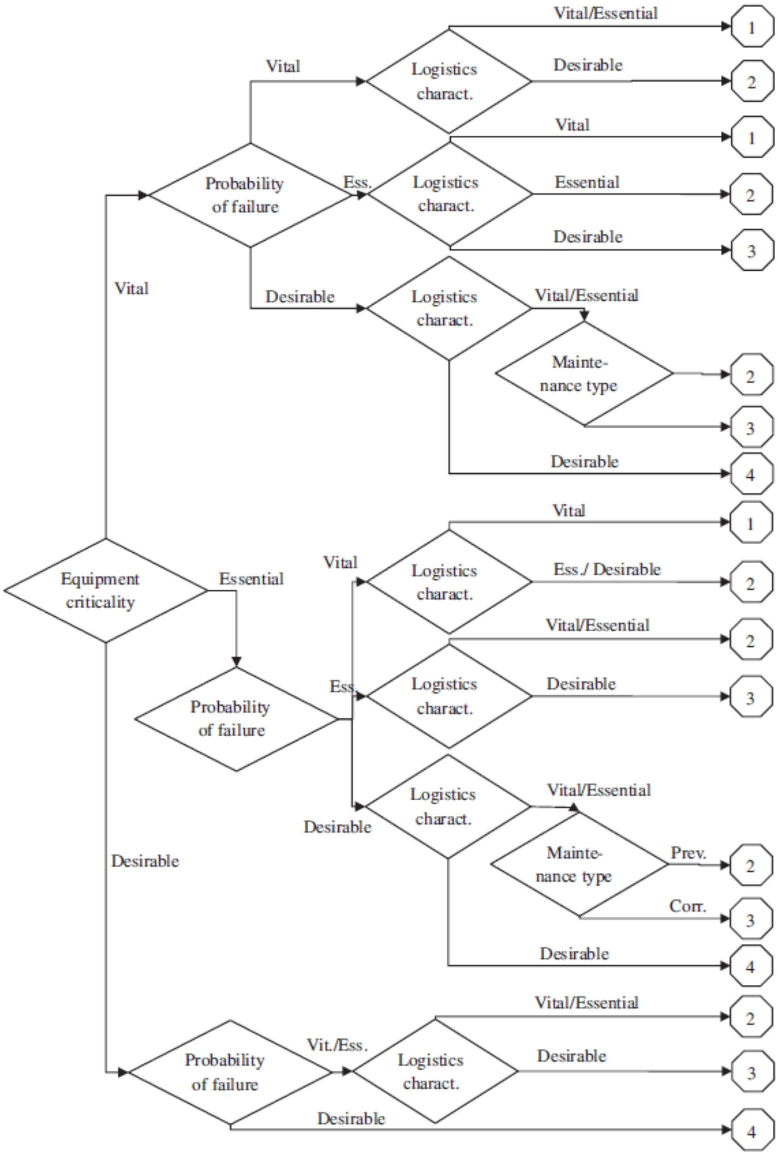


Figure 11. *Example of a decision tree used for spare parts criticality classification (Molenaers et al., 2012, p. 577).*

3.5 Criticality of spare parts

This section covers the concept of criticality. In many academic publications, the relevance of item criticality in efficient warehouse and inventory management is highlighted. To name a few, Stoll et al. (2015, p. 225) emphasise individual item criticality when considering optimal strategies for procurement, stocking, and supply. Many authors use criticality as a fundamental classification criterion. In their comprehensive literature review of main journals dealing with operations management, Bacchetti and Saccani (2012, p. 724) discovered that item criticality is applied as classification criterion in 15 out of 25 publications. Despite the fact that the criticality of an item is perceived as one of the most important item characteristics for logistics practitioners (Huiskonen 2001, p. 129), little attention has been devoted to analysing in which context each classification criterion is relevant (Bacchetti & Saccani 2012, p. 723). Boylan and Syntetos (2007), however, recommend the use of item criticality for technical systems over commercial products.

Literature recognises criticality as an essential criterion to classify spare parts. However, there is no clear definition for item criticality or guidelines to measure it. This is because criticality can be perceived differently under varying conditions, in addition to which there can be many contributory factors affecting it. Due to the broad understanding of criticality, it is justified to review the definition of criticality and the factors affecting it in more detail as the concept is of primary importance in this study. Huiskonen (2001, p. 129) divides the aspect of criticality into process criticality and control criticality. This approach is widely accepted for criticality analysis of spare parts and it is often cited in academic literature.

3.5.1 Process criticality

Dekker et al. (1998, p. 69) define the criticality of a spare part based on its importance for ensuring safe and efficient production. In addition to the continuity of production and safety aspect, it is worth noting that criticality of an item is also determined by the impact a shortage can have on the environment, as Molenaers et al. (2012, p. 571) state. Huiskonen (2001, p. 129), on the other hand, defines the criticality of a part in relation to the consequences caused by the failure of a part on the process in case a replacement is not readily available. Thus, parts that cause immediate shutdown in production process are more critical than parts that have no effect on the production process, safety, or the environment.

When considering spare parts process criticality, there are a few important elements that need to be acknowledged. First, the production process as a whole must be taken into account. Literature highlights (Veinott, 1965; Topkins, 1968, p. 160) that the same spare part can receive different criticality classes depending on its location in the production process. Also, in addition to the factors leading to production downtime, elements affecting its protraction must be considered as well (Cavalieri et al., 2008, pp. 379–380).

3.5.2 Control criticality

While process criticality reflects consequences for the process in case of failure, control criticality refers to the possibility to control the situation (Huiskonen 2001, p. 129). In their research, Paakki et al. (2011) refer to control criticality as a risk of availability, which is determined by lead-time variance and accuracy of delivered quantities.

Regarding control criticality, Texeira et al. (2018) define a spare part as critical in case it is difficult to control the possibility to ensure immediate availability of the part. However, Huiskonen (2001, p. 129) emphasises the importance of time available to react to the demand. From the logistics point of view, the control situation is different whether the need for replenishment is immediate or whether there is some time to react. It can therefore be concluded that control criticality of an item is not unambiguous as it depends on the situation, and thus process criticality is a fundamental factor in classifying the control situations of spare parts (Huiskonen 2001, p. 129).

3.5.3 Criticality criteria used in literature

In many publications, item criticality is used to develop strategies for spare parts logistics and stock control policies. According to Botter and Fortuin (2000, p. 655, 673), the need for stock keeping depends on the criticality of an item, whereas the amount and location of stocked items should be based on their usage and value. As mentioned earlier, criticality can be perceived differently under varying conditions and there can be many contributory factors affecting it. A vast number of criteria for evaluating criticality can be found from literature. A literature review of spare parts criticality classification methods conducted by Roda et al. (2014) compiles some of the criticality criteria that are considered in the literature research works or that are used in practice. These criteria are summarised in Table 3, grouped into four thematic subsets called clusters.

Table 3. *Criticality criteria from several literature references (Roda et al. 2014, p. 532).*

Cluster	**Criteria**
Spare parts plant criticality	Quality problem Production loss (referred to as stock out cost when assuming an economic focus) Domino effect Environmental and safety aspects
Spare parts usage characteristics	Number of identical components in the plant Usage rate/usage volume Frequency/probability of failure Demand volume/predictability Expiration date Redundancies
Spare parts inventory problems	Price Spaces required Turnover rate Obsolescence rate Deterioration problems
Spare parts supply characteristics	Lead time Number of potential suppliers Substitution cost Masked time Cannibalism Standardisation/standard parts (or, oppositely: specificity/specific parts can be used)

However, the relevance of the different criteria proposed in literature should be assessed independently for the situation at hand (Fortuin & Martin 1999, p. 959). For this study, the most relevant criteria for evaluating criticality are examined in more detail below.

In Table 3, criteria included in spare parts plant criticality cluster reflect process criticality discussed in Subsection 3.5.1. Theoretically, criticality of a part can be evaluated by production loss caused by the failure, which, however, is often difficult to evaluate in practice. As mentioned earlier, production process as a whole should be taken into account when considering process criticality as well as elements affecting the length of possible production shutdown. In reference to this, a practical approach proposed by Huiskonen (2001, p. 129) is to connect the criticality to the time in which the failure must be corrected.

One of the most traditional control characteristics applied to all materials is item value. As stated above, item value becomes an important factor when deciding how many parts to stock and where (Botter & Fortuin, 2000, p. 665). High item value makes stocking unattractive for any party in the logistics chain, and it drives to pursue alternative solutions for stock keeping. With items other than make-to-order, Huiskonen (2001, p. 130) notes that stocks must be held after which the details of stock keeping are a question of objectives, negotiation power, and cooperation of the parties in the supply chain. On the contrary, low value item logistics should be organised in a cost-efficient way to avoid high administrative costs in relation to the value of the items themselves.

In scientific publications, lead time is perceived as one of the most important criteria for part classification (Roda et al., 2014, p. 541). Spare parts should be available when needed to avoid protracted production downtimes. For some parts, however, availability is difficult to guarantee. Deliveries for special parts can take time due to their design and manufacturing but also because of their needs for special transport (Godoy et al., 2013, p. 200). According to Jaarsveld and Dekker (2011, p. 1583), lead times for make-to-order parts for complex equipment may exceed a year whereas other parts can be accessed from a central warehouse within a day. According to Huiskonen (2001, p. 131), safety stocks are needed for any part with lead times longer that the time to tolerate a stockout situation in a case of failure.

In addition to the above-mentioned, there are many other factors affecting the availability of items, each of which can be used as criteria for evaluating control criticality. These factors can be related, inter alia, to supplier characteristics such as their location, number, and quality. Supplier-related uncertainty can be controlled by relationship management in the supply chain by taking into consideration the degree of co-operation and risk sharing between parties. (Huiskonen, 2001, p. 128) Also, by making sure that technical specifications, such as a bill of materials or cad-drawings, are available and up to date, the plant owner can promote item availability. Molenaers et al. (2012, p. 573), for example, consider the availability of technical specifications in their spare parts criticality classification model.

Among the most cited classification criteria in literature is item specificity, though it can be difficult to quantify (Roda et al., 2014, p. 537, 543). Specificity is an important spare parts characteristic as it can have a great impact on part availability. With unreliable or insufficient data on lead times at hand, Paakki et al. (2011, p. 167) use availability risk as a criterion to assess spare part supply characteristics. They categorise parts into three groups that reflect risk of availability: key parts, industry specific parts, and commercial parts. When it comes to key parts, the number of potential suppliers is considered to be very low as these parts are commonly made-to-order. For this reason, these parts are characterised with long lead times, which poses a greater risk on availability in case of urgent replenishment. Though industry-specific parts are commonly fabricated according to company-specific drawings, they are more generic in nature. For this reason, there are more vendors available and lead times for these parts are considerably shorter. Commercial parts, on the other hand, are common items, such as screws and bolts, that are widely used in different industries. These parts are well available from several sources with short lead times. According to Huiskonen et al. (2001, p. 129), there is a possibility to cooperate with suppliers due to high volume of these parts.

In addition to the fact that many of the spare parts needed for process equipment can be classified as special parts, it is worth noting that they can often be compatible with each other. According to Sarmah and Moharana (2015, p. 463), spare part commonality is an important criterion which can be used to investigate the number of equipment where the same part is used. In case a part is common for many equipment, there is a greater risk for production shutdown due to the shortage of this part. However, only few studies consider the number of identical parts in the plant in spare parts classification (Roda et al. 2014, p. 538).

On the other hand, the number of identical parts in the plant can influence to the availability of a part in case of failure. In their proposed multi-criteria classification model for spare parts inventory management, Braglia et al. (2004, p. 59) consider cannibalism to have an impact on spare parts supply. This criterion takes into consideration whether or not it is possible to replace a part with a similar one removed from the plant, and with what consequences. Here, functional criticality of the part for each equipment must be assessed separately.

4. MATERIALS AND METHODS

4.1 Research approach

As the objective of this thesis is to design a decision-making tool and to test its applicability by implementing it, this research is a combination of deduction and induction approaches. With induction, an understanding of the research context is gained by collecting data, which will be analysed to design the tool. After this, the tool will be tested with pilot plants, which involves important characteristics of the deduction approach. (Saunders et al. 2009, pp. 124–126)

From a research methodological perspective, this thesis follows a case study strategy where an assignment by the case company is studied in its real-life context. More specifically, to design a spare parts classification method that facilitates a decision-making process of the case company managers, this thesis is conducted with a constructive research approach. The basis of this thesis fits well with the approach as ideally a constructive research solves a real-life managerial problem with an implemented new construction that has both theoretical and practical contribution. The constructive research intends to implement the developed solution and thus test its practical applicability. Due to the nature of the research, in which experiential learning is expected to occur, a close cooperation between the researcher and the case company is required. (Lukka, 2000, pp. 2–3)

The constructive approach emerged in the literature of management research methodology during the 1990s when it was explicitly developed in the field of business administration (Kasanen et al., 1993; Lukka, 2000). Nevertheless, the approach can be applied in many fields of research, and it has also gained a lot of positive attention among engineering researchers (Lukka, 2003, p. 83).

As mentioned earlier, within the constructive research a construction, i.e. a solution to the initial problem, is produced. This construction forms the basis of the constructive approach and the potential realisations of the construction are endless. All socially constructed artefacts, such as models, new treatments, medicines, artificial languages, mathematical algorithms, and organization structures, are constructions. The main characteristic feature of socially constructed artefacts is that they are invented and developed, not discovered. (Lukka, 2000, p. 3; Lukka, 2003, pp. 83–84)

The constructive research can be described with process phases as defined by Kasanen et al. (1993) and Lukka (2000). The constructive research process of this thesis can be described with the following seven phases. Each phase is covered in more detail in sections indicated inside the parentheses.

1. Finding a relevant practical problem that could also contribute to theory building (4.2)
2. Examining the potential for cooperation with the case company (4.2)
3. Obtaining both practical and theoretical understanding of the research topic (4.3)
4. Innovating a solution and developing a problem-solving construction (4.4)
5. Implementing the solution and testing its applicability (4.5)
6. Evaluating the scope of applicability of the solution (4.6)
7. Reflecting the findings to prior literature (6.2)

The structure of the thesis is presented in Figure 12. Although the phases of the constructive research process were conducted party simultaneously and iteratively, the figure below gives an overview of the research structure.

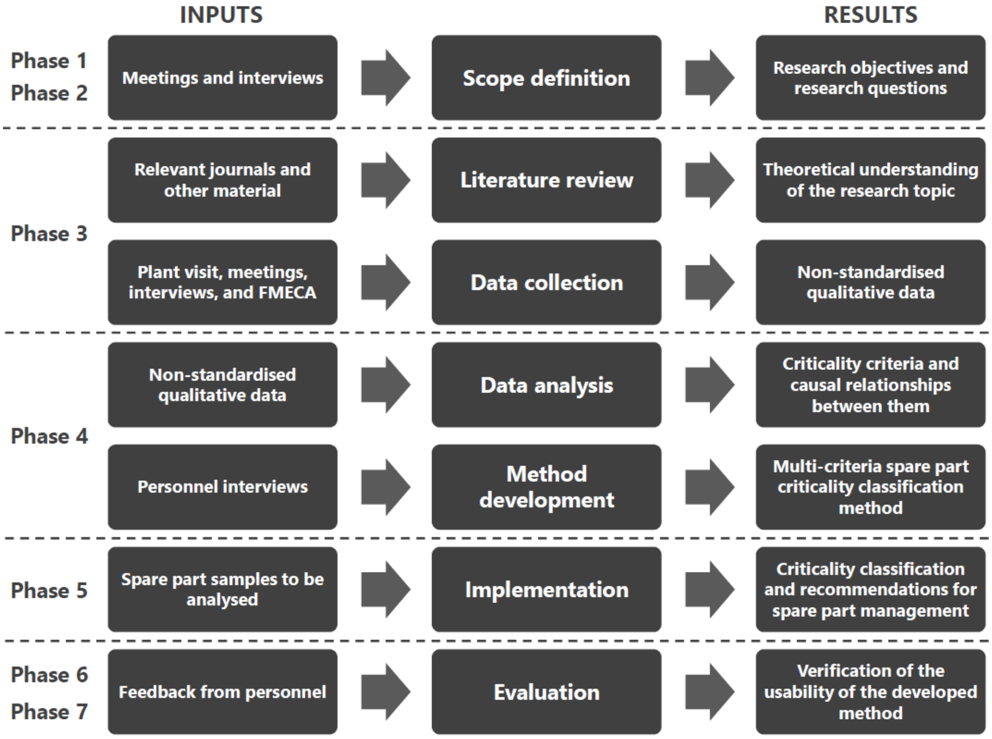


Figure 12. *Constructive research process phases and structure.*

4.2 The case company and its needs for the research

The maintenance strategy of the case company is based on the philosophies of TPM (Total Productive Maintenance) and RCM (Reliability Centred Maintenance). Within both approaches the focus in on costs (McCarthy & Rich, 2015, p. 20). The main objective of TPM is to continuously improve equipment effectiveness by activating employees through a sense of equipment ownership (Järviö et al., 2013, p. 112). RCM, on the other hand, is a systems analysis process that can be used to establish a company-specific preventive maintenance programme (Järviö, 2007, p. 6). The RCM methodology is described with the following four features (Smith & Hinchcliffe, 2003, p.66):

1. Preserve functions
2. Identify failure modes that can defeat the functions
3. Prioritise function need (via failure modes)
4. Select applicable and effective preventive maintenance tasks for the high priority failure modes

In the RCM, all the functions and equipment of the system are identified and prioritised. SRCM (Steamlined reliability centred maintenance), however, is a method that focuses only on critical equipment, and is applied in the case company due to its lighter structure.

The starting point for this thesis is the development research conducted in the case company by Laine in 2018. One purpose of the development research (Laine, 2018) was to develop and standardise the maintenance model across the company's biogas plant network in Finland. In his research, Laine conducted a failure mode, effect, and criticality analysis (FMECA) for the biogas plants with an aim to identify failure modes which could lead to process failure, and methods to prevent them. In addition to actual maintenance activities, the research found spare parts management to be of primary importance in the asset management of some equipment.

Even though the interconnection between spare parts inventory control and RCM is recognised in literature (Jaarsveld & Dekker, 2010, p. 4), the case company does not have a clear strategy nor policies for spare parts management. As the company has adopted the RCM philosophy and strives to enable efficient operation of its equipment, the need for research focusing on spare parts management was noted in the process and maintenance team. Therefore, the research addresses a practically relevant problem, and the Phase 1 of this constructive research process can be considered as successful in this respect.

Also, from the theoretical perspective this research topic is ideal since there is a distinct gap between scientific research and practice in spare parts management. Various spare parts classification schemes can be found from literature but very few studies consider solution implementation. Also, and perhaps partly for this reason, the use of spare parts multi-criteria classification methods among practitioners is still limited. (Syntetos et al., 2009; Bacchetti & Saccani, 2012; Molenaers et al., 2011; Roda et al., 2013, p. 540)

According to Lukka (2003, p. 86), the purpose of Phase 2 of the constructive research process is to ensure that both the researcher and the case organization are committed to putting significant effort into the project. Lukka also notes that the researcher should typically become a member of the team devoted to the research project. Before research project kick-off, the researcher had worked in the organization under study, i.e. the Biogas business unit, but during the research was working in a different business unit. The case company management as well as many experts provided significant input to the research process, and hence it can be said that a balance between supply and demand was reached in the research project.

4.3 Data collection

This section covers the Phase 3 of the constructive research process, i.e. obtaining both practical and theoretical understanding of the research topic. In this phase, the researcher applies various ethnographic methods to obtain profound insights of the current state of the case company. A proper analysis is required to reveal explicit and implicit problems and purposes of the research subject. The understanding obtained in this phase also lays the foundation for profitable communication between the researcher and the practitioners of the case company. (Lukka 2000, pp. 5–6) In addition to prior knowledge of the actual subject of the research, Lukka (2000, p. 6) emphasises the responsibility of the researcher to be aware of prior theory on the topic area. A practical and theoretical understanding of the research topic not only enables further development work but also supports the analysis of the theoretical contribution of the empirical work.

To answer the research questions and to meet the objectives, this study required a combination of primary and secondary data. The researcher collected primary data, i.e. data collected specifically for the research project (Saunders et al., 2009, p. 598), through observation as well as using interviews and questionnaires. Information obtained from the meetings was also an important source of primary data. Secondary data, i.e. data that were originally collected for some other purpose (Saunders et al., 2009, p. 599), were reviewed from literature and various documents.

Since several qualitative and quantitative measures have an effect on spare parts criticality (see 3.5.3), this research is conducted as a mixed-model research by combining quantitative and qualitative data collection techniques and analysis procedures. In addition to this, quantitative and qualitative approaches are combined at other phases of the research. This means that within this research qualitative data are quantified, i.e. converted into numerical codes that can be analysed statistically. (Saunders et al., 2009, pp. 151–153) The data collection methods used in this thesis are depicted in Figure 13 below.

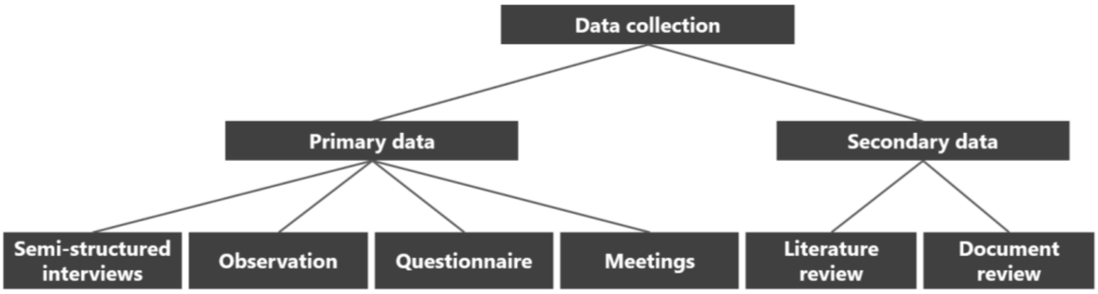


Figure 13. *Data collection methods used in the thesis.*

As illustrated in Figure 13, the data collection consists of multiple methods, each chosen according to the objectives of the thesis. This section presents all the data collection methods and the rationale behind them. Also, the process of data collection for each method will be described.

4.3.1 Literature and document review

Secondary data of this research cover both literature sources and various case company documents and are utilised both in obtaining theoretical understanding and later when implementing the problem-solving construction. Consequently, the secondary data are utilised together with primary data sources.

Obtaining theoretical understanding of the research topic is an important part of the constructive research process (Lukka, 2000, p. 6). Therefore, literature is reviewed to understand the operating environment of the research, i.e. biogas production plant, and to determine the state of spare parts classification in an industrial context. The solution of this constructive research is a multi-criteria spare parts classification method. To develop the method, the literature review aims to discover relevant criticality criteria and classification schemes that are considered when classifying spare parts. Based on this knowledge, the first iterations of the decision tree were constructed.

Case company documents utilised in this research cover process flow diagrams and former FMECA reports. The sample of items to be analysed in this thesis is derived from the FMECA reports, whereas process flow diagrams provided important support in spare parts criticality analyses, especially when assessing consequences related to spare part failure regarding production process, safety, and the environment. However, process flow diagrams and FMECA reports are not presented in this thesis due to their confidential nature.

4.3.2 Spare parts management observation

To see how the spare part inventories are managed in the case company, a visit to a biogas plant was arranged during the first months of the research project. Here, the researcher collected primary data through participant observation. In participant observation, the researcher participates in the lives and activities of subjects and therefore becomes a member of their organization (Saunders et al., 2009, p. 289). Saunders et al. (2009, p. 291) note that a participant observer may as well be a member of an organization which the research covers. In this case, before research project kick-off, the researcher had worked in the organization under study but was working in a different business unit during research.

As the researcher observed the activity in the biogas plant without concealing his identity, the role of an observer as participant was adopted. In this role, the researcher will not take part in the activities under study which allows to focus entirely on conducting research. For example, the researcher was able to concentrate on discussing with the participants and taking notes on important insights. On the other hand, participant observation, where the researcher studies a group by both observing and by participating in the activities of the group, enables researchers not only to observe what is happening but to also share their experiences of emotional involvement (Gill & Johnson, 2002, p. 144). In this study, due to the researcher's role as an observer participant, experiences of emotional involvement did not have an effect on the primary data.

4.3.3 Personnel meetings and interviews

To develop the solution further, better understanding of the research subject in the context of the case company was needed. For this reason, both meetings and interviews were arranged with several employees of the case company. Before and after the research project kick-off, several brief meetings were held with the maintenance manager responsible of the biogas plants. The initial discussions about the research topic were also held with a production manager. These discussions were informal in nature, aimed to explore the research area more closely. The discussions with the maintenance manager as well as the production manager helped gain more understanding of the research topic, and this knowledge was used to plan the following interviews.

Interviews can be used as an efficient measure to gather valid and reliable data relevant to the research questions and objectives of the study (Saunders et al., 2009, p. 318).

First and foremost, interviews in this study serve as a means to obtain practical understanding of spare parts management in the case company. More specifically, the interviews were aimed to gain deeper understanding of the spare parts management practices in the biogas plants. For this reason, seven biogas plant managers as well as one plant operator were interviewed. These interviews were conducted on a one-to-one basis, except for one group interview, and in a semi-structured manner by utilising both exploratory and explanatory approaches. According to Saunders et al. (2009, p. 320), in a semi-structured interview the researcher will have a list of themes and questions to support the interview process, but the execution and questions may vary from interview to interview. This was the case in these interviews as many additional questions were required during the first interviews for the researcher to clarify his understanding of the problem. This reflects the exploratory nature of the interviews in which the aim is to find out the status quo and to seek new insights by interviewing experts in the subject field (Robson, 2002, p. 59). To innovate a solution and to develop a problem-solving construction, establishing causal relationships between different criteria affecting spare parts criticality was an important part of the interviews as well. This again reflects the explanatory nature of the interviews. (Robson, 2002, p. 322)

For the semi-structured interviews, topics for discussion and a list of questions were planned in advance. Although interviews were adjusted according to the context and the interviewees' expertise in some respects, they were conducted to gather information from the following topic areas:

- The current state of spare parts management
- Relevant criteria for analysing spare parts criticality in the context of biogas production
- Causal relationships between different criteria affecting spare parts criticality as well as their relative importance
- The logistics system including network structure and supply chain relationships
- The interviewee's perspective on how to develop spare parts management in the case company

Most of the meetings and interviews had to be organised remotely via audio connection using a business communication platform. Only one interview was held on a face-to-face basis. Remotely arranged interviews made it possible to interview participants over a large geographical area. With permission of the interviewees, the business communication software was used to record four interviews in total. This allowed the interviewer to concentrate on questioning and listening as there was no need to take exhaustive notes during the interview. Later the audio recordings were listened to again and partially transcribed into text, after which the audio recordings were destroyed. However, possible disadvantages of audio-recording the interviews must be taken into account here. According to Tuomi and Sarajärvi (2018, p. 156), a good interviewer is present and strives to listen to the interviewee carefully while observing body language and other cues such as tone of voice. This was party unfeasible in remote interviews as video connection was not used. Audio-recording the interview may also inhibit some interviewees responses, thus reducing reliability (Saunders et al., 2009, p. 341). Party for these reasons, some of the interviews were decided to be conducted without audio-recording. All the interviews introduced in this section as well as their implementation time and duration are summarised in Table 4.

Table 4. *Interviews.*

Job title	Method	Date	Duration
Plant Manager A	Semi-structured	11.1.2021	2h 20 min
Plant Manager B	Semi-structured	13.1.2021	2h 23 min
Plant Manager C	Semi-structured	14.1.2021	1h 30 min
Plant Manager D	Semi-structured	18.1.2021	45 min
Plant Manager E	Semi-structured	19.1.2021	1h 20 min
Group interview: Plant Manager F and Plant Operator	Semi-structured	20.1.2021	1h 15 min
Plant Manager G	Semi-structured	20.1.2021	1h 30 min

All the data gathered above were analysed in Phase 4 of the constructive research process, i.e. innovating a solution and developing a problem-solving construction, to design the spare parts multi-criteria criticality classification method introduced in Section 4.4. After designing the method, more data were needed to be collected during the implementation of the criticality analysis method, which is Phase 5 in the constructive research process. Therefore, the data gathered from the above described interviews were not used only in the classification method building but also in the design of the questionnaire of this research.

4.3.4 Criticality analysis method implementation and questionnaire

In Phase 5 of the constructive research process, the developed spare parts criticality classification method was implemented in three biogas plants during which data were collected from the plant managers with a questionnaire. In this thesis, questionnaire refers to techniques of data collection in which a person is asked to respond to the same questions in a predetermined order (deVaus, 2002). To confirm the spare parts criticality classes by using the developed criticality classification method, various information of the spare parts is needed. As there are no systematically collected data of spare parts in the case company, a questionnaire was found as an appropriate data collection method for this purpose.

The research questions of this thesis suggest an explanatory research where, in this case, various spare part attributes determine how individual parts are managed (Saunders et al., 2009, p. 140). The proposed spare parts multi-criteria criticality classification introduced in Subsection 4.4.3 is based on a decision diagram called a decision tree, which is used to establish a suitable criticality class for each spare part. The decision tree is composed of nodes presenting different spare part attributes, and edges that present the alternatives. The questionnaire, which is used as a classification tool, is based on so-called category questions for which each answer of the respondent can fit into only one category (Saunders et al., 2009, p. 376). The decision problem at each node of the tree is solved within the questionnaire by selecting the alternative that best reflects the spare part characteristics. This is executed by quantifying the data, i.e. converting qualitative aspects of spare parts into numerical codes (Saunders et al., 2009, p. 153).

The questionnaires in this study were filled in by both interviewer-administered and self-administered manner. In each case there was a social interaction between the researcher and the participant. First, the motive to conduct the survey was explained and the basic principle of the questionnaire was reviewed. Next, each classification criteria as well as their respective response categories and the coding schemes were clarified. After the preliminary explanations the actual questionnaire was administered by asking the respondent which of the response categories in question best reflect the spare part characteristics in relation to criteria under review. This was repeated for each criterion and each spare part, and the responses to interviewer-administered questionnaires were recorded by the interviewer. This type of a questionnaire is also referred to as a structured interview which is used to collect quantifiable data (Saunders et al., 2009, p. 320). In one case, the time required to go through all the spare parts under examination proved to be longer than the time reserved with the participant to complete the questionnaire. In this case, it was decided to complete the questionnaire in a self-administered manner where the questionnaire was completed by the respondent.

4.3.5 Summary of data collection methods

All the data collection methods used in this thesis are listed in Table 5. All possible data collection methods were evaluated and from those the most appropriate ones were selected. The selection of the most appropriate methods was guided by the research questions and the objectives of this thesis but also by the constraints of the study, such as access to data and time restrictions. As listed in Table 5, some data collection methods were used in several phases of the constructive research process.

Table 5. *Summary of the data collection methods used in the thesis.*

Data collection method	Data type	Phase of the constructive research process
Meetings	Qualitative	Phase 1. Finding a relevant practical problem that could also contribute to theory building Phase 2. Examining the potential for cooperation with the case company Phase 3. Obtaining practical understanding of the research topic
Literature review	Qualitative	Phase 3. Obtaining theoretical understanding of the criticality analysis methods
Document review	Qualitative	Phase 3. Obtaining practical understanding of the research topic Phase 5. Implementing the solution and testing its applicability
Observation	Qualitative	Phase 3. Obtaining practical understanding of the research topic
Semi-structured interviews	Qualitative	Phase 3. Obtaining practical understanding of the research topic Phase 4. Innovating a solution and developing a problem-solving construction
Questionnaire	Quantitative	Phase 5. Implementing the solution and testing its applicability

4.4 Development of criticality analysis method

This section covers Phase 4 of the constructive research process, i.e. innovating a solution and developing a problem-solving construction. Lukka (2000, p. 6) notes that the nature of this phase of research tends to be creative and heuristic due to which very little generic methodological advice exists. Notwithstanding, the development of the construction is proposed to be conducted in a close cooperation between the researcher and the case company. Also, both practical and theoretical knowledge should be exploited in the construction development. The nature of this development work may be iterative, which was the case in this study as well.

In this thesis, the solution of a constructive research approach is the spare parts multi-criteria criticality classification method. Theoretical knowledge related to spare parts criticality classification were covered in the previous chapters of this thesis. Also, methods for collecting data needed in this phase were covered earlier. This section describes the development process of the criticality analysis method as well as its construction and components. The evaluation of the analysis method is also presented.

4.4.1 Data analysis during development process

The first iteration of the classification method was drafted based on the literature review and initial discussions with the case company. In order to develop the method further and to evaluate the initial prototype idea, more input from the employees of the case company was needed. For this purpose, interviews with seven plant managers and one plant operator of the case company were arranged. Also, a visit to a biogas plant was arranged to collect primary data through observation. The execution of the observation as well as the interviews are described in more detail in Subsections 4.3.2 and 4.3.3 respectively.

Regarding the interviews, discovering the relevant criteria affecting spare parts criticality in biogas plants of the case company was of primary importance. In addition to this, understanding causal relationships between the criteria was an important objective. In order to achieve the aforementioned objectives, proper data analysis is needed. Here, data analysis was conducted for data collected from meetings, the plant visit, and interviews.

In this thesis, an inductive approach for data analysis was used. Using an inductive approach, the data are collected after which they are explored to see which themes or topics to investigate further (Yin, 2003; Strauss & Corbin 2008). Thus, theory emerges after data collection and analysis (Saunders et al., 2009, p. 490). Due to the creative and heuristic nature of the classification method development, the data analysis in this study is defined as less structured.

The non-standardised and complex nature of the qualitative data collected sets conditions for the analysis as, in this study, the data needed to be summarised and restructured as a narrative to be interactable (both discussed later). As mentioned in Subsection 4.3.3, a total of four semi-structured interviews were audio-recorded and subsequently transcribed into text. Even though the interviewer should ensure that the focus of the discussion remains within the topic of the interview, here the researcher allowed, to some extent, side paths of the interviewees as proposed by Hyvärinen et al. (2017, p. 24). Thus, some interviews lasted a relatively long time, and preparing the data from audio-recordings for analysis proved to be remarkably time consuming. For this reason, data sampling was used as an alternative way to reduce the time needed to transcribe the audio-recordings. In this process, the entire recording is listened carefully first, after which only sections relevant to the research are transcribed (Saunders et al., 2009, p.486). The relevant sections here are the elements that later help structuring data into a narrative.

Data collected from each meeting, the plant visit, and interviews were gathered in research notes. After writing up the notes, a summary of the key points was produced into a single document. In this summary, the long statements were compressed into shorter statements without losing the message behind them. According to Saunders et al. (2009, p. 490), note taking allows to understand data as well as to integrate data from different research notes, and by summarising data one will become conversant with the key themes or patterns emerged from data collection (Saunders et al., 2009, p. 491).

In this research, data structuring using narratives was utilised in combination with text condensing to support data interpretation. Coffey and Atkinson (1996) define a narrative as an abstract of an experience that is narrated as a sequence of events that are relevant for the narrator and which convey meaning to the researcher. During the interviews of this study, the researcher particularly encouraged participants to provide abstracts that, at least partly, take the form of narratives. For example, below are some sample questions that were asked from the interviewees in order to get information that helps to structure data in a form of a narrative:

> Question 1: *“Can you describe a situation where the production process has stopped unexpectedly?”*
>
> Question 2: *“In your experience, what are the main reasons for spare part unavailability and why?”*
>
> Question 3: *“If there is a failure in equipment type X, what would be the consequences?”*
>
> Question 4: *“How would you handle a situation of a sudden failure of production equipment?”*

In literature, narrative structuring commonly follows an apparent structure. Based on prior research, Coffey and Atkinson (1996) outline the structural elements that often occur in narratives. These elements can be roughly presented in the following form:

- What the story is about
- What happened, to whom, whereabouts and why?

- The consequences that arose from this
- The significance of these events
- The final outcome

The form presented above served as a good guideline for narrative structuring in this study, but it was not meticulously followed in all cases. Coffey and Atkinson (1996) also note that these elements may not appear in the order listed above and some elements may also reappear in a provided narrative. It must also be emphasised that the narratives structured within the research are partly related to real-life cases but also to hypothetical situations. In this qualitative analysis process, condensation, that is summarising of meanings, was used in combination with data structuring. To get an idea of how the relevant aspects of empirical data were structured using narratives, the following is an example of one narrative that is structured by utilising the form outlined by Coffey and Atkinson (1996) above.

> ***What the story is about:*** *Vertical mixer of a biogas digester.*
>
> ***What happened, to whom, whereabouts and why?*** *The vertical mixer breaks down unexpectedly.*
>
> ***The consequences that arose from this:*** *The failure will not cause immediate shutdown nor serious consequences related to safety or the environment. However, the failure causes malfunctions as without proper mixing the composition of the feed inside the digester becomes uneven, which in turn causes uneven biogas production. In addition, this would prevent a uniform temperature distribution throughout the digester. The price of the mixer is perceived as rather high, and currently the company finds it unattractive to store a spare equipment in the plant storage. Since there is no spare equipment in the plant storage, digester capacity would have to be reduced by 50 % in order to minimise malfunctions caused by the breakdown. This, on the other hand, would lead to 25 % decrease in biogas sales as there are two digesters in total.*
>
> ***The significance of these events:*** *As the equipment in this case is special and its main components are fabricated according to specific drawings, the number of potential suppliers is low, in addition to which they are located outside the country of biogas production of the case company. For this reason, lead time for this equipment and its main components is four months. In a situation like this, it would be necessary to inquire the availability of spare parts from the other biogas plants of the company. However, the broken mixer in this case is one of a kind in the*

> *plant network, and even if other plants would have spare parts in stock, they would not be compatible here. From this point of view, the unavailability of a spare part would lead to protracted production losses with direct consequences on the profit of the company.*
>
> ***The final outcome:*** *The possible failure modes of the vertical mixer and their consequences on the production process are rather well identified, but precautionary measures are not sufficient. Because the vertical mixer as well as its main components are characterised with long lead times, this poses a great risk of availability in case of urgent replenishment. The stocking policy for this equipment need to be revised by considering several aspects related to inventory management.*

The qualitative data analysis presented above helped to identify recurring aspects related to spare parts management in the case company. In addition to explicit issues, the analysis revealed many implicit problems and functions of the research subject. With this knowledge, the proposed spare parts classification method based on multiple criteria was constructed.

4.4.2 Criticality criteria

Through meetings, interviews, and the plant visit, 19 criteria for assessing item criticality in biogas plants of the case company were initially outlined. Including each of these criteria into a classification method would generate an uncontrollable number of different classes of items. This would make spare parts management unnecessarily complicated for the operational environment of the case company. To ensure the usability of the classification method, the number of criticality criteria was limited to the most relevant and generic ones. As a result of the data analysis, a total of five criteria were composed and grouped as clusters as listed in Table 6. With the analysis, it was also possible to ensure that the criteria used did not overlap. This subsection introduces all the criteria incorporated in the criticality classification and the rationale behind the chosen criteria.

Table 6. *Criticality criteria incorporated in the criticality classification approach.*

Criteria	Description
Functional criticality	This criterion takes into account the consequences related to spare part failure or its shortage in regard to production losses, safety, or the environment.
Alternative production	This criterion determinates the possibilities to control the failure in terms of alternative production and solutions.
Availability	This criterion evaluates the risk of availability which, in this case, is determined by lead time which in turn is commonly affected by item characteristics such as specificity as well as number, quality, and location of potential suppliers.
Value	This criterion is a universal control characteristic, and in many cases, companies find it unattractive to store valuable items, regardless of item criticality. On the other hand, storing parts that are not essential in ensuring uninterrupted production may tie unnecessary amount of capital.
Demand pattern	This criterion evaluates the frequency and predictability of item failure. When defining spare part criticality, parts with low and sporadic demand pose challenges to inventory control, particularly in cases where a part has high value and is essential in ensuring uninterrupted production.

Functional criticality. To assess the elements included in process criticality covered in Subsection 3.5.1, functional criticality was found a suitable criterion. There is a clear consensus among the plant managers interviewed that the criticality of an item is most affected by the impact of its failure or shortage in terms of production loss, safety, or the environment. Here, the production process as a whole must be taken into account. For example, a possible domino effect of part failure must be assessed covering the whole process. In this research, the approach introduced by Huiskonen (2001, p. 129) was found as the most practical way to evaluate functional criticality. Here, criticality is linked to the time in which the failure must be repaired. For example, the biogas plants of the case company are wet digestion plants meaning that the mass within the production process is moved by pumps in the pipelines. For this reason, a pump failure would, in many cases, require immediate attention, and necessary spare parts should be available instantly. In most cases sensor failure, on the other hand, would not interrupt the production process but would cause malfunctions. In this case, the failure can be tolerated for some time before corrective actions are needed. Finally, there are also failures that have no effect on the production process, safety, or the environment, which is why there are no specific time restrictions for corrective actions and spare parts can be replenished over a longer period of time. As Huiskonen (2001, p. 129) notes, integrating the time dimension in criticality assessment facilitates control system planning such as making choices between material and time buffers.

Alternative production. For some functionally critical items, it was found that there are a few possible practices to control the failure in terms of alternative production, which were initially recognised as criticality criteria as such. Redundancy is one example how reliability of critical functions can be increased. For example, some functionally critical pumps have been duplicated, so if there is a failure in one pump, the other can be put into operation immediately, thus avoiding production downtime. Irrespective of the alternative production method, the purpose of this criterion is to determine whether it is possible to avoid, or tolerate, the possible consequences caused by part failure. Together with functional criticality, this criterion determinates the process criticality of a part.

Availability. To assess control criticality, i.e. the possibility to control a failure or shortage, a measure of availability is used. This criterion evaluates the risk of availability which, in this case, is assessed by lead time. Lead time was found to be affected by many factors which were also initially considered to be used as criticality criteria as such but proved to be difficult to implement due to lack of available data within the case company. For this reason, all factors that have an impact on lead time were combined to the evaluable availability criterion. In this case, lead time can be evaluated by item characteristics in terms of specificity as well as number and quality of potential suppliers. Regarding make-to-order parts or parts that are fabricated according to specific drawings, the number of potential suppliers is considered to be low and they are mainly located outside the country of biogas production of the case company. These parts are characterised with long lead times, which poses a great risk of availability in a case of urgent replenishment. Commercial parts, on the other hand, are standard parts that are widely used in different industries; examples are consumables and auxiliary materials or other mechanical components such as bearings, chains, and valves. These parts are easily available from several sources within the country of biogas production with short lead times.

Value. Item value is a universal control characteristic to all materials, and in many cases, companies find it unattractive to store valuable items, regardless of item criticality. On the other hand, storing parts that are not essential in ensuring uninterrupted production may tie unnecessary amount of capital. Regarding the significance of this criterion, differences were found within the company. In general, plant managers would be willing to store more parts into site whereas threshold for stocking is higher for organization management. By incorporating value into the criticality classification, it is possible to evaluate whether or not it is justified to stock items with regard to process and control criticality. By incorporating value into the criticality classification, different stocking strategies and possible co-operation with different parties in the supply chain can be considered.

Demand pattern. This criterion evaluates the frequency and predictability of item failure. When defining criticality, parts with very low and sporadic demand pose challenges to inventory control, particularly in cases where a spare part has high value and is essential in ensuring uninterrupted production. Many spare parts in the biogas plants of the case company have all these elements. Demand pattern, coupled with above-mentioned spare parts characteristics, introduces control situations with varying strategies and policies for spare part stocking. By incorporating demand pattern into criticality classification, parts suitable for centralised storage can be identified. As the case company owns several relatively closely located biogas plants, different centralised storage solutions such as co-operative stocking pools may be feasible.

4.4.3 Criticality analysis method based on interview analysis

The criticality analysis method constructed for spare parts classification in the case company is based on a decision tree method, as depicted in Figure 14. The structure of the decision tree, i.e. the sequence and the causal relationships between the criteria, was constructed based on the data analysis presented in Subsection 4.4.1. The objective of the constructed decision tree is to assess spare parts criticality in an easy and logical way and thus it can serve as a transparent tool to support maintenance and plant managers in their decision-making.

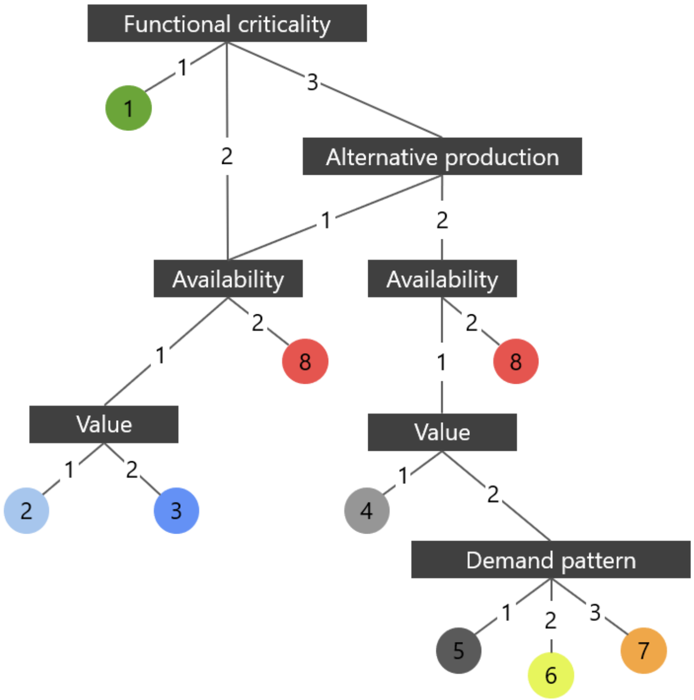


Figure 14. *Decision tree for spare parts criticality classification in biogas plants.*

The ruling criteria of the classification method are the criteria introduced in Subsection 4.4.2: functional criticality, alternative production, availability, value, and demand pattern. These five aspects of spare parts criticality are presented as decision nodes in a decision tree. The edges of the decision tree, on the other hand, illustrate the decision options for the decision nodes.

The idea of the proposed decision tree is to guide the analyst towards the most suitable criticality class of a spare part within a multi-criteria problem. This is done by following the decision paths by choosing the alternative that best reflects the item characteristics concerning the criticality criteria. The numbers for different alternatives follow the logic of VED classification (see Section 3.4) in which number 3 stands for the most critical alternative (vital) while 1 stands for the least critical one (desirable). In nodes with only two decision alternatives, number 2 stands for vital plus essential, and 1 stands for desirable. However, to keep the classification method constructed onto Microsoft Excel sheet as simple as possible, using numbers as decision alternatives was found the most practical way to convert the qualitative judgements into codes that can be analysed statistically. The decision alternatives for each criterion are summarised in Table 7.

Table 7. *The decision tree nodes and their respective decision alternatives.*

Criterion	Criterion characteristics	Alternative
Functional criticality	No effect on production, safety, or the environment; there are no specific time restrictions for corrective actions in case of failure	1
	Failure causes malfunction: the failure can be tolerated for some time before corrective actions are needed	2
	Failure causes such consequences to production, safety, or the environment that immediate corrective actions are needed	3
Alternative production	The consequences caused by failure can be avoided or tolerated for a limited time by applying temporary arrangements	1
	Alternative production solutions cannot be arranged in case of failure	2
Availability	Lead time is expected to be shorter than the time to tolerate a stockout situation in case of failure	1
	Lead time is expected to be longer than the time to tolerate a stockout situation in case of failure	2
Value	Low/mediocre	1
	High	2
Demand pattern	High and steady demand	1
	Low and sporadic demand	2
	Very low demand, not expected to fail	3

Because functional criticality is considered as the most important element in classifying spare parts based on criticality levels, it is the first node of the decision tree. The first question in the decision tree reads as follows: *What are the consequences caused by the failure of an item, and when corrective actions are needed?* The highest points are assigned to items whose failure or shortage has the most severe consequences with regard to production losses, safety, or the environment. The selected answer guides the analyst to the next node. If alternative 1 is selected, detailed examination is excluded as no special attention is needed, and “standard” inventory management methods are proposed for these items. If alternative 3 is selected in the first node, the alternative productions methods are considered before evaluating the control aspects.

The knowledge of alternative production possibilities, such as redundancies, is crucial as the case company uses same spare parts in different pieces of equipment which may vary regarding functional criticality. The purpose of the alternative production criterion is to prevent unnecessary classifying of parts as critical if consequences caused by the failure can be avoided or tolerated for a limited time by applying temporary arrangements.

The third node of the decision tree considers item availability. Since there are no systematically collected history data of lead times, in addition to which there are items that have never been ordered before (lack of experiential knowledge), the availability of an item needs to be evaluated by taking into consideration numerous aspects such as item specificity as well as the number, quality, and location of potential suppliers. If alternative 2 is selected, i.e. lead time is expected to be longer than the time to tolerate a stockout situation in case of failure, the remaining two criteria are not considered, regardless of the branch of the decision tree.

The purpose of the fourth decision node, value, is to acknowledge situations where solutions other than stock holding should be considered. Regarding the criterion alternatives, value is considered “high” in the case company if unit price exceeds five thousand euros. High value directs to higher criticality classes while low and mediocre value items are considered less critical. Within this research, alternative production, availability, and value are dichotomous in nature and therefore they were decided to have only two possible alternatives each.

The fifth decision node, demand pattern, is considered only in specific situations. This criterion evaluates the frequency and predictability of the item failure to establish different provisioning and stocking policies. For this criterion, the highest points are assigned to items with very low demand as they are difficult to control and therefore considered as more critical.

4.4.4 Criticality classes and respective spare parts management approaches

The criticality class of an item is discovered by following the correct path in the decision tree presented in Figure 14 above. This study recognises eight criticality classes of which class 1 items are the least critical while class 8 items are the most critical. Despite the fact that some of the decision alternatives in Table 7 above occur in several criticality classes, each class represents a unique combination of item characteristics. The different criticality classes are described in Table 8 below.

Table 8. *Criticality classes.*

Criticality class	Description
1	- Failure or shortage has no effect on production, safety, or the environment - No specific time restrictions for corrective actions in case of failure
2	- Failure or shortage causes malfunction - Lead time is expected to be shorter than the time to tolerate a stockout situation in case of failure - Low/mediocre value
3	- Failure or shortage causes malfunction - Lead time is expected to be shorter than the time to tolerate a stockout situation in case of failure - High value
4	- Failure causes serious consequences to production, safety, or the environment - Lead time is expected to be shorter than the time to tolerate a stockout situation in case of failure - Low/mediocre value
5	- Failure causes serious consequences to production, safety, or the environment - Lead time is expected to be shorter than the time to tolerate a stockout situation in case of failure - High value - High and steady demand
6	- Failure causes serious consequences to production, safety, or the environment - Lead time is expected to be shorter than the time to tolerate a stockout situation in case of failure - High value - Low and sporadic demand
7	- Failure causes serious consequences to production, safety, or the environment - Lead time is expected to be shorter than the time to tolerate a stockout situation in case of failure - High value - Very low demand, not expected to fail
8	- Failure causes malfunction or serious consequences to production, safety, or the environment - Lead time is expected to be longer than the time to tolerate a stockout situation in case of failure

Based on the final spare parts criticality class, the recommended spare parts management policies and stocking strategies for a specific part will be established. The recommended policies and strategies are based on the findings of the literature review as well as the data analysis. Thus, recommendations for spare parts management found in literature have been considered and, where applicable, utilised herein, in addition to which the operating environment of the case company has also been considered. The recommendations for spare parts management according to criticality class are summarised in Table 9 below.

Table 9. *Spare parts management matrix.*

	Spare parts criticality class							
Recommended approach	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Purchase on demand	x	x	x					
Ordering automated by WMS		x						
Stocked by supplier			x					
Plant network co-operative stock pools or stocking in central warehouse							x	
Time guaranteed delivery contract with accredited service company						x		
Close co-operation with small and local vendors								x
Stocking on site				x	x			x
Standardisation of parts							x	x

4.5 Criticality analysis method implementation

In accordance with Phase 5 of the constructive research process, the proposed criticality analysis method was implemented, and its applicability was tested after constructing the solution. The technical configuration of the operating environment of this research, i.e. biogas plants of the case company, is summarised in Table 10. Three co-digestion plants of the case company were selected for the implementation phase. The main feedstocks of the plants consist of sewage sludge, biodegradable waste from food industry, and separately collected and packaged biowaste. Each of these plants represents a mesophilic wet digestion technique. The core process of the plants is biological, anaerobic treatment in which organic matter is added into CSTR-reactors using pumps. The digestion is carried through a two-stage digestion system (multi-stage). The continuous mode of operation of the biogas plants works seven days a week and 24 hours a day, and the annual availability is over 8,500 hours.

Table 10. *Configuration of the biogas plants of the case company.*

Main feedstock	Sewage sludge, biodegradable waste from food industry, separately collected and packaged biowaste, and manure and field biomass from agriculture
Waste processing capacity	60,000 – 130,000 tonnes/year
Biogas process	Mesophilic
Solids content of the feedstock fed to the digesters	< 15 %
Process type	Wet digestion
Reactor type	Continuously stirred tank reactor
Digestion system	Multi-stage
Gas production capacity	30 – 61 GWh/year

In terms of spare part inventories, biogas plants have thousands of items that need to be managed, and therefore classifying all of them in a way that requires expert judgement would take a very long time. Considering the scope of this research, i.e. focusing on the most "critical" parts, the pre-screening of the items included in the criticality analysis is based on an FMECA approach formerly conducted in the case company. The purpose of the FMECA has been to define all process failure modes and the respective maintenance strategies to ensure proper production capacity and undisturbed biogas production. Therefore, equipment that would not interfere with the production process in case of failure, such as building services equipment, have been excluded from the FMECA as well as from the spare parts criticality analysis. In cases where deemed necessary, the equipment covered in the FMECA were examined in more detail in this research. For example, FMECA considered a pump as a whole whereas criticality analysis of this research examined the main components of a pump such as stator, rotor, shaft, motor, and gear as well. This kind of detailed examination was conducted for equipment that could be repaired in the site in case of failure.

The criticality analysis was performed for different items included in the process flow diagram, that is for main process equipment and other items with reference tag numbers and their components. Thus, in some cases, an item was analysed at several different locations in the process.

The objective of the developed criticality classification method is to assess spare parts criticality in an easy manner. Therefore, the analysis tool was constructed onto Microsoft Excel sheet since every user of the analysis tool is familiar with the program. Plant managers were selected to conduct the criticality analysis as they have the most extensive experience and knowledge of the spare part assortment of the biogas plant. Before conducting the analysis, the basic principle of the criticality classification method was reviewed and the classification criteria (see Table 6) as well as their respective decision alternatives and the coding schemes (see Table 7) were clarified. After the preliminary explanations the actual analysis was conducted by asking the plant manager which of the decision alternatives best reflect spare parts characteristics in relation to criteria under review. After this, the decision alternatives were filled into the analysis tool where the appropriate criticality class is automatically generated based on the decision alternatives. Repeating this process for each spare part the criticality of items can be evaluated by using subjective judgements and experiential knowledge.

4.6 Criticality analysis method evaluation

This section is part of the Phase 6 of the constructive research process, i.e. evaluating the scope of applicability of the solution. Lukka (2000) notes that in this phase, the researcher should remain impartial when analysing the results of the research together with the case company. A broader evaluation of the results and the scope of applicability are discussed later in Sections 5.3 and 6.2. The developed problem-solving construction and its validity is evaluated next.

Evaluation of the criticality analysis method is conducted by considering nine evaluation criteria presented by Sink (1985). These evaluation criteria are widely used to evaluate measurement systems, and thus considered as suitable for evaluating the developed criticality classification method and how it, in turn, evaluates spare part criticality. The evaluation considers the following criteria:

1. Validity
2. Accuracy
3. Collective exhaustiveness
4. Uniqueness or mutual exclusiveness
5. Reliability
6. Comprehensibility
7. Quantifiability
8. Controllability
9. Cost-effectiveness

The evaluation is based on the insights gained from Phase 5 of this constructive research process covered in Section 4.5. The objective of the developed criticality classification method is to assess spare parts criticality in an easy manner. Feedback from the case company personnel on the achievement of this objective were gathered both during and after the method implementation. Thus, the criticality classification method is evaluated in the case company context.

Validity concerns ensuring that the right phenomenon is being measured or tested (Sink, 1985). Therefore, validity of the developed criticality classification method is evaluated based on how well it measures spare part criticality. There is no clear definition for spare parts criticality or guidelines for measuring it in the academic literature. However, in order to assess spare part criticality, which must always be assessed case-by-case, literature recommends multi-criteria classification approach (Stoll et al., 2015, p. 226). The developed method considers five relevant criteria for analysing spare parts criticality from the perspective of a biogas plant equipment owner. The case company considers the criteria to be relevant as well as the number of criteria to be sufficient to reflect the criticality of a spare part. The method also considers both process and control criticality, which is a widely accepted approach in academic literature. Furthermore, both qualitative and quantitative aspects are considered, which is also recommended for multi-criteria classification of spare parts (Roda et al., 2014, p. 531).

Accuracy. Requirements regarding how accurately and precisely spare parts criticality should be assessed were not defined during the research process. The developed method is based on expert knowledge and judgement, which contributes to the accuracy of the analysis. However, the decision alternatives presented in Table 7 are considered as adequate to reflect spare parts characteristics. One of the plant managers interviewed commented on the accuracy of the criticality method as follows:

> *"With this accuracy, the method provides a good starting point for reviewing spare parts criticality so that parts can be managed according to criticality class."*

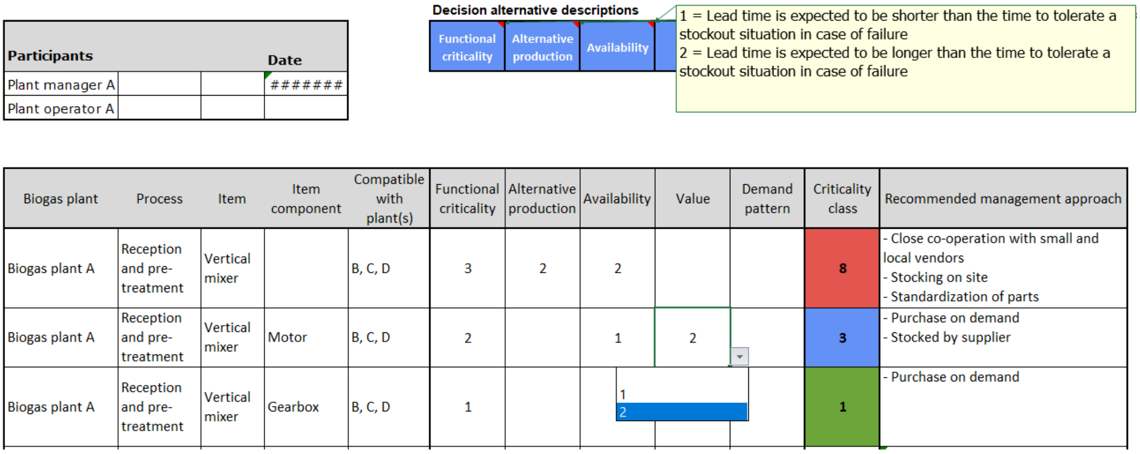
Collective exhaustiveness concerns whether the criteria used in the method are sufficient to assess spare part criticality. As noted above when discussing Validity, the case company considers the criteria to be relevant as well as the number of criteria to be sufficient to reflect the criticality of a spare part. Through meetings, interviews, and a plant visit, 19 criticality criteria were originally discovered. As one plant manager also pointed out, including more criteria in the method would be a trade-off between usability. For this reason, the number of the criteria was limited to the most relevant and generic ones. However, many of the criteria consider several attributes. For example, availability criterion evaluates the risk of availability, i.e. lead time estimate. This was found to be affected by many factors such as item specificity as well as number and quality of potential suppliers.

Mutual exclusiveness. As a result of data analysis, a total of five criteria were composed and grouped as clusters reflecting unique properties of the criticality phenomenon. This way it was possible to ensure that the criteria included in the method do not overlap.

For instance, the number of potential suppliers as well as their quality and location were all initially considered to be used separately as criticality criteria. This, however, would not serve the purpose of the analysis since the rationale in considering these would be to evaluate procurement lead time. For this reason, all factors influencing lead time were combined to the evaluable availability criterion.

Reliability. The greatest disadvantage of the developed method is that it requires expert judgement which exposes to a high level of subjectivity. This, however, is necessary due to insufficient inventory data available in the case company. Among others, these factors affect to the reliability of the method.

Comprehensibility. Rather than developing an approach purely theoretical in nature, the objective was to construct practical and easy-to-use approach for spare parts classification that could support maintenance and plant managers in their decision-making. Therefore, the analysis tool was constructed onto Microsoft Excel sheet as the case company personnel is familiar with the program. The basic principle of the criticality classification method is covered in the Excel sheet. Furthermore, the classification criteria as well as their respective decision alternatives and the coding schemes are clarified as illustrated in Figure 15**.** Regarding usability, the method was seen as user-friendly and comprehensible. One of the plant managers commented that his entire plant staff could use the method in the future.



Participants			Date
Plant manager A			#######
Plant operator A			

Decision alternative descriptions

Functional criticality	Alternative production	Availability

1 = Lead time is expected to be shorter than the time to tolerate a stockout situation in case of failure
2 = Lead time is expected to be longer than the time to tolerate a stockout situation in case of failure

Biogas plant	Process	Item	Item component	Compatible with plant(s)	Functional criticality	Alternative production	Availability	Value	Demand pattern	Criticality class	Recommended management approach
Biogas plant A	Reception and pre-treatment	Vertical mixer		B, C, D	3	2	2			8	- Close co-operation with small and local vendors - Stocking on site - Standardization of parts
Biogas plant A	Reception and pre-treatment	Vertical mixer	Motor	B, C, D	2		1	2		3	- Purchase on demand - Stocked by supplier
Biogas plant A	Reception and pre-treatment	Vertical mixer	Gearbox	B, C, D	1					1	- Purchase on demand

Figure 15. Screen capture of the developed criticality analysis tool.

Quantifiability. By quantifying the data, i.e. converting qualitative aspects of spare parts into numerical codes as decision alternatives, and presenting the criticality class as a numerical value, the results derived from the analysis can be understood and presented in a meaningful way. Criticality analysis key findings are presented in Section 5.1.

Controllability. The purpose of the controllability criterion is to evaluate whether the criticality criteria included in the method can be controlled (Sink, 1985, pp. 68–69). Functional criticality as well as demand pattern are considered difficult, if not impossible, to control. On the other hand, using the method to systematically analyse spare parts may reveal parts that should be subject to various follow-up actions. For example, many spare parts with poor availability were discovered during the method implementation. Availability can be controlled by, for example, looking for other possible suppliers.

Cost-effectiveness. Finally, the last evaluation criterion considers whether the criticality analysis using the proposed classification method is worth performing in relation to the resources it requires. Due to the expert judgement needed, the criticality analysis turned out to be rather laborious. In a broader sense, one of the plant managers interviewed commented on the usefulness of the method as follows:

> *"The method seems unnecessarily complicated. Over time and experience I know which spare parts are critical and which are not. However, the method could prove useful in case a new plant manager is recruited."*

Nevertheless, the manager who made the previous comment said he is aware that there may be spare parts that were not previously considered as critical, and for such parts, the method could help to prevent potential availability problems, for example. Other plant manager interviewed commented on the cost-effectiveness of the method as follows:

> *"Regardless of the working hours required, the analysis is worth performing. The systematic analysis provides means to discover critical spare parts that would not otherwise have been considered as such. For example, there are equipment that have never failed. For some of these equipment, spare parts are not stocked on site in addition to which their availability have never been considered before. I think it would be useful to implement the method at each biogas plant of the company in addition to which it could be used to support inventory management throughout the organization."*

5. RESULTS AND DISCUSSION

5.1 Criticality analysis key findings

This Section presents the key findings of the criticality analyses conducted in three biogas plants of the case company. Figure 16 below presents the criticality classification of the items analysed using the constructed classification method. Criticality classes were covered earlier in Table 8. It is worth bearing in mind that the criticality analysis was performed separately for different reference tag numbers and their components included in the process flow diagram. Therefore, in some cases, identical spare parts may have different criticality classes depending on their location in the production process.

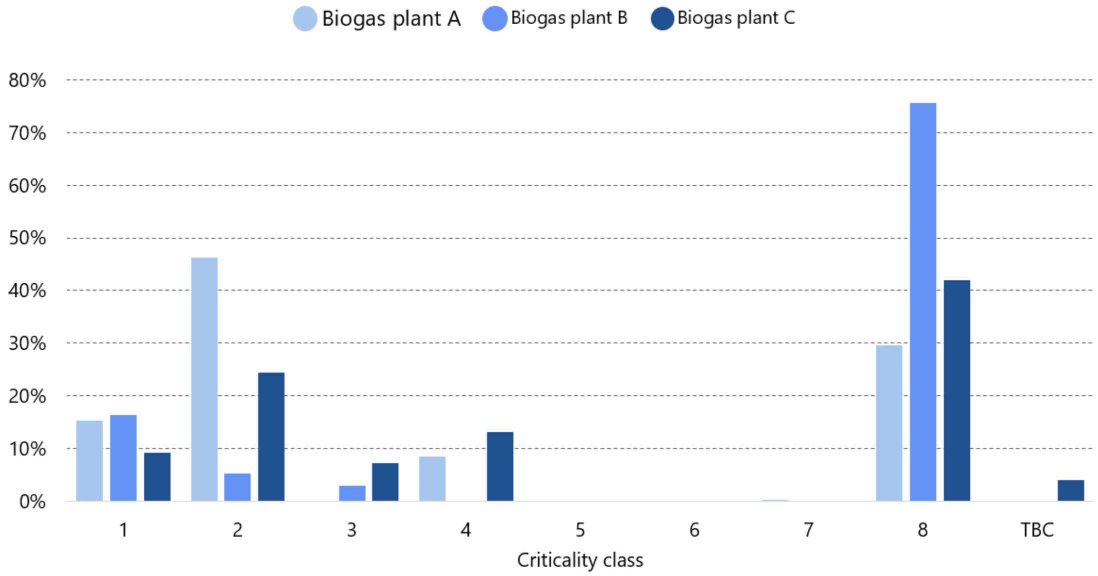


Figure 16. *Spare parts criticality classification of the analysed items.*

Although the results vary between the biogas plants (A, B, and C), clear generalisable similarities can be distinguished. It can be noted that for each biogas plant, a large proportion of the analysed items fall into criticality class 8. This can be partly explained by the fact that the sample of items to be analysed was selected on the basis of an FMECA pre-screening. One major finding of the analysis is that a significant proportion, 76 percent, of the analysed items in biogas plant B fall into class 8. In addition, no items with a criticality class of 5 or 6 were found for any of the biogas plants examined, and only few class 7 items were discovered for plant A. For classes 5 and 6, this is partly due to very low demand volumes, which is a typical characteristic of spare parts (Roda et al., 2014, p. 531).

Figure 17 below presents the decision alternative division by decision criteria for each of the analysed biogas plants. The decision alternative descriptions for each criticality criterion were covered earlier in Table 7. Decision alternative division not only reflects the characteristics of the analysed items but also explains the spare parts criticality classification. Due to inadequate availability data, a small proportion, 4 percent, of the analysed items in biogas plant C are unclassified, and their criticality class are to be confirmed (TBC) later. Looking at the criticality class division in Figure 16 above, it can be concluded that very few decision paths of the analysed items proceeded into the demand pattern decision node (see Figure 14). Particularly for biogas plant B, this was partly due to the fact that for many analysed items, lead time is expected to be longer than the time to tolerate a stockout situation in case of failure (alternative 2 of Availability), which therefore leads analyst to class 8. With more favourable lead time estimates (alternative 1 of Availability), item values were mostly considered as low (alternative 1 of Value), which also prevented decision paths proceeding into the demand pattern decision node and thus explains the scarcity of classes 5 and 6 and the small division of class 7. This finding indicates that items that are characterised with short lead times are more often commercial parts with low value. Also, one major finding is that a significant proportion, 90 percent, of the analysed items in biogas plant B received alternative 2 for the availability criteria. This division differs significantly from the results of biogas plants A and C. Of the biogas plants examined, plant B is several years older than the other two. According to the experts interviewed, this could contribute to the availability of spare parts.

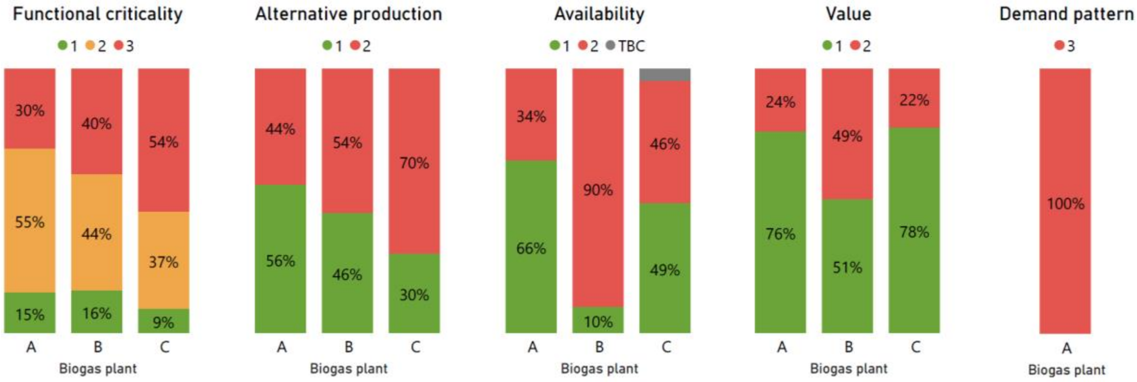


Figure 17. *Decision alternative division by decision criteria.*

Spare parts criticality classification by process step for each of the examined biogas plants can be found in Appendix A. It is worth mentioning that the results between biogas plants A, B, and C may not be fully comparable due to differences in the samples of the analysed items. Despite this, by looking at the combined classification in Figure 18 below, general conclusions can be made. It should be noted that unclassified spare parts are not included in Figure 18. First of all, a great percentage (85 %) of the analysed items in a hot water system fall into criticality class 8. For instance, a boiler unit included in the hot water system is a vital part of the biogas production process as it ensures sufficient and continuous thermal energy production; thermal energy is needed in the biological process as well as in the sanitation process. Therefore, item failure or shortage in the hot water system can, in the worst case, cause serious multiplier effects on the biogas production process. It is to be noted that in end product upgrading, a large proportion of the analysed items fall into criticality class 1 (82 %), meaning that item failure or shortage has no effect to production, safety, or the environment and thus there are no specific time restrictions for corrective actions in case of failure.

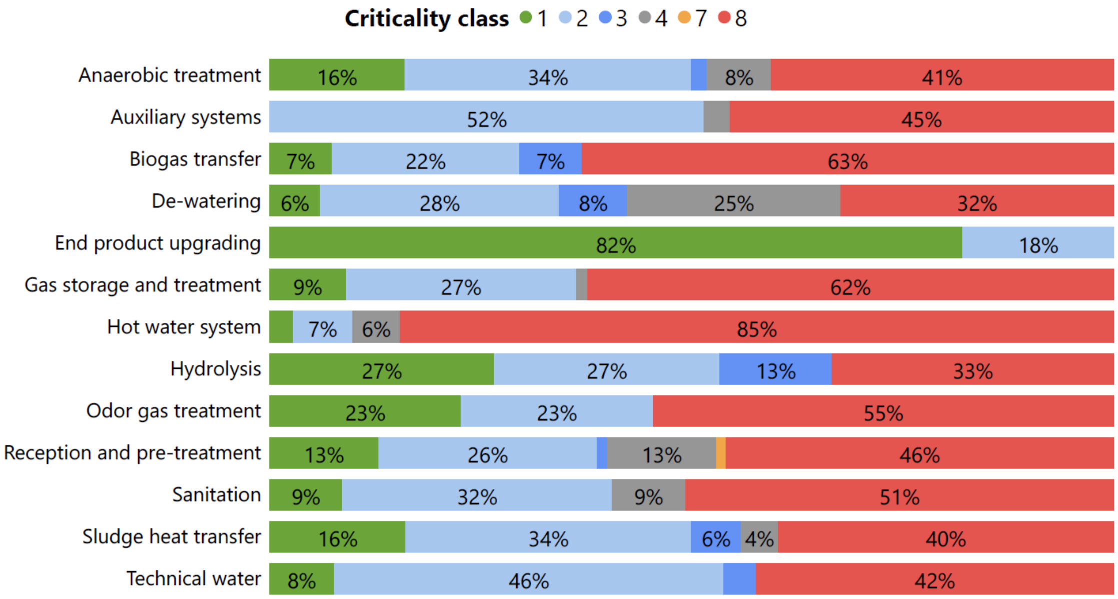


Figure 18. *Combined spare parts criticality classification by process step.*

Criticality classification by item type for each of the examined biogas plants can be found in Appendix B. Again, the results between biogas plants A, B, and C may not be fully comparable due to differences in the samples of the analysed items. However, general conclusions can be made by looking at the combined classification of the analysed item types in Figure 19. The review excludes item types for which the results cannot be expected to represent criticality class division reliably due to the small number of analysed items. Such item types include e.g. bearings, belt conveyors, controllers, filters, hydraulic parts, seals, and stators. Subsection 4.4.1 covered the process of structuring empirical data using narratives by examining the consequences of a vertical mixer failure. From the figure below, it can be seen that all of the analysed vertical mixers (covering 19 items) fall into criticality class 8. Most vertical mixers are used for anaerobic treatment or sanitation.

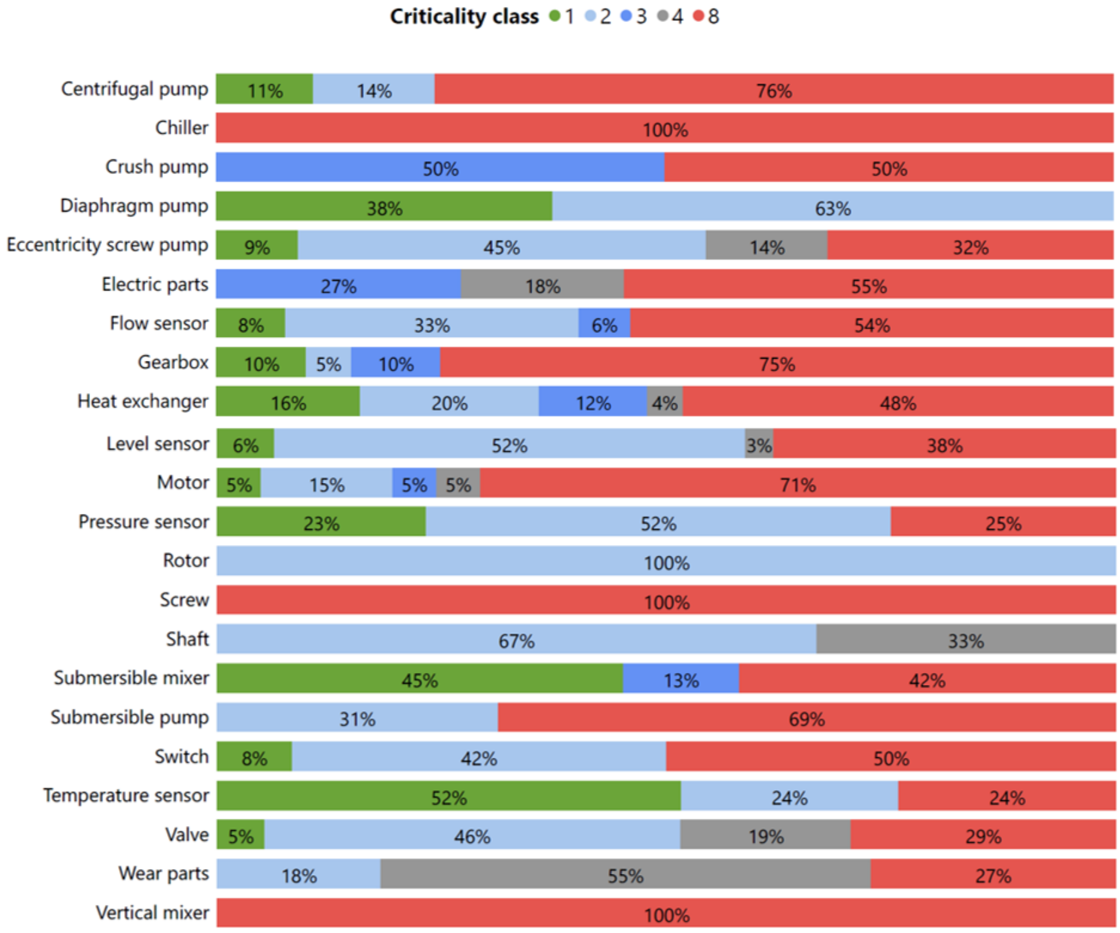


Figure 19. *Combined criticality classification by item type.*

In order to understand which attributes have contributed to the criticality classification of different item types, a closer examination of the decision alternative division in each decision node is needed (see Table 7). Appendix C presents the decision alternative division by item type in functional criticality decision node. These results provide an overview of the process criticality of different spare parts in the examined biogas plants, that is, the urgency for corrective actions in case of failure. For instance, sensor failure or shortage would not cause immediate shutdown, but rather malfunctions. For example, 52 percent of the analysed pressure sensors would cause malfunctions. In most cases, sensor failure or shortage can be tolerated for some time before corrective actions are needed. In many cases screw failure, on the other hand, would cause such consequences to production that immediate corrective actions are needed.

The decision alternative division by item type in alternative production decision node can be found in Appendix D. These results provide an overview of spare parts for which consequences caused by failure can be avoided or tolerated for a limited time by applying temporary arrangements. For some functionally critical items, a few possible practices to control the failure in terms of alternative production were found. For instance, some functionally critical pumps have been duplicated. Thus, if one pump fails, the other one can be put into operation immediately, and the production downtime can be avoided. However, there are some differences between the examined biogas plants as the pumps in biogas plant B have not been duplicated and, according to the plant manager, would not be possible due to lack of space in the production facility. Another alternative production practice found during the criticality analysis is the so-called cannibalism where a broken part is replaced with another one removed from the process. As there are several identical instruments such as temperature or pressure sensors in the plant, cannibalism is, in many cases, applicable alternative for these items. A biogas flow meter used to define biogas sales volumes, on the other hand, differs from other flow meters in the plant, and hence cannibalism was not found possible for this item. This indicates that spare parts criticality should be assessed in its process context rather than in a vacuum. As a final example of an alternative production method, mention should be made of automation system bypassing in cases where manual operation is possible.

The decision alternative division by item type in availability decision node can be found in Appendix E. These results provide an overview of spare parts and their expected lead times in relation to the time to tolerate a stockout situation in case of failure. Lead time was found to be affected by many factors such as item specificity as well as the number, quality, and location of the potential suppliers. Regarding make-to-order parts or parts that are fabricated according to specific drawings, the number of potential suppliers was estimated to be low in addition to which they are located outside the country of biogas production. These parts are characterised with long lead times, and therefore decision alternative 2 was selected for these items in the Availability node. In the examined cases, the majority of vertical mixers, screws, chillers, and centrifugal pumps are characterised with availability of this kind. Commercial parts such as wear parts and valves, on the other hand, were found to be available from several sources within the country of biogas production with acceptable lead times, and therefore decision alternative 1 is more dominant for these item types.

The decision alternative division by item type in value decision node can be found in Appendix F. These results provide an overview of the price level for different item types. As described in Subsection 4.4.3, the purpose of the value decision node is to pinpoint spare parts for which solutions other than stock holding should be considered. However, it should be emphasised that importance for this decision node and its results are recommended to be given only in cases where the lead time estimate, i.e. availability, is at an acceptable level. By looking at the results of decision alternative division for value, it is possible to see which item types need to be given more consideration when making stocking decisions. However, though the motive to stock spare parts on site commonly originates from the need to ensure continuity of safe and reliable production, one has to consider other goals within the organization as well such as controlling and optimising costs in the maintenance budget.

Finally, due to insufficient data, decision alternative division for demand pattern decision node cannot be presented. This is because very few decision paths of the analysed items proceeded into the demand pattern decision node. The reasons for this were discussed in more detail earlier in this chapter.

The constructed criticality classification method demonstrated some weaknesses that should be mentioned. First of all, the greatest disadvantage of the method is that it requires expert judgement which, in turn, exposes to a high level of subjectivity. Furthermore, as there are no systematically collected data of spare parts in the case company, the analysis had to be performed manually which turned out to be rather laborious. Regardless of the above-mentioned weaknesses, explicit advantages exist. One major advantage of the method is that it allows assessing spare parts criticality in a transparent and systematic manner by considering several criteria affecting criticality. The spare parts classification also provides a means to support maintenance and plant managers in their decision-making. For instance, classification can serve as a justified basis for spare parts management policies such as stocking decisions.

5.2 Recommendations for spare parts management

This Section presents the recommendations for spare parts management in the case company. Based on the findings of the interview analysis as well as spare parts criticality analysis, several actions regarding spare parts management in the case company are recommended. First of all, based on the criticality classes derived from the criticality analysis, spare parts are recommended to be managed according to the spare parts management matrix presented in Table 9. The recommended spare parts management policies and stocking strategies serve as general guidelines for managing spare parts with varying characteristics and must be adapted case-by-case according to the operating environment of the case company. Recommended actions regarding spare parts management in the case company are compiled in Table 11 at the end of this Section.

However, the recommendations and the rationale behind them are discussed in more detail next.

Spare parts to stock on site. According to the spare parts management matrix presented in Table 9, stocking on site is recommended for items with criticality class 4, 5, or 8. Figure 20 presents the stock status of items for which stocking on site is recommended as well as items for which solutions other than stock holding is recommended. As can be seen from the pie charts below, not enough “critical” spare parts are being stocked on site under the proposed method during the implementation of the criticality analysis method.

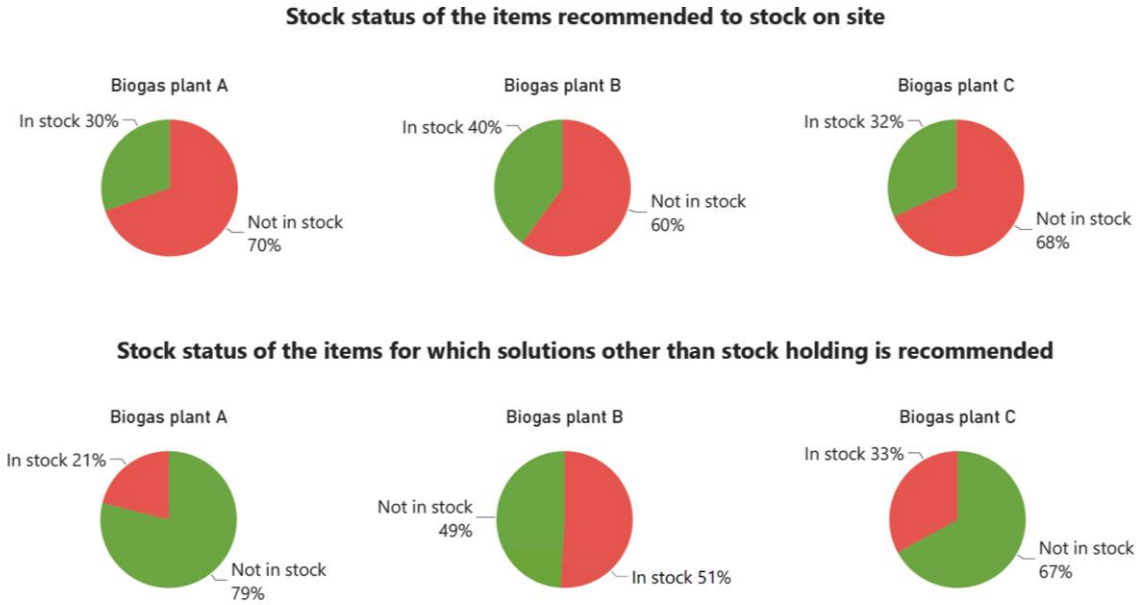


Figure 20. *Current stock status of items compared to recommendations.*

It was found that regarding items recommended to stock on site, current service levels are higher for low value items; 55 % of the items held that are also recommended to stock on site are low or mediocre value items while 18 % of them are high value items. Consequently, it is recommended that stocking decisions are made according to the proposed spare parts management matrix, yet special consideration must be made with high value items. This means that production losses caused by stockouts must be evaluated with relation to the value of the item in question: is the stockout situation accepted or is safety stocking justified despite of high inventory holding costs? The proposed spare parts management matrix recommends stocking on site for all the spare parts for which lead time is expected to be longer than the time to tolerate a stockout situation in a case of failure. From another perspective, it is also recommended that inventories are reduced where appropriate. By looking at Figure 20, it can be concluded that of the examined cases biogas plant B is, in relative terms, holding the most items for which other than stocking on site is recommended.

Co-operative stock pools or central warehousing. Several challenges regarding spare parts management and current ways of working were discovered when interviewing plant managers. First of all, according to plant managers interviewed, there is no clear strategy nor policies regarding inventory management in the case company. Furthermore, the company has earlier acquired several biogas plants which still operate their inventories for the most part in the same way today as before acquisitions. Therefore, it appears that the company may not take full advantage of the wider network of its biogas plants and the benefits it enables. In relation to this, co-operative stock pools or central warehousing are recommended for process critical items with acceptable lead times that are characterised with high value and very low demand. The case company has several rather closely located biogas plants with similar technical configurations. With this premise, the case company has good chances to utilise one plant's premises which in turn would serve the needs of other members of the plant network. Plant network co-operative stock pooling is recommended for spare parts that fall into criticality class 7, but only few such items were discovered in the criticality analysis. Therefore, class 8 items with remarkably high value and low and sporadic demand could be considered for stock pooling as well. For example, if stocking on site is recommended, as for class 8 items, but is not considered as a viable option due to high value and low demand, plant network co-operative stock pool may justify stocking by consolidating low and sporadic demands of several plants into steadier and uniform requirements, thus reducing demand variability across the plant network. The benefit in co-operative stock pooling for the case company is that it is possible without investing in new premises. Items classified as suitable for co-operative stock pools could be suitable for central warehousing as well. However, it is beyond the scope of this thesis to compare the feasibility of these two options.

Warehouse management system. Another challenge discovered regarding spare parts management in the case company is that there is no warehouse management system employed at the moment. Therefore, inventory management rely upon the memory of individual employees as well as various notebooks and spreadsheet files. According to some employees of the company, the greatest challenge of such a practice is to remember what parts are stocked, how many, and where. This approach in inventory management is prone to flaws in information sharing between plant staff as well as the maintenance manager. Thus, warehouse management system is recommended to be deployed in the case company as it can provide solutions to these challenges.

For the co-operative stock pool discussed above to be operative, up-to-date inventory information needs to be available for all users in real-time. For this purpose, warehouse management systems provide viable solutions. For instance, users could check the location, technical specifications, and stock balance of spare parts using the WMS. The author of this thesis has compiled the technical specifications of various process equipment into the maintenance management system of the case company. This provides a good starting point for the WMS users, such as plant managers, to check whether the spare parts within the stock pool are compatible with their equipment.

Other advantages can also be achieved by introducing WMS, for example, the case company may align the WMS with the spare parts criticality classes. For instance, as items with criticality class 2 are characterised with low value, simple and cost-efficient replenishment practices become necessary. Thus, it is recommended that orders for class 2 items could be automatically generated by WMS, based on predetermined reorder points.

It is also recommended that synergies between maintenance and warehouse management systems are utilised. For example, availability of spare parts needed to complete a work order could be viewed through a maintenance management system. Thus, one can check whether it is safe to schedule the work order. Furthermore, if parts needed to complete a work order are not available, a purchase order could be created directly from the work order within the maintenance management system.

Standardisation of parts. According to the proposed spare parts management matrix, standardisation is recommended for items with criticality class 7 or 8. Spare part compatibility can, at times, be poor between biogas plants with different plant suppliers. Therefore, where possible, spare parts are recommended to be standardised across the biogas plants in case plant network co-operative stock pools are used. Regarding class 8 items, standardisation is recommended due to poor availability, and hence the goal is to reduce lead times by using parts that are more easily available from several sources. However, standardisation may require trade-offs regarding functional quality, and therefore special consideration must be used regarding process critical spare parts.

Co-operation and contracts with vendors. For items that fall into criticality class 8, lead times are expected to be longer than the time to tolerate a stockout situation in the event of a malfunction. Usually this is due to high specificity, which is why these items may be ordered on make-to-order basis or they are fabricated according to specific drawings. Moreover, these items are generally characterised with high value and low demand due to which stocking them on site can be found unattractive, regardless of item functional criticality. Stocking these items on site can also be challenging, for example, due to their large size. With this premise suppliers are not keen to hold such items in their premises for the specific needs of a single customer. In these conditions, it is recommended to look for a supplier that could fabricate this type of parts for the case company with shorter lead times when required. As the case company is a leading supplier of biogas and the biggest processor of biodegradable waste fractions in the Nordic countries, it could take advantage of its negotiation power over smaller machine shops and to pursue a supply agreement with predetermined lead times. These kinds of agreements may be possible especially if the machine shop receives a large share of its orders from the case company.

As stated above, high value makes stocking on site unattractive, regardless of the functional criticality of an item. When it comes to more standard parts that are widely used in different industries and thus have a greater number of potential suppliers, it is recommended to push stocks towards suppliers. The rationale here is that with parts that are used by several prospective customers, suppliers are more willing to hold stocks and offer fast deliveries to gain clients. The case company of this research could benefit from this and avoid holding safety stocks on site even regarding functionally critical parts. This strategy is recommended to be considered for parts with criticality class 6 and could be viable especially for parts with obsolescence risks or other requirements such as yearly checks that require special qualifications. For instance, this strategy could be considered for frequency converters. To ensure reliable service, it is recommended to pursue time-guaranteed delivery contracts with accredited service companies.

Clarify missing information from suppliers. Looking at Figure 16, it can be noted that a small proportion of the analysed items in biogas plant C are unclassified. This is due to inadequate availability data, which is recommended to be clarified. This information can, for example, be obtained from vendors by requesting a proposal.

Implement the criticality analysis method for other biogas plants. The constructed criticality analysis method was implemented for three biogas plants of the case company. Even though the number of the examined cases was considered as sufficient to test its applicability, the spare parts criticality analysis is recommended to be conducted for other biogas plants of the case company as well.

Table 11. *Summary of the spare parts management recommendations.*

Aspect	Recommended action
Spare parts to stock on site	- Stock class 4, 5, or 8 items on site. However, special consideration must be made regarding high value items. - Reduce inventories where appropriate
Co-operative stock pools or central warehouse	- Consider co-operative stock pools or central warehousing for class 7 items - Due to small number of identified class 7 items, consider class 8 items with high value and low and sporadic demand as well
Warehouse management system (WMS)	- Deploy WMS - Apply WMS for co-operative stock pooling - Align WMS with the spare parts criticality classes - Generate automatic orders for applicable parts (recommended for class 2 items) via WMS, based on predetermined reorder points - Utilise synergies between maintenance management system and WMS
Standardisation of parts	- Across the biogas plants, standardise parts that are stocked in stock pools or centrally - Due to poor availability, standardise class 8 items to shorten lead times
Co-operation and contracts with vendors	- Regarding class 8 items with poor availability and remarkably high value or other barriers for stock holding, look for a supplier that could fabricate these types of parts when required. In this case, negotiation power over smaller machine shops could be used to pursue a supply agreement with predetermined lead times. - With functionally critical yet more standard parts that are characterised with high value (e.g. class 6 items), consider time-guaranteed delivery contracts with accredited service companies
Clarifying missing information from suppliers	- Obtain the missing information of the unclassified items from vendors
Implementing the criticality analysis method for other biogas plants	- Conduct the spare parts criticality analysis for other biogas plants as well

5.3 Limitations

This thesis focuses on a single case study and the results are company-specific which poses some limitations to the theoretical and practical implications. First, the developed classification method considers a specific operator in the supply chain, the production plant equipment owner. Secondly, criticality can be perceived differently under varying conditions, and the classification method considers criteria that are relevant for the case company specifically. Thus, the operating environment as well as rationale behind the ruling criteria in the classification method should be understood before applying the method to another context.

The reliability of the developed criticality classification method as well as the findings of the analysis can be questioned. The developed method is based on expert knowledge and judgement which exposes to a high level of subjectivity. Moreover, the criticality analysis review excludes item types and process steps for which the number of items analysed were considered too small to reliably present the results. The access to data and the rigorous schedule set for the thesis were some of the apparent constraints of this research. With more time available, the method could have been implemented for other biogas plants of the case company as well, which would have increased the reliability of the study. Therefore, the criticality analysis results should be viewed critically before making any assumptions.

6. CONCLUSIONS

6.1 Answering to research questions

In this section, the practical realisation of the research work is critically assessed through research questions. The objective of this thesis was to design a spare parts multi-criteria criticality classification method and to provide a blueprint for spare part stockkeeping. The method was designed successfully, and the construction of the method is illustrated in Figure 14. The main research question from which the research objectives originate concerns how to manage spare parts with varying characteristics in biogas plants. Answer to the main research question can be provided by going through the sub-questions that specify the main research question and the answers provided to them.

The first sub-question was: "*What are the criticality criteria to consider when managing spare parts?*". An answer to this question is provided through literature research and the interview analysis. The findings from literature conclude that criticality can be perceived differently under varying conditions and there can be many contributory factors affecting it. A vast number of criteria for evaluating criticality were found from literature, which are summarised in Table 3. However, little attention has been devoted to analysing in which context each criticality criterion proposed in literature is relevant (Bacchetti & Saccani 2012, p. 723), and the relevance is recommended to be assessed independently for the situation at hand (Fortuin & Martin 1999, p. 959). Thus, the most relevant criteria for the case company to consider when managing spare parts were established based on the interview analysis. As a result, a total of five criteria were composed: functional criticality, alternative production, availability, value, and demand pattern.

The second sub-question concerns how to classify spare parts based on the composed criteria above. An answer to this question is also provided through literature research and the interview analysis. In addition to discovering relevant criticality criteria, literature was reviewed to determine the latest methods used in the classification of spare parts in an industrial context. Findings from literature conclude that traditional classification schemes that are based on one parameter, such as ABC analysis, are not the most appropriate for spare parts management as they do not take into account the highly varied assortment of spare parts with special characteristics. With this premise, literature recommends multi-criteria perspective. Again, a vast number of spare parts classification schemes were found from literature, and the first iteration of the classification method was drafted based on the literature review and initial discussions with the case company.

The case company of the research strive for practical and realistic approaches for spare parts criticality classification which can be used as a management tool in the company. The method for spare parts criticality classification was provided through interview analysis in the form of a decision tree in Subsection 4.4.3. The above-mentioned five aspects of criticality are incorporated in the criticality classification method. By using the method, spare parts criticality class can be assessed in an easy and logical way by following the correct path in the decision tree. This thesis proposes eight criticality classes of which class 1 items are the least critical while class 8 items are the most critical. The constructed criticality classification method was evaluated in Section 4.6 according to nine criteria presented by Sink in 1985.

The third sub-question concerns the criticality classification in the examined cases. An answer to this question is provided through the criticality analysis. The constructed criticality classification method was implemented in three biogas plants of the case company, and Figure 16 presents the criticality classification results. Section 5.1 presents the criticality analysis key findings. In addition to the criticality classification of the total sample of analysed items, criticality classification by process step and item type are provided. These results provide a wide-ranging overview of the characteristics of different spare parts in the examined biogas plants.

Finally, the fourth sub-question concerns how to manage different spare part classes, i.e. where to stock them and what kind of stocking policies should be applied to them. Based on the criticality class derived from the criticality analysis, spare parts are recommended to be managed according to spare parts management matrix presented in Table 9, which serves as a general guideline for spare parts management in the case company. Section 5.2 clarifies the recommendations and the rationale behind them in more detail. The recommended policies and strategies are based on the findings of the literature review as well as the interview analysis.

6.2 Contribution of research work

The developed multi-criteria classification method was used to categorise the spare parts assortment into relevant categories in three biogas plants of the case company. The spare parts classification is considered as valuable information for both maintenance and plant managers. Decisions regarding stock keeping, for example, can now be based on objective information provided in this thesis. Published case studies also indicate that organizations can achieve great benefits by implementing simple, non-optimised classification and spare parts management methods. (Nagarur et al., 1994; Syntetos et al., 2009) The transparency of the decision tree -based classification scheme as well as the user-friendliness of the method were found as the major advantages of the approach. Although this thesis focuses on a single case study and the results are company-specific, this research can provide insights for other practitioners as well.

The contribution of the thesis focused not only on the development of the criticality classification method but also on the implementation in an industrial environment. The conducted criticality analysis promotes the case company's knowledge on the criticality of their production equipment. Also, the criticality classification figures presented in Section 5.1 provide a comprehensive overview of spare parts criticality classification in biogas plants, and thus they can provide meaningful insights for practitioners in similar industrial settings.

As covered earlier, there is a distinct gap between scientific research and practice in spare parts management. Various spare parts classification schemes can be found in literature but very few studies consider the actual implementation of practical multi-criteria classification methods. In that respect, this thesis can be seen as a contribution towards bridging the gap between spare parts management research and practice.

6.3 Recommendations for further research

During the research process, a few potential topics emerged that could be worth researching in the future. First, co-operative stock pools or central warehousing is recommended especially for process critical spare parts with acceptable lead times that are characterised with high value and very low demand. However, as far as the author is aware of, very little research on co-operative stock pools from the spare parts management perspective have been carried out. Therefore, conducting research on co-operative stock pooling could provide useful information to this end. For instance, a comparative feasibility study of stock pooling and central warehousing for critical spare parts would be an interesting topic of future research.

Another interesting topic for future research concerns more the case company of this thesis. As biogas plant spare parts are not managed using a warehouse management system at the moment, implementation of such a system is recommended to be studied next. For example, automated orders for low value items are recommended to be generated in the future by WMS to reduce administrative costs. However, as inventory control is beyond the scope of this thesis, research on economic reorder points would provide valuable knowledge that could be utilised when setting the inventory levels that trigger WMS-managed replenishment actions.

REFERENCES

Altay Guvenir, H., & Erel, E. (1998). Multicriteria inventory classification using a genetic algorithm. *European Journal of Operational Research, 105*(1), 29–37. doi:10.1016/S0377-2217(97)00039-8

Bacchetti, A., & Saccani, N. (2012). Spare parts classification and demand forecasting for stock control: Investigating the gap between research and practice. *Omega, 40*(6), 722–737. doi:10.1016/j.omega.2011.06.008

Bhat, K. S. (2008). *Materials management*. Mumbai, India: Himalaya Publising House.

Boone, C. A., Craighead, C. W., & Hanna, J. B. (2009). Critical challenges of inventory management in service parts supply: A Delphi study. *Operations Management Research, 1*(1), 31–39.

Botter, R., & Fortuin, L. (2000). Stocking strategy for service parts - a case study. *International Journal of Operations & Production Management. 20*(6), 656–674.

Bounou, O., El Barkany, A., & El Biyaali, A. (2017). Inventory models for spare parts management: a review. *International Journal of Engineering Research in Africa, 28*, 182–198. doi:10.4028/www.scientific.net/JERA.28.182

Boylan, J., & Syntetos, A. (2008). Forecasting for inventory management of service parts. In K. Kobbacy & D. Murthy (Eds), *Complex system maintenance handbook* (pp. 479–506). London, England: Springer. doi:10.1007/978-1-84800-011-7_20

Braglia, M., Grassi, A., & Montanari. R. (2004). Multi-attribute classification method for inventory management. *Journal of Quality In Maintenance Engineering, 10*(1), 55–65. doi:10.1108/13552510410526875

Cavalieri, S., Garetti, M., Macchi, M., & Pinto, R. (2008). A decision-making framework for managing maintenance spare part. *Production Planning & Control, 19*(4), 379-396. doi:10.1080/09537280802034471

Coffey, A., & Atkinson, P. (1996). *Making sense of qualitative data.* Thousand Oaks, CA: Sage.

deVaus, D. A. (2002). *Surveys in social research*. Abingdon, England: Routledge.

Dekker, R., Kleijn, M., & de Rooij, P. (1998). A spare parts stocking policy based on equipment criticality. *International Journal of Production Economics, 56*(1), 69–77. doi:10.1016/S0925-5273(97)00050-9

Dekker, R., Pinçe, Ç., Zuidwijk, R., & Jalil, M. (2013). On the use of installed base information for spare parts logistics: A review of ideas and industry practice. *International Journal of Production Economics, 143*(2), 536–545. doi:10.1016/j.ijpe.2011.11.025.

Deublein, D., & Steinhauser, A. (2011). *Biogas from waste and renewable resources: An introduction* (2nd rev. and exp. ed.). Weinheim, Germany: Wiley-VCH.

Dolfing, J. (1988). Acetogenesis. In Zehnder, AJ. B. (Ed.), *Biology of Anaerobic Microorganisms* (pp. 417–468). New York, NY: John Wiley & Sons

Flores, B. E., & Clay Whybark, D. (1986). Multiple Criteria ABC Analysis. *International journal of operations & production management, 6*(3), 38–46.

Fortuin, L., & Martin, H. (1999). Control of service parts. *International Journal of Operations & Production Management, 19*(9), 950-971. doi:10.1108/01443579910280287

Gill, J., & Johnson, P. (2002). *Research methods for managers* (3rd ed.). London, England: Sage.

Godoy, D. R., Pascual, R., & Knights, P. (2013). Critical spare parts ordering decisions using conditional reliability and stochastic lead time. *Reliability Engineering & System Safety, 119*, 199–206. doi:10.1016/j.ress.2013.05.026

Gopalakrishnan, P., & Benerji, A. K. (2004). *Maintenance and spare parts management* (4th ed.). India, New Delhi: Prentice-Hall.

Happonen, A. (2011). *Muuttuvaan kysyntään sopeutuva varastonohjausmalli (*Doctoral Thesis). Lappeenranta University of Technology, Lappeenranta.

Harvey M. Wagner. (2002). And Then There Were None. *Operations research, 50*(1), 217–226. doi:10.1287/opre.50.1.217.17777

Haverila, M., Uusi-Rauva, E., Kouri, I., & Miettinen, A. (2009). *TeollisuustAlous* (6th ed.). Tampere, Finland: Infacs johtamistekniikka.

Hellgrén, M. (1999). *Energia ja ympäristö* (3th ed.). Helsinki, Finland: Opetushallitus.

Huiskonen, J. (2001). Maintenance spare parts logistics: Special characteristics and strategic choices. *International Journal of Production Economics, 71*(1–3), 125–133. doi:10.1016/S0925-5273(00)00112-2

Hyvärinen, M., Nikander, P., Ruusuvuori, J., & Aho, A. (2017). *Tutkimushaastattelun käsikirja*. Tampere, Finland: Vastapaino.

Jaarsveld, W., & Dekker, R. (2010). *Integrating Reliability Centered Maintenance and Spare Parts Stock Control* (Report). Econometric Institute, Erasmus University Rotterdam.

Jacobs, R. F., Berry, W. L., Whybark, C. D., & Vollmann, T. E. (2018). *Manufacturing planning and control for supply chain management: The CPIM reference* (2nd ed.). New York, NY: McGraw-Hill.

Järviö, J. (2007). *Luotettavuuskeskeinen kunnossapito* (1st ed.). Kunnossapitoyhdistys ry.

Järviö, J., & Lehtiö, T. (2013). *Kunnossapito: tuotanto-omaisuuden hoitaminen* (5th ed.). Helsinki, Finland: KP-Media.

Kasanen, E., Lukka, K., & Siitonen, A. (1993). The constructive approach in management accounting research. *Journal of Management Accounting Research, 5,* 243–264.

Kennedy, W., Patterson, J. W., & Fredendall, L. D. (2002). An overview of recent literature on spare parts inventories. *International Journal of Production Economics, 76*(2), 201–215. doi:10.1016/S0925-5273(01)00174-8

Kymäläinen, M., & Pakarinen, O. (2015). *Biokaasuteknologia: raaka-aineet, prosessointi ja lopputuotteiden hyödyntäminen*. Hämeenlinna, Finland: Hämeen ammattikorkeakoulu.

Laine, E. (2018). *Biokaasulaitosten kunnossapitomallin kehittäminen ja yhtenäistäminen* (Master’s thesis, Turku University of Applied Sciences). Retrieved from http://urn.fi/URN:NBN:fi:amk-2018112117678

Latvala, M. (2009). *Biokaasun tuotanto suomalaisessa toimintaympäristössä: paras käytettävissä oleva tekniikka (BAT)*. Helsinki, Finland: Suomen ympäristökeskus.

Lehtomäki, A., Paavola, T., Luostarinen, S., & Rintala, J. (2007). *Biokaasusta energiaa maatalouteen* (Research reports in biological and environmental sciences). Jyväskylä Innovation Oy. Retrieved from https://jyx.jyu.fi/dspace/bitstream/handle/123456789/47694/978-951-39-3075-2.pdf?sequence

Lohiniva, E., Mäkinen, T., & Sipilä, K. (2001). Lietteiden käsittely: Uudet ja käytössä olevat tekniikat (Research notes No. 2081). Espoo, Finland: VTT Technical Research Centre of Finland Retrieved from http://www.vtt.fi/inf/pdf/tiedotteet/2001/T2081.pdf

Louit, D., Pascual, R., Banjevic, D., & Jardine, A. K. S. (2011). Optimization models for critical spare parts inventories – a reliability approach. *The Journal of the Operational Research Society, 62*(6), 992–1004. Retrieved from https://doi.org/10.1057/jors.2010.49

Lukka, K. (2000). The key issues of applying the constructive approach to field research. *Management Expertise for the New Millennium*, 113–128.

Lukka, K. (2003). The constructive research approach. Publications of the Turku School of Economics and Business Administration, 83–101

Luostarinen, S. (2015). Biokaasuprosessit ja laitostaseet. In M. Kymäläinen, & O. Pakarinen (Eds), *Biokaasuteknologia: raaka-aineet, prosessointi ja lopputuotteiden hyödyntäminen* (pp. 82–93). Hämeenlinna, Finland: Hämeen ammattikorkeakoulu.

Mackie, R. I. & Bryant, M. P. (1995). Anaerobic digestion of cattle waste at mesophilic and thermophilic temperatures. *Applied Microbiology and Biotechnology, 43*(2), 346–350. Retrieved from https://doi.org/10.1007/BF00172837

McCarthy, D. & Rich, N. (2015). *Lean TPM: A blueprint for change* (2nd ed.). Oxford, England: Elsevier Science & Technology.

Molenaers, A., Baets, H., Pintelon, L., & Waeyenbergh, G. (2012). Criticality classification of spare parts: A case study. International Journal of Production Economics, 140(2), 570–578. Retrieved from https://doi.org/10.1016/j.ijpe.2011.08.013

Mukhopadhyay, S.K., Pathak, K. & Guddu, K. (2003). Development of decision support system for stock control at area level in mines, *Technology management conference*. IEEE International. Retrieved from https://www.researchgate.net/publication/255653584_Development_of_Decision_Support_System_for_Stock_Control_at_Area_Level_in_Mines

Paakki, J., Huiskonen, J., & Pirttilä, T. (2011). Improving global spare parts distribution chain performance through part categorization: A case study. *International Journal of Production Economics, 133*(1), 164–171.

Partovi, F. Y. & Anandarajan, M. (2001). Classifying inventory using an artificial neural network approach. *Computers & Industrial Engineering, 41*(4), 389–404.

Quinlan, J. R. (1990). Decision trees and decision-making. *IEEE Transactions on Systems, Man, and Cybernetics, 20*(2), 339–346.

Regulation (EC) No 1069/2009 of the European Parliament and of the Council of 21 October 2009 laying down health rules as regards animal by-products and derived products not intended for human consumption and repealing Regulation (EC) No 1774/2002 (Animal by-products Regulation)

Robson, C. (2002). *Real world research* (2nd ed.). Oxford, England: Blackwell.

Roda, I., Macchi, M., Fumagalli L. & Viveros, P. (2014). A review of multi-criteria classification of spare parts. *Journal of Manufacturing Technology Management, 25*(4), 528–549.

Rolamo, N., Järvinen, M., Nissinen, P., & Sahlstedt, K. (2017). Risk Assessment of Nutrient Discharges from Biogas Production: Finland. Helsinki, Finland: Aalto University, School of Engineering

Saaty, T. L. (1980). *The analytic hierarchy process: Planning, priority setting, resource allocation*. New York, NY: McGraw-Hill.

Saaty, T. L. & Vargas, L. G. (2012). *Models, methods, concepts and applications of the analytic hierarchy Process*. New York, NY: Springer.

Sakki, J. (2014). *Tilaus-toimitusketjun hallinta: Digitalisoitumisen haasteet.* Vantaa, Finland: Jouni Sakki Oy.

Sarmah, S.P. & Moharana, U.C. (2015). Multi-criteria classification of spare parts inventories – a web based approach. *Journal of Quality in Maintenance Engineering, 21*(4), 456-477.

Saunders, M., Philip, L., & Thornhill, A. (2009). *Research methods for business students* (5th ed.). London, England: Pearson Education Limited.

Schultz, C. R. (2004). Spare parts inventory and cycle time reduction. *International Journal of Production Research, 42*(4), 759–776. doi:10.1080/00207540310001626210

Sink, S. D. (1985). *Productivity management: Planning, measurement and evaluation, control and improvement.* Hoboken, NJ: Wiley.

Smith, A. M. & Hinchcliffe, G. R. (2003). *RCM--Gateway to world class maintenance*. Oxford, England: Elsevier Science & Technology.

Stoll, J., Kopf, R., Schneider, J. & Lanza, G. (2015). Criticality analysis of spare parts management: A multi-criteria classification regarding a crossplant central warehouse strategy. *German Academic Society for Production Engineering, 9*(2), 225–235.

Suomala, P., Sievänen, M., & Paranko, J. (2002). The effects of customization on spare part business: A case study in the metal industry. *International Journal of Production Economics, 79(*1), 57–66. doi:10.1016/S0925-5273(00)00060-8

Syntetos, A. et al. (2009). Demand categorisation in a European spare parts logistics network. *International Journal of Operations & Production Management, 29*(3), 292–316. doi:10.1108/01443570910939005

Söderena, P., Suomalainen, M., Kajolinna, T., & Melin, K. (2019). *Biometaanin välivarastointi ja varastointi ajoneuvossa: Tulevaisuuden mahdollisuudet* (Report No. VTT-R-06978-18). VTT Technical Research Centre of Finland.

Teixeira, C., Lopes, I., & Figueiredo, M. (2018). Classification methodology for spare parts management combining maintenance and logistics perspectives. *Journal of Management Analytics* *5*(2), 116–135. doi:10.1080/23270012.2018.1436989

Topkis, D. M. (1968). Optimal ordering and rationing policies in a nonstationary dynamic inventory model with n demand classes. *Management Science, 15*(3), 160–176. Retrieved from https://doi.org/10.1287/mnsc.15.3.160

Tuomi J., & Sarajärvi A. (2018). *Laadullinen tutkimus ja sisällönanalyysi*. Helsinki, Finland: Tammi.

Van Kampen, T. J., Akkerman, R., Van Donk, D. P. (2012). SKU Classifiction: A literature review and conceptual framework. *International Journal of Operations & Production Management, 32*(7), 850–876. doi:10.1108/01443571211250112

Van Jaarsveld W, Dekker R. (2011). Spare parts stock control for redundant systems using reliability centered maintenance data. *Reliability Engineering and System Safety, 96*(11), 1576–86.

Veinott, A. F., Jr. (1965). Optimal policy in a dynamic, single product, nonstationary inventory model with several demand classes. *Operations Research, 13*, 761–778.

Vertes, A. A. (2009). *Biomass to biofuels: Strategies for global industries*. Hoboken, NJ: Wiley.

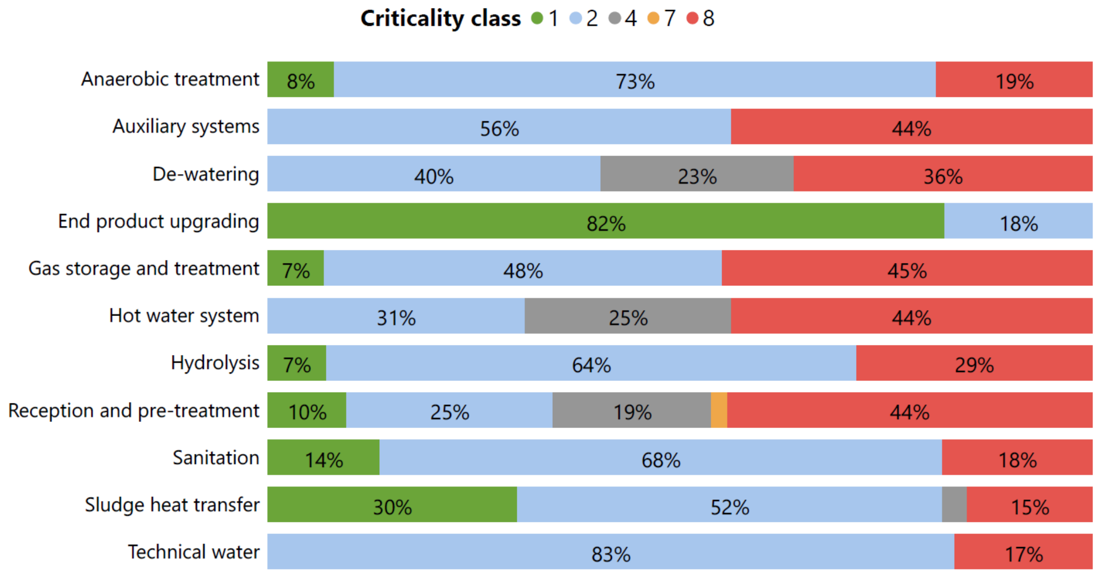
Wellinger, A. (1999). *Process design of agricultural digesters*. Ettenhausen, Switzerland: Nova Energie GmbH.

Wellinger, A., Murphy, J., Baxter, D., & Braun, R. (2013). *The biogas handbook: Science, Production and Applications* (vol. 52). Cambridge, England: Elsevier Science & Technology.

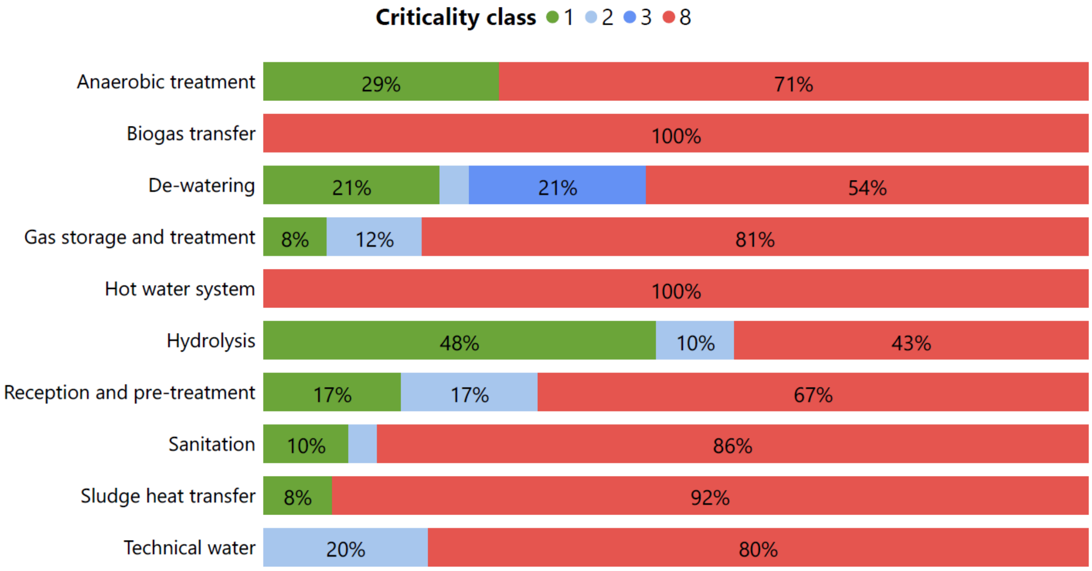
Yin, R.K. (2003). Case study research: Design and method (3rd ed.). London, England: Sage.

APPENDIX A: SPARE PARTS CRITICALITY CLASSIFICATION BY PROCESS STEP IN THE EXAMINED BIOGAS PLANTS

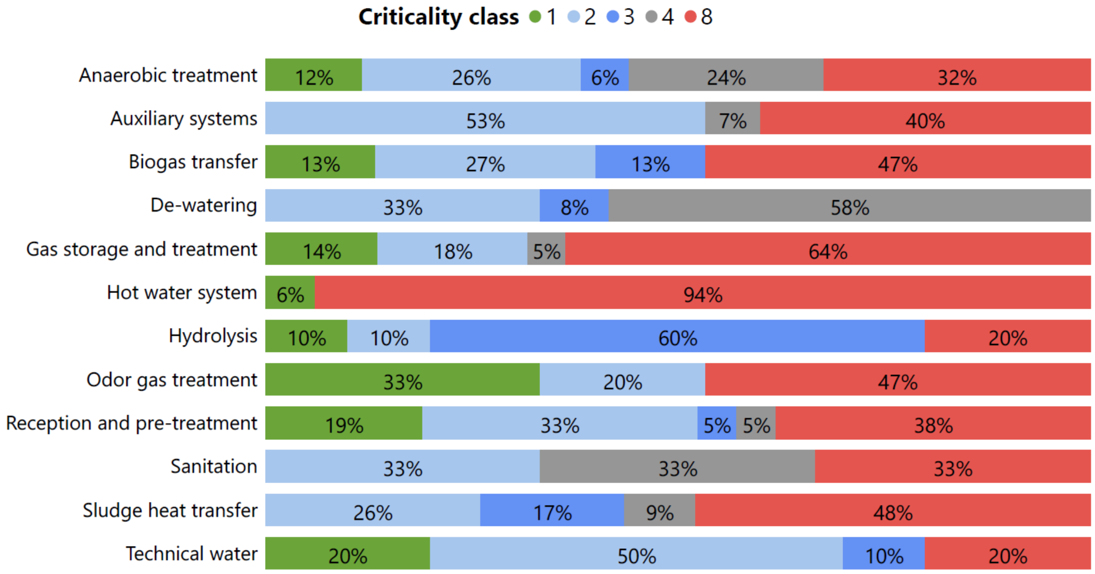
Biogas plant A



Biogas plant B

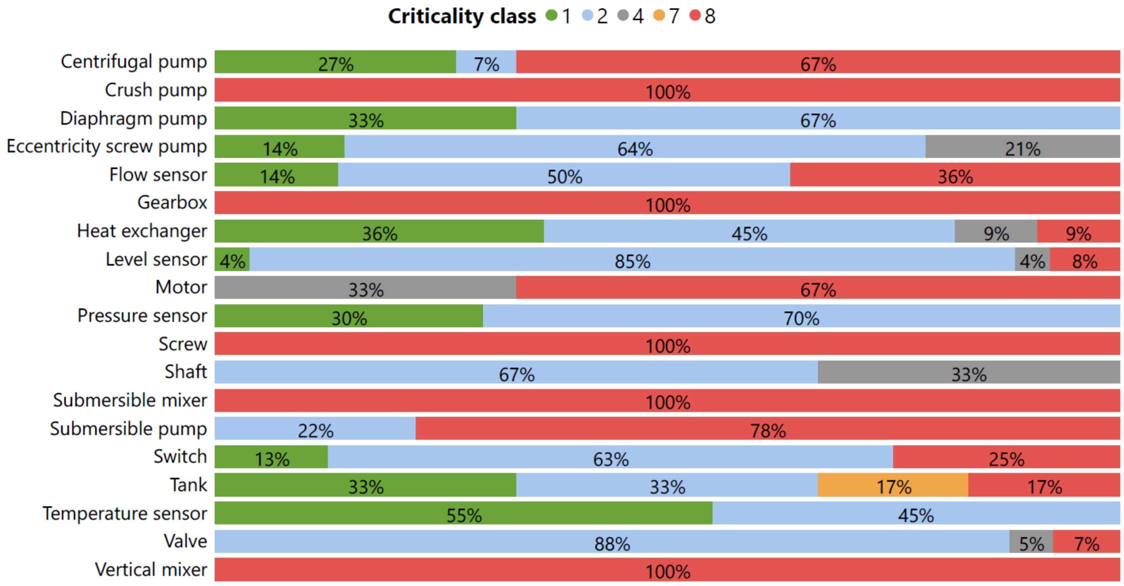


Biogas plant C

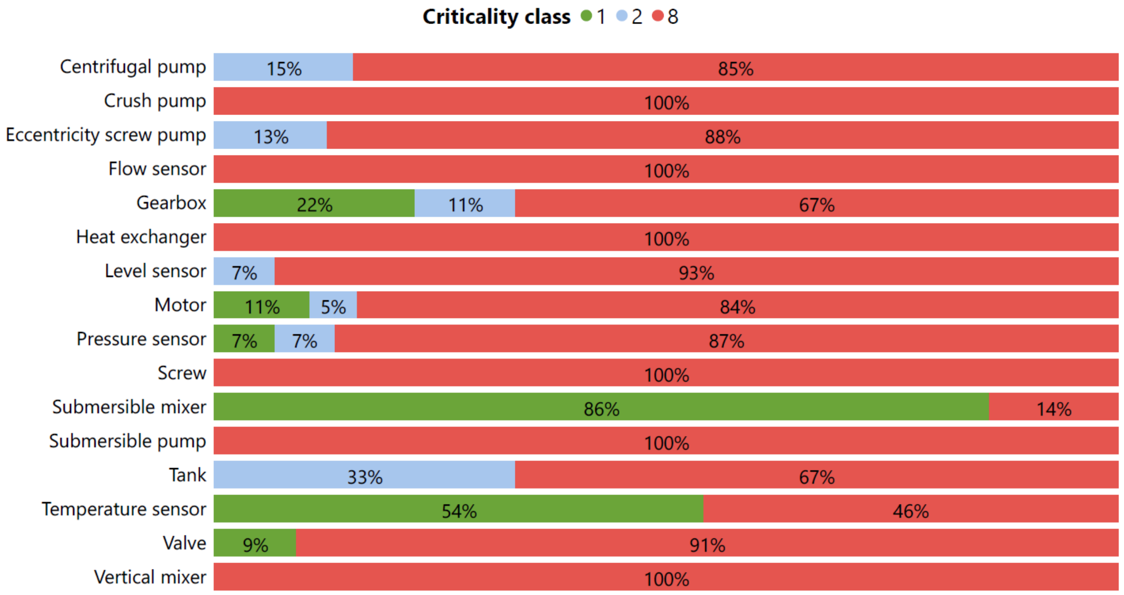


APPENDIX B: SPARE PARTS CRITICALITY CLASSIFICATION BY ITEM TYPE IN THE EXAMINED BIOGAS PLANTS

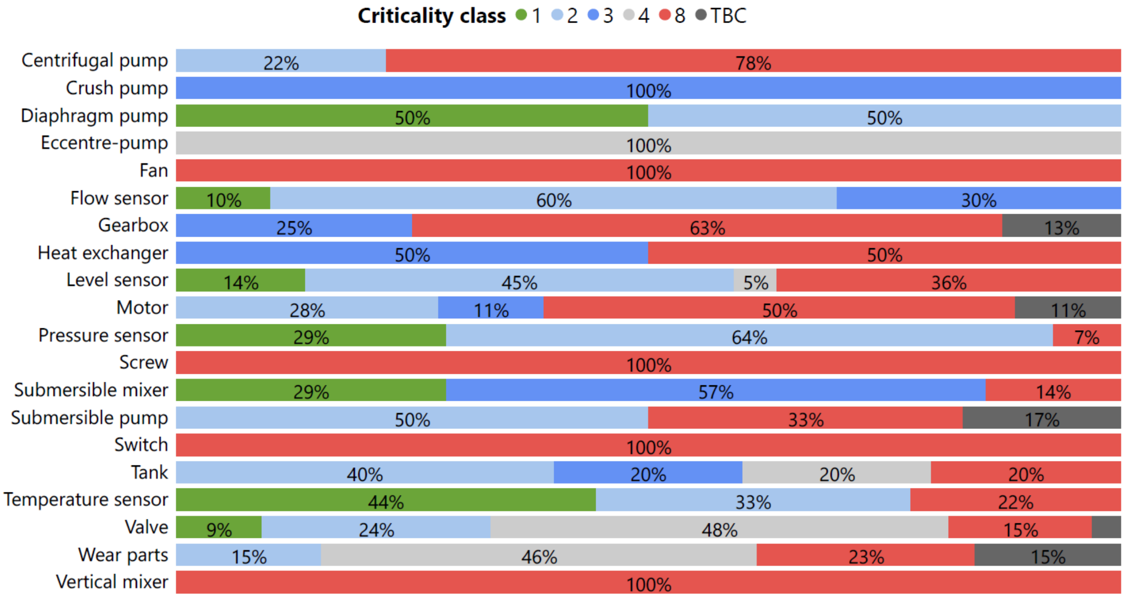
Biogas plant A



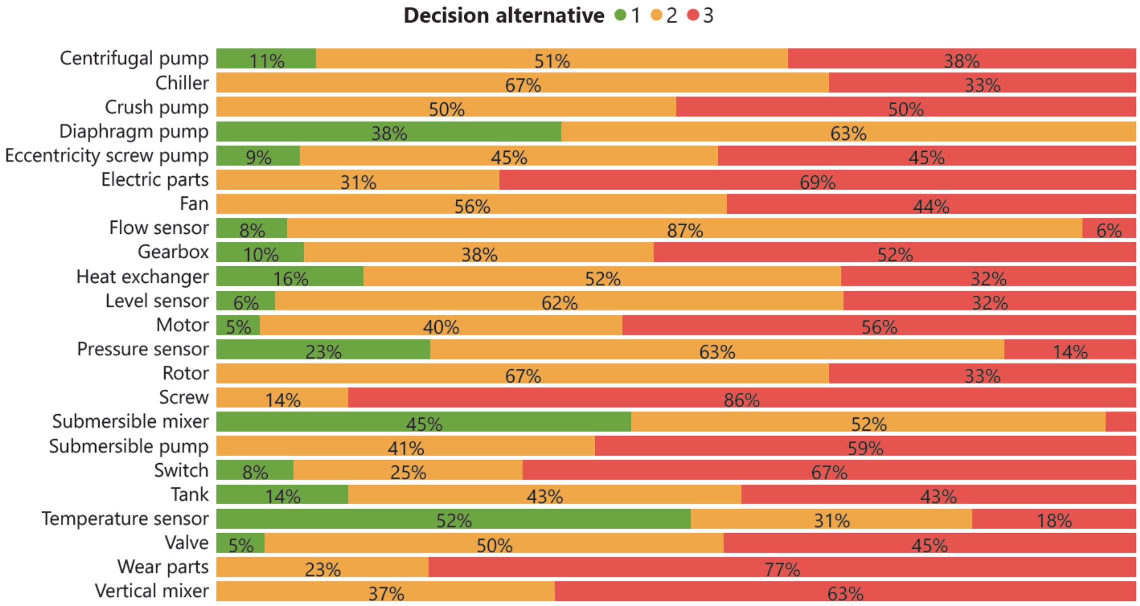
Biogas plant B



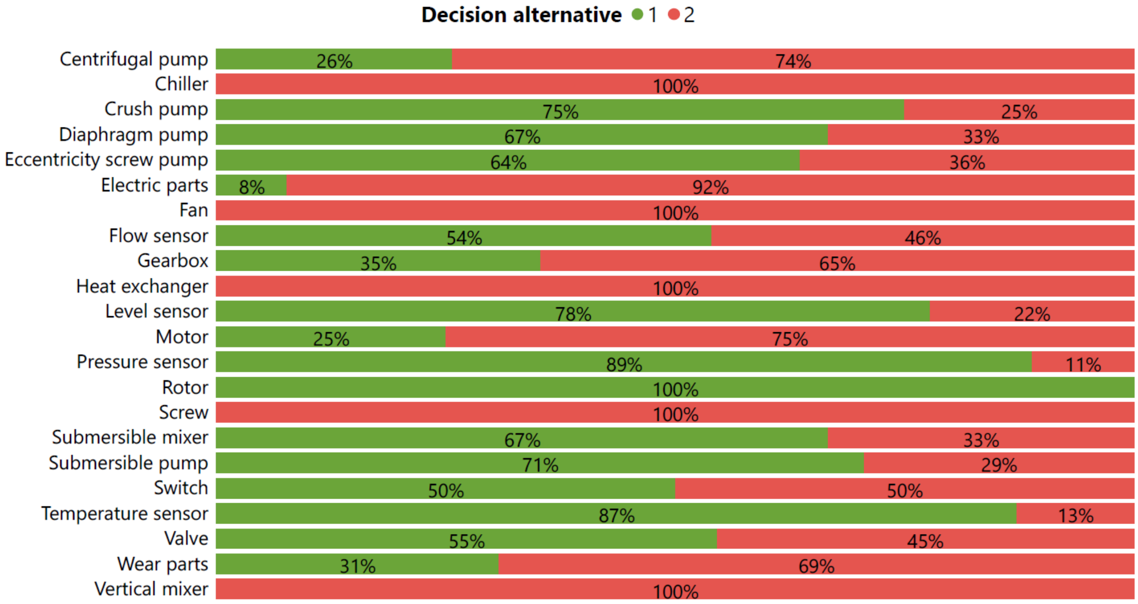
Biogas plant C



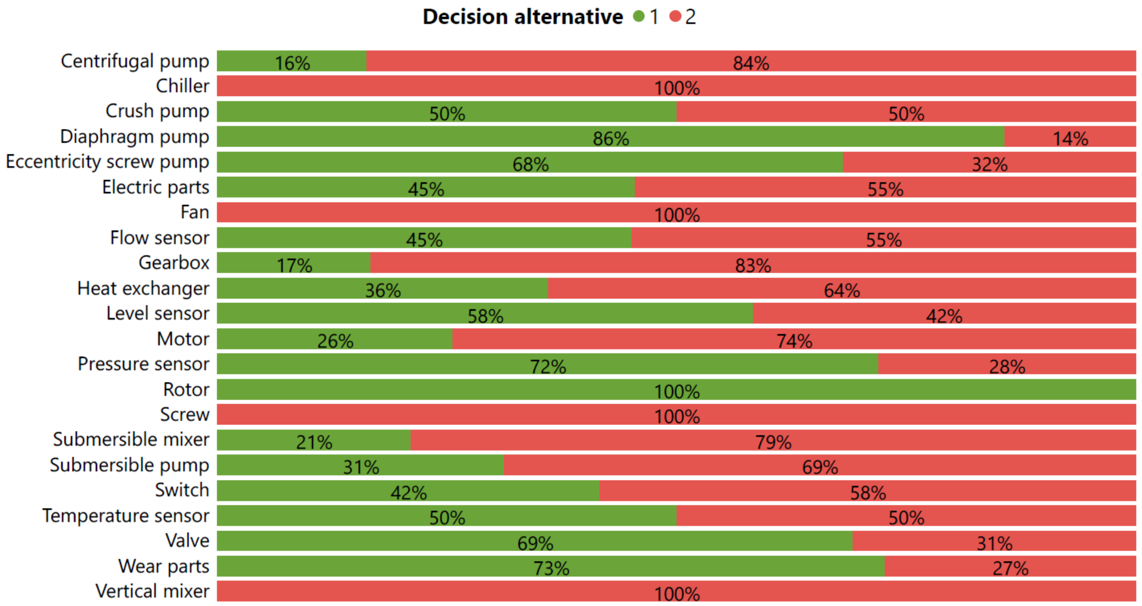
APPENDIX C: DECISION ALTERNATIVE DIVISION BY ITEM TYPE IN FUNCTIONAL CRITICALITY DECISION NODE



APPENDIX D: DECISION ALTERNATIVE DIVISION BY ITEM TYPE IN ALTERNATIVE PRODUCTION DECISION NODE



APPENDIX E: DECISION ALTERNATIVE DIVISION BY ITEM TYPE IN AVAILABILITY DECISION NODE



APPENDIX F: DECISION ALTERNATIVDE DECISION BY ITEM TYPE IN VALUE DECISION NODE