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OPTIMAL MAINTENANCE PROGRAM OF A WASTE-TO-ENERGY PLANT

Case Study: wasteWOIMA®

School of Technology and Innovations

Master´s Thesis in Industrial Systems Analytics

Vaasa 2022

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Title of the Thesis : Optimal Maintenance Program of a Waste-to-Energy Plant Case Study: wasteWOIMA®
Degree : Master of Science in Technology
Programme : Industrial Systems Analytics (ISA)
Supervisor : Ahm Shamsuzzoha
Year : 2022 **Number of pages** : 92

ABSTRACT

Waste-to-energy (WtE) plant is a complex system which requires different maintenances to be reliable and available in its full functionalities. Maintenance has a crucial impact on the performance, availability and reliability of the WTE plant. The inadequacies of WTE plant lifetime maintenance may increase the production costs, and more it negatively affects the competitiveness, makes the downtime longer and the Mean-Time-Failure is bigger.

The thesis focuses on the maintenance of WtE plant and it reviews the existing literature about Waste-to-Energy maintenance program and then find the best combination that better suits a Waste-to-Energy plant. This thesis has into two parts: the first part identifies the critical factors that enable high availability of Waste-to-Energy plant and the second addresses the identification of the right criteria for spare part selection. Both parts are aimed at enhancing the availability of Waste-to-Energy plant.
A survey was sent to Waste-to-Energy professionals to collect data and compare that data to the findings in literature.

Key findings of the study revealed that human, economic, equipment and tools, management and environment factors have important impact of the effectiveness of the maintenance and the availability of the WtE plant, whatever the maintenance strategies from preventive to corrective maintenance through the condition maintenance. Quality, Lead time, Price and severity of spare part failure are keys criteria to consider while selecting spare part for WtE plant.

The main limitation is that, the sample was a bit small since only few responds to the survey. Limitation of the thesis is related to the amount of the data collected. The findings cannot be generalized as it is affected by the limitation. The survey encounters probably the lack of cooperation from respondents as the study was not directly requested and done from their companies.

Keywords: Maintenance Program, Corrective Maintenance, Optimization, Maintenance Strategy, Availability, maintenance spare part, Multi Criteria Decision Making

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ABBREVIATIONS

WtE	Waste-to-Energy
RDF	Refuse Derived Fuel
MSW	Municipal Solid Waste
O&M	Operations and Maintenance
OEM	Original Equipment Manufacturer
RCM	Reliability Centered Maintenance
CBM	Condition Based Maintenance
TPM	Total Productive Maintenance
OMETA	Operations, Maintenance, Engineering, Training, Administration
DEMATEL	Decision Making Trial and Evaluation Laboratory
ISO	International Organization for Standardization
CM	Corrective Maintenance
PM	Preventive Maintenance
TBM	Time Based Maintenance
CMMS	Computerized Maintenance Management System
MM	Maintenance Management
MTTF	Mean Time-To-Failure
OEE	Overall Equipment effectiveness
AHP	Analytic Hierarchy Process
MCDM	Multi Criteria Decision Making

ELECTRE	Elimination and et Choice Translating Reality
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
TOPSIS	Technique for Order Reference by Similarity to Ideal Solution
ISM	Interpretive Structural Modeling
ABC	Activity Based Costing

1. INTRODUCTION

1.1 Background

In the last decades, the rapid growth of municipal solid waste has endangers the human health and environment, and the management of the huge amount of wastes is a challenge our generation and future generation face (World Energy Council, 2016) . The only viable way to minimize large amount of material waste is by recycling or reusing them (European Union, 2008).

All the materials cannot be recycled, and energy recovery method is s suitable method to treat undesired remaining from the recycling (Solheimslid, Harneshaug, & Lümmen, 2015). The energy recovery method helps in treating the non-reusable and non-recyclable waste as well as converting the energy into electricity and heat. Diverse methods or processes can be used to convert solid waste into energy. The common are biochemical conversion (composting, vermicomposting, anaerobic digestion / biomethanation), thermal conversion, and chemical conversions (Kalyani & Pandey, 2014; Singh, Tyagi, Allen, Ibrahim, & Kothari, 2011). The thermal conversion method includes incineration (combustion), gasification, pyrolysis, and refuse derived fuel (RDF) (Kalyani & Pandey, 2014). Incineration is the most widely used technology for MSW treatment (Giro-Paloma et al., 2020) and WtE incineration in recent years become viable for municipal waste disposal due to its large development (Y & Khandelwal, 2017). Waste-to-energy inclinators one of the important technologies used for MSW (Ali et al., 2021). For instance, in china, the amount of incinerated Municipal Solid Waste (MSW) has been increased by 5 compared to the past (China NBS, 2019).

Incineration is a waste treatment technique of burning organic waste and other components into heat and the resulted heat from the process, is converted into steam or electricity.

In Europe, waste incineration is often used due to its speed of process, significant amount of waste destruction and its energy production potential (Setyan, Patrick, & Wang, 2017). In Sweden, Japan and Denmark, half or more than 70% of municipal waste (MSW) are treated through incineration. Incineration allows the waste reduction in volume (90%) and mass (70%), it helps to eliminate the environmental impact of landfilling and it helps to mitigate the global warming (Saikia et al., 2007).

There are three different incineration technologies: fluidized bed, moving grate and rotary-kiln. Moving grate is the most widely used technology. The maintenance of the equipment or item is essential for the smooth running of all the items and equipment in a power plant, without any component failures, to improve the overall efficiency, availability, reliability,

Waste-to-energy (WtE) plant is a complex system which requires different maintenances in order to be reliable and available in its full functionalities. Maintenance has a crucial impact on the performance, availability and reliability of the WTE plant. Each firm or organization should have an effective O&M strategy, and not as “necessary devil”. There is a huge possibility to increase the availability and the profitability of the plant by improving the operations and maintenance strategy (B. de Jonge, P.A. Scarf, 2020).

1.2 Problem Statement

As the world grows, so does the amount of waste generate. That impact negatively the environment. Waste-to-Energy (WtE) is part of a solution, by transforming the waste (municipal solid waste etc) into energy. WtE evolves different complex systems and equipment. The availability of the plant is strongly associated with the parts reliability and the maintenance program and policy. Due to technological limitations and costs, it is difficult and impossible to design maintenance free systems. To keep all the plant system efficiency high and to operate as expected during its lifetime, it is important to maintain them. For a WtE plant, it is the top management concerns, to keep the asset availability and reliability, and reducing costs related to asset maintenance, repair. In response to these concerns, it is important to have a reliable maintenance program and policy.

As maintenance is also a combination of tools, methods, timing and spare part management, there is a need to develop and adequate and optimal maintenance program to ensure high reliability and availability of the plant.

Maintenance optimization is performed in a plant to ensure that tasks are done on the right equipment at the perfect time. It is a continuous and systematic approach.

1.3 Research objectives and questions

The study plan is explained in this section, data collection, research design, and data analysis. DEMATEL methodology is used. The research is based on qualitative and quantitative methodologies.

The first objectives are:

- to mitigate the risk of unavailability of plant due to maintenance tasks
- to mitigate the unavailability due equipment failures.
- to optimize the outage duration.

The first objectives are addressed by answering the question below:

1) What are the critical factors that enable high plant availability?

The second objectives are:

- to reduce the lead time
- to reduce spare part shortage and costs
- to optimize the spare part usage.

The other objective is addressed by answering the question below:

2) What are the best criteria when choosing maintenance critical spare parts?

3) How to optimize the WTE plant maintenance program?

Table 1: Research questions and data source

Objectives	**Question**	**Data source**
- to mitigate the risk of unavailability of plant due to maintenance tasks - to mitigate the unavailability due equipment failures - optimize the outage duration	What are the critical factors that enable high plant availability?	Literature review Survey
- Reduce the lead time - Reduce spare part shortage and costs - Optimize the spare part usage.	What are the best criteria when choosing maintenance critical spare parts?	Literature review Survey
All above	How to optimize the WTE plant maintenance program?	Literature review Survey

1.4 Structure of Master´s Thesis

The thesis topic, the background, scope, the problem statement research objective and questions are descried in the first chapter.

The second chapter focuses on the case company, their background, services and products.

The third and fourth chapters form a theoretical framework for the thesis. This part includes the literature review of the maintenance in general and especially the Waste-to-Energy plant maintenance. The fourth focuses on the types of maintenance, maintenance strategies as well as the availability critical factors. It also covers the maintenance spare part, the best criteria when choosing maintenance spare part.

The fifth chapter describes the methodology used in this master's thesis. It also describes the data collection approach, how the data analysis is performed using the sample and population. Research validity and reliability are done in this chapter.

Results of the survey is done in the sixth chapter as well as the answers to the thesis questions. The questions are then compared with the theoretical framework.

The seventh chapter provides the findings of the thesis. It presents how the survey results are linked or correlate with the literature.

The conclusion and the discussion are done in chapter eight. In this part, the topic is review and the results and recommendation are done. The limitation and further researches suggestion are made.

2. LITERATURE FRAMEWORK OF THE STUDY

In the global and changing business environment, organizations develop their capabilities and competences to add and create new values to the customers and to improve their competitiveness. This improve the operations of the equipment (Tsang, 2002). To be competitive, firm or organizations needs to mitigate the costs, risks to improve the quality of their products or services and find other sources of revenue. For instance, in manufacturing industries, organizations turn their business market model from products oriented to services oriented, by providing services as maintenance, repair services and spare parts to their installed based to generate additional revenues. Business models have been changed in the following organization; Siemens, ABB, CISCO. These organization started offering services besides their products (Gebauer, Paiola, Saccani, & Rapaccini, 2020; Baines, Bigdeli, Sousa, & Schroeder, 2020). Through the maintenance and leasing contracts, services allow more profits and generate stable flow payments because the service generate financial, marketing and strategic benefits (Martinez Hernandez et. 2017), even though the service offering created more challenges for products companies (Baines et al., 2020). The concept is called servitization or service transition, defined by Vandermewe and Rada who in their concept make bundles and packages containing services, good, support, knowledge and products (Vandermerwe & Rada, 1988).

Servitization is growing because in one hand, customers want to develop their core competencies by outsourcing other services. In other hand, customers want to improve their processing, production thus increase the availability of their assets by maintaining them in order to use the assets in their full capabilities (Baines et al., 2009). The term servitization is still understood and called differently, for instance in Scandinavian country, the concept is called Product-Service System (PSS) while in Germany it is Industry 4.0 an in United Kingdom, it focuses on innovation and circular economy so there is no single terminology about the concept. The service itself may be different in different levels.

For instance, manufacturers have provided services as maintenance and installation which have been a necessity rather than profitable business (Crespo Marquez & Gupta, 2006).

Maintenance is an important function of any asset life cycle. Maintenance is considered as “necessary evil” by many managers and they don’t recognize that an effective maintenance can improve the availability of the plant, thus the production (Patton, 1980). Maintenance started to be considered as a support function of a business with the introduction of preventive and conditional maintenance during 1950 and 1980.

The diversity and the nature of the items, equipment and assets has changed the way maintenance has been done previously since the items required different maintenance methods and techniques. The idea that fixed-term preventive maintenance is giving way to reliability centered- maintenance methods. Maintenance philosophy has changed from reactive to preventive and later to proactive approach. Maintenance management has become an important integrated part of business processes because it creates additional value for the organization. The process of coordinating activities to make profits is called asset management.

2.1 Definition of maintenance

Maintenance is defined as the combination of the technical and associated administrative tasks to maintain, to keep, to preserve an item or an equipment, or restore it to, a state in which it can perform its desired, expected function (ISO 14224, 2006). The definition emphasized at least four (4) mains keys aspects: maintenance (meaning the asset needs to be maintain), restoration (meaning to correct a default), expected function (meaning full capability of the asset) and optimal cost. The maintenance role is to ensure plant availability or asset availability.

The aim of maintenance is to ensure the high availability of the asset, items and equipment at low costs. Dhillon (2002) defined maintenance as the combination of activities undertaken to restore a component or machine to a state in which it can continue to perform its designated functions. The inadequacies of WTE plant lifetime maintenance may increase the production costs, and more it negatively affects the competitiveness of the organization, thus increases all kinds of risks; longer downtimes, recurrent failures. According to Moley (1990), about one third (1/3) of the total production costs is allocated to the maintenance labor and materials. Sometimes, depending on the industry, 70% of the total production costs are allocated to the maintenance (Bevilacqua and Braglia (2000). There are unnecessary costs in the maintenance. Wireman (2003) stated that 33% of the maintenance costs are spent unnecessarily or wasted. There is a need for improvement to execute and establish an optimal maintenance strategy. Of course, many Independent Service Providers (ISPs) and Original Equipment Manufacturers (OEMs) provide maintenance service but those services were second revenue stream. However, in the last decade, with the growing demand in the market, the attention to maintenance has increased due to the fact, there is an awareness that a proper maintenance keeps and improves the availability of the plant, the quality of the output (product), the cost effectiveness and the safety requirements (Al-Najjar and Alsyouf, 2013). Different resources are needed to perform a maintenance: the labor, the tools and methods, the timing and the spare part (logistic). A good maintenance program can enhance the performance of plant systems and the competitiveness of the company (Coetzee, 1999).

This has forced many organizations to adopt different maintenance strategy from the traditional one, reactive, to more efficient and effective maintenance strategies such as Total Productive Maintenance (TPM), Condition Based Maintenance (CBM) and Reliability Centered Maintenance (RCM) (Sharma et al., 2005). According to Meador (1995), There are five well-defined elements that forms the basis of an effective O&M (Operations and Maintenance): Operations, Maintenance, Engineering, Training, and Administration. It is called OMETA. This thesis covers only the maintenance part.

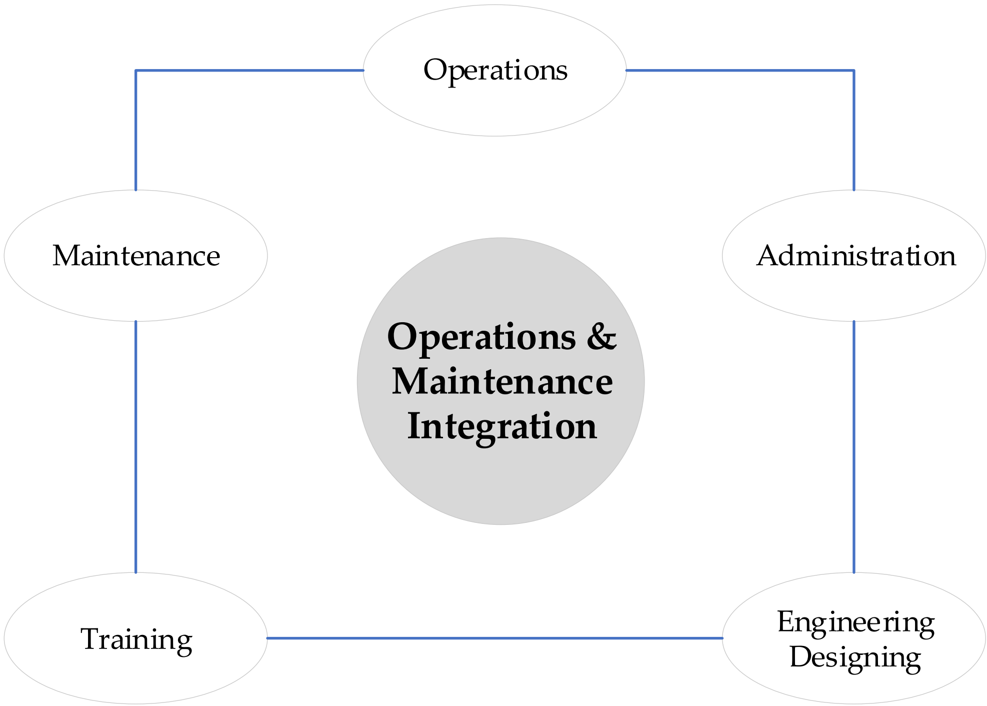

Figure 1: Operations & Maintenance elements (Meador, 1995)

To minimize the effect of all the failures and issues mentioned previously, there is need for an optimum maintenance program. The maintenance program can be optimized for maximum availability of the plant, for maximum productivity, to meet scheduled production target etc. In this thesis, the maintenance program for maximum availability of the plant was optimized.

The maintenance is a mix of management, technology, operations and business strategy.

Risk mitigation, breakdown minimization, availability and profits maximization at low costs are the main objectives of the maintenance.

The main objective of a maintenance is to reduce the risk of negative effect of breakdown and to increase the availability at low cost, also to increase performance and maximize the profits (Simeu-Abazi & Sassine, 2001). Marquez (2007) defined maintenance as the whole of the technical actions taken to keep or protect an asset so that it can fulfill its necessary functions during the desired life cycle. It is rephrased by Heizer and Render as all the activities and related procedures done on the equipment to get the desired output under a specific condition (2012).

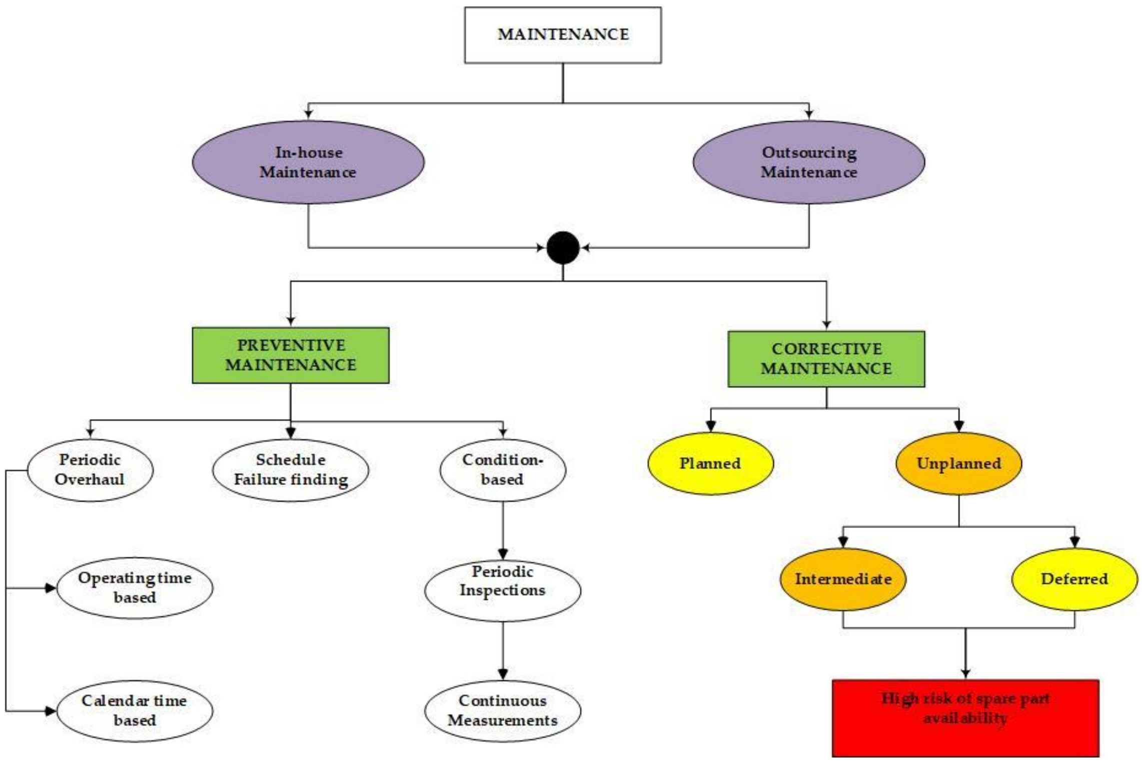

Figure 2:Main maintenance types

2.1.1 Types of maintenance

Corrective maintenance (CM) or failure-based maintenance and preventive maintenance (PM) are the two traditional maintenance groups.

2.1.1.1 Failure based Maintenance (corrective)

The Failure based maintenance, called corrective is a reactive type and it is executed when an item or asset fails, or a fault is detected, and actions needs to be taken to repair the asset. Basically, it is overhauling item and it is unplanned or planned. The unplanned corrective maintenance (CM) is immediate or deferred repairs (Moubray, 1997) and it is classified into five categories: salvage, rebuild, fail-repair, overhaul and service. the descriptions of the categories are below:

Salvage: When the non- repairable assets are disposed, and the salvaged materials of the non-repairable assets are used in the repair of the system.

Fail-repair: The faulted asset is restored to its operational state.

Rebuild: When an asset is restored to a standard state close to its original state in appearance, performance and lifetime expectation. Basically, it consists of disassembling the item, analyzing all the parts and repair or replace the faulted parts according to the original guidelines. The item at the end is assembled and tested with the original guidelines.

Overhaul: When restoring an asset to its total serviceable state using the maintenance serviceability standard with inspect and repair approach.

Servicing: It is the repairing and servicing of parts of the item, refilling or recharging are few examples.

The issues about corrective maintenance is that, it involves huge cost and reduces the availability of the plant, especially when a failure of an equipment or asset occurs. It involves many components replacement while the whole system is operating (Chitra, 2003). With CM the risk of spare parts availability shortage is high. There is always a need for CM in any equipment but the whole maintenance strategy cannot rely on it.

There are different sequential steps needed to perform a good corrective maintenance. Omdahl T. P. (1988) presented nine applicable steps: isolate, localize, adjust, repair, disassemble, align, interchange, reassemble and checkout while in McKenna, T. and Oliverson, R. (1997) approach there are seven steps: isolation, localization, disassembly, interchange, alignment, reassemble and checkout. The downtime needed for the corrective actions, depends on the failures, severity and the impact, the item has on the whole system. Corrective maintenance downtime is made up with active time, logistic time, administrative and delay time from fault detection, tools preparation time, calibration time, fault correction time, adjustment, preparation time, spare part lead time, and checkout time. Reducing any of those time, will reduce the downtime of the maintenance, thus it will have a positive impact on the maintenance. Experiences show that fault recognition, location and isolation, consume most of the time in corrective maintenance but with a good strategy, well-built maintenance procedures and fault indicators, those downtimes could be reduced.

2.1.1.2 Preventive Maintenance (PM)

Preventive Maintenance is the planned approach where different actions are performed to improve the equipment life by preventing impairment and excess depreciation. It is a vital key of the maintenance activities and tasks and it is a proactive type of maintenance and the actions are usually, adjustment, lubrification, cleaning, repairs, replacement (Wireman, 1990). Even though PM might sometimes be an unnecessary cost, the small shutdowns are sometimes counter-productive because any equipment needs a shutdown (Jayabalan and Chaudhuri, 1992).

There are different preventive maintenance actions: calibration, alignment, inspection, servicing, testing, installation and adjustment.

Preventive maintenance can also be grouped into three categories: condition-based maintenance CBM (monitoring), periodic overhauls maintenance and schedule failure finding. Condition-based requires periodic inspection and continuous measurement while periodic overhauls are based on calendar time (TBM) or up running time which is a user-based maintenance (UBM) and usually based on item manufacturer (Rausand & Vatn, 2008). The aim of the CBM is to detect the failed component, the roots of its failures. This type of maintenance strongly depends on the predefined or predetermined value got from measurement or monitoring. It initially limited to high risk environment like nuclear plant, aviation but nowadays commonly used in many fields (Veldman, Klingenberg, & Wortmann, 2011).

Despite the choice and the implementation of the best maintenance program, there are still serious issues like equipment failures, plant shutdown which leads to longer downtimes, low productivity and lower availability. Therefore, there is a need to develop the best maintenance management approach to reduce the risks related to the availability, and to shorter the downtimes.

Maintenance management (MM) has gained attention and many frameworks as well as model have been created to get the optimal benefits of it; Reliability Centered Maintenance (RCM), Total Productive Maintenance (TPM), Computerized Maintenance Management System (CMMS) and Condition Based Maintenance (CBM), (Crespo Marquez & Gupta, 2006) .

RCM can be used to minimize LCC (Life Cycle Cost) and maximize the availability of the operating expenditures (Rausand &Vatn, 2008). Maintenance is concerned by different researchers; Lin & Yang (2018), discovered that the optimal operating expenditures and business can be reached when Big Data and Internet of Things (IoT) (Russom, 2011) assist in maintenance analysis. By collecting and analyzing asset data and maintenance data, the risk of complete failure can be avoided because it is easier to know when to maintain or changed a component of the system (Peshkin & Hoerner, 2004).

Maintenance optimization is a continuous process. There is a sometimes comprise between the requirements and available resources to perform the tasks. That the reason, it is needs to be improved by lessons learnt, experiences. Having an effective maintenance program, makes the whole process easier, because it helps achieving the reliability and the availability of the plant by considering the costs, the safety and environment. It is about focuses the available resources for the right tasks, and areas at the right time for short and long term.

The performance of the maintenance activities will determine how reliable was and is the equipment. Without a good reliability, the plant or equipment, the effectiveness of the plant availability cannot be maximized.

2.2 Maintenance Outsourcing

Outsourcing is the transferring of company or organization's internal activities and operations to an external service provider (Handley, 2008)

One of the best strategies to improve competitiveness and reduce operating costs is the outsourcing, which requires a good decision-making tools in outsource selection.

Companies prefer to focus on their core competencies and processes, so they sometimes use subcontractors, consultants who are not directly employed by the companies, but who provide competencies, knowledge or manpower for the maintenance operations. The outsourcing of the maintenance is even becoming the popular way to deal with the maintenance and support the maintenance requirements.

In a survey, it has been proved that about 84% of the surveyed companies used maintenance contractors and see it useful (64 % of the companies) with high value added (Jensen, 2006).

Outsourcing and subcontracting are different. Subcontracting is on a job-by-job basis where works are assigned to an external supplier. Basically, an external individual or company come in the organization to perform tasks related to the business or project whereas outsourcing entails a long-term relationship, partnership between organization, company and supplier. High degree of risk is shared between the organization and the supplier (Gilley & Rasheed, 2000).

In general, outsourcing maintenance logistic is one of the best strategies to achieve flexibility and efficiency at the same time. Outsourcing focuses on two strategies of achieving competitive advantages: first is to concentrate the company's resources on their core competencies, what they do the best; and second, to outsource all the non-ore competences and activities to external supplier (Nordin, 2008). Internal competences are maximized by using efficiently and effectively the internal resources. It is a way to protect again competitors.

Even though, capacity, quality of asset is critical, many companies have been outsourcing the risky activities.

An undesirable outcome or the factors that leads to an undesirable outcome is called risk. Few concerns, while outsourcing are loss of management control and information security in outsourcing (Collins, 1995 & McLellan, 1994).

Organization should plan before moving toward the outsourcing. Before taking any steps towards outsourcing. All the stakeholders should be involved to identify the risk and all the cation and activities needed as well as the consequences that might occurred.

With a good plan, outsourcing helps to reduce costs even though it is ticket to success. The timing and the contest of the company or the local market and restriction need to be considered. The company's readiness can be access and validate the issues that could be outsourcing. Few questions that could be answered before taking about outsourcing:

- Does it make sense for the company? what is the feasibility of the outsourcing?
- Is the organization ready for it?
- What activities should be outsourced?

- Are the company' objectives achievable?
- What tactic is the best for the outsourcing?
- What are the alternatives?
- What will be the criteria to choose or validate the outsourcing companies?
- what is the cost
- What are the risks involved?

2.3 Plant Availability Critical Factors

Availability is the ability of an asset to perform its desired, required function, in certain time interval set by the manufacturer (IEC, 1990, CEN, 2010). Availability is always related to the reliability, the maintainability and the maintenance (IEC, 1990, CEN, 2010).

An asset is reliable when under a given condition, it performs its desired function. It is called reliability (IEC, 1990), while maintainability is when an asset can be maintained under a given conditions, in a certain time interval under the condition stated in advanced using stated resources and procedures (IEC, 1990).

Plant availability factors are factors that make the plant operations goes smoothly. Those factors are critical for the productivity of the plant. Different factors affect and impact the plant reliability and availability: human factors (training and competence), economic factors (maintenance costs), management factors (procedures and organizational control) and procurement (spare parts) factors.

2.3.1 Human factors

Over the past two to three decades, human factors in the maintenance environment have gained researchers attention. Human factors impact not only the maintenance but the functional operation of the asset until the maintenance. Human knowledge, personal characteristics, abilities and competences are the keys elements of the competence (KSAPs). Competence is defined as a group of the activities related to knowledge and attitudes, and skills that affect a job (Lucia & Lepsinger, 1999).

Some of the competence elements can be gained through a proper training or continuous learning. For instance, human is an essential actor in Total Productive Maintenance (TPM), especially, his ability to perform basic maintenance activities like lubrification and so on.

Human factor is a leading indicator that predict the quality of the maintenance activities or tasks, in compliance with the safety procedures and policies.

Competence management can identify employee and organizational knowledge and determine a good maintenance strategy to cover and provide the knowledge both need to make the maintenance effective and efficient. Maintenance staff motivation also essential because it is in fact impact the output, the result and the quality of the maintenance.

Motivation is the perseverance and the processes that show human’s intensity, direction toward a goal (Robbins *et al.* 2009).

Human error has been researched and in some industries like oil industries, about 40 % (Sklet, 2006) of the errors that occurred are human errors, while in petroleum the percentage is 40 (Rooney,2006). In aviation, about 70 to 80% of the accidents are caused by humans (Shappell, 2000).

The problem-solving behavior of the maintenance technician or engineer could have impact on the effectiveness of the maintenance. Most of the maintenance procedures and actions are done based on the standard document set by the maintenance organization but sometimes the failures are corrected case by case, meaning that it is case based reasoning, based on the maintenance technician experience, he can decide what actions to perform and to avoid long down time. Maintenance technicians behaviour has been investigated by Schaafstal, Schraagen, and van Berlo, (2000), in Dutch navy and found out that experienced technicians often see novice technicians as lacking the functional understanding of the whole maintenance procedures. They argued that the training giving for maintenance technicians or engineers should rather, greater focus on the troubleshooting strategies, and less on acquiring system knowledge. Teamwork and communication are also very important to achieve effective and efficient maintenance. The following are keys characteristics of proper functioning team: supportive environment, communication, and mutual error-checking. Even though individual competence is needed, it is important to develop a supportive culture in the environment. For a better and an effectiveness teamwork, sharing an understanding between teams' members should involve more than the required tasks but also how the tasks should be performed. A common agreement should be established on how the technician proceed with the tasks. The error detection and the communication among the team members must be part of the job design and even team structure (Konogiannis, 1999). To avoid or prevent frequent failures, each error or failures should be communicated to the team members. The communication is essential for effective and efficient maintenance. The best way to communicate according to Larkin (1994) is:

- Direct Communication between employees and supervisors.
- Face-to-face communication

The lack of Communication and excessive Belief (e.g., assumptions) could become a hinder for the maintenance. A vague team member responsibility impact negatively the maintenance and teamwork (Hudson, 2007). Each team member's role should be defined, the supervisor, the leadership etc. The quality of the supervision and the style of leadership play an important role in maintenance group performance. In an oil-refining company, communication of safety priorities on weekly basis, from managers to supervisors helps improving the safety parctices (Zohar, 2002b).

The lack of awareness is also a big hinders to a good maintenance. The maintenance operator or plant operator should know why the maintenance is performed and the impact and effect, a wrong asset or failure can have on the overall output. The lack of awareness is due sometimes to the lack of knowledge and practical training.

The lack of practical training impacts negatively the maintenance and the operation of the plant, especially when performing TPM (Total Productive Maintenance). Without a proper training, the plant operator or maintenance engineer cannot perform their tasks efficiently and effectively. The training program related to a plant should be continuous by keeping the plant operator and maintenance engineer up to date. In the remote area or region, the lack of training can even be huge because of lack of accessibility to ICT tools. In those area also, the low level of education can also affect the maintenance because, people might not have the required knowledge to organizations skills and tools; tools can be damaged or not even be in order.

2.3.2 Equipment, Asset and Tools Factors

Equipment, asset is vital in the reliability of the maintenance. Reliability is crucial to the understanding of the factors affecting the maintenance activities.

Reliability is the probability that an equipment or asset performs his assigned duty or operation in a period without failure (Sharma & Kumar, 2008). Lewis (1996) defined it as Mean Time-To-Failure (MTTF), which is the time between two failures. Reliability is an important factor and it got huge attention from academics. A technique for improving availability of the thermal power plant and improving maintenance reliability by Jagtap et al. (2020, 2021).

It is in the reverse of non-operation period called downtime. The downtime can either be planned (preventive maintenance) or unplanned in case of failures (corrective maintenance). The availability can be better when the maintainability of the asset, equipment or an item is effective, because the maintainability improves the reliability.

When an asset or item under a given conditions, is restored to its original state to performs the required function, it is called maintainability (The International Standards Organization (2006a)). Maintainability is essential even before designing of an asset because it ensures that the technical design facilitates the maintenance. It is crucial for the maintenance itself because it ensures the safety of the asset operator or the maintenance engineer.

Technical limitations are most of the risks that occurred during the maintenance. The plant performance depends on technical designs and engineering specifications which impact the Overall Equipment effectiveness (OEE). Bamber Castka, Sharp, & Motara, (2003) defined the Overall Equipment effectiveness as the function of:

- the time an asset, an equipment is accessible
- how it operates
- the output.

2.3.3 Maintenance financial costs

The maintenance cost of the plant cannot be ignored. The maintenance cost could be ranged in the range of 15% to 70 % of the total operation costs (Colledani &Tolio, 2012). Maintenance is efficient when the agreed maintenance is done with minimum costs (Wolfson Maintenance Engineering Ltd, 2001). Maintenance costs includes direct and indirect costs; maintenance budget, contractor cost, labor costs and material costs (spare parts) (Ingalls, 2000). The material costs are not the costs of the spare parts only but also the total inventory costs, meaning the logistic costs. the consumable item and the cost of the facility. depending on the maintenance. The labor costs depend on several factors as such level of education, years of experience and the degree of the machinery or part with safety level. Based on We et al., 2004; Ross, et al., the poor skill level of the maintenance team is sometimes, one of the factors affecting the effectiveness of the maintenance. One third of the maintenance costs are due to overtime costs, bad planning and scheduling, unnecessary costs (Wireman, 1990).

Table 2: Availability factors and related references.

Human Factors	Competence, skills	Lucia & Lepsinger, (1999)
	Skills, knowledge, personal characteristics	Robbins et al. (2009), Ahire et al., (1996)
	Human error	Sklet (2006), Shappell (2000)
	Operator error	Lorenzo, Vanden Heuvel, and Rooney (2006)
	Training, Tools	Dhillon and Liu (2006)
	Training, Education	John & Amrik (1989)
	Employee Empowerment and Involvement	Ahire et al. (1996)
	Team work	Hudson (2007)
	Technician behavior	Chaafstal, Schraagen, and van Berlo (2000)
Management Factors	Human error management	Reason and Hobbs (2003)
	Communication, tasks	Konogiannis (1999), Larkin (1994)
	Communication, Feedback system	Sanders (1994)
	Leadership	Hackett and Spurgeon 1998, Sheety 1994
Equipment Factors	Reliability	Sharma & Kumar (2008)
	Maintainability	The International Standards Organization (2006a)
	Availability	D. and Mitra, S. (2016)
	Availability	Patankar et al., (2009)

	Planning & Schedule	Papakostas et al. (2010)
	OEE	Castka, Sharp, & Motara, 2003
	Planning & Schedule	Mobley (2002)
Financial Factors	Maintenance cost	Colledani &Tolio, 2012, Moubray (1994)
	Material cost, labor, spare part cost	Ingalls (2000)
	Costs	Bose, G.K., Jana, D.K., Bose (2016)
	costs due to planning	Wireman (1990)
	Maintenance costs	Wireman (2003)
	Maintenance strategy costs	Ilangkumaran and Kumaran (2012)
	Direct and indirect costs, outsourcing costs	Waeyenbergh & Pintelon (2002)
	Indirect costs	Järviö (2017)
Logistic / Supply chain Factors	Spare part, ABC method	Uskonen, J. and Tenhiälä, A. (2012)
	MCDM	Ilangkumaran, M. and Kumanan, S. (2009),
	Spare Parts	Willemain, T. R., et al. (2004).
	Spare Parts Inventory	SHAHIN, A., GHOLAMI, M. (2014)
	Availability & lead time	Braglia, Grassi, & Montanari (2004)
	Spare Parts Management	Boylan (2010)
	Lead times	Dohi et al., (1998)
	Dematel	Tang HWV, (2018)

2.4 Maintenance Spare Part

A good maintenance plan or management requires a good spare part demand forecasting which itself is essential and it involves a good spare part demand inventory planning and controlling, and to avoid high spare part shortage and holding costs.

Managing spare parts is the biggest challenging in maintenance and material management. Previous researches have proved that the shortage of spare part has a big impact of the maintenance management, it increases the outage duration and the downtime. The unavailability of the asset or plant can jeopardize the productivity of the plant, increase delays in delivery. Spare part is used either in corrective maintenance for part replacement or in preventive maintenance to avoid outage of the asset. Holding extra item or spare part of a Waste-to-Energy plant components (safety stocks) could be used to avoid spare part shortage but it involves high and excessive holding costs for firm or organization (Altay Guvenir & Erel, 1998). Overhaul inventories, maintenance, repair can cost up to 40% of the procurement cost in organizations (Donnelly, 2013).

Spare parts management improve and enable a better availability of the spare parts at the right time, at the right place, the right quantity, at the right price, , and all at lowest cost by keeping high quality and safety standards.

Huiskonen (2001) pointed out the inefficacity that arise when general inventory stock management methods are used in maintenance spare parts inventory management. He mentioned that maintenance spare parts inventory should be as special because the control characteristics of the spare are neglected when the general inventory methods are used. Spare parts can be categorized into two:

- reparable spare parts: parts that are economically and technically reparable for use again (reuse). The parts in this case, could be repaired on site, or sent to the supplier.
- Non-reparable spare parts: those also called disposable or consumables are not repaired but through away, recycle or retire.

Spare parts are different than common end-product, which are more like fast moving and have independent demand. Spare parts are required when installed part or component fails or needs to be replaced preventively (Fortuin & Martin, 1999).

Many inventory managers have difficulty to forecast the spare parts, to estimate the stock level, and to solve that issue, some forecast tools, models, methods are needed. When there is spare part shortage, the production is negatively affected and when too high parts level is stored, it causes extra costs which also affect negatively the production (Fortuin and Martin 1999, p. 953).

Spare part is intermittent and most of the standard forecasting techniques provide inaccurate result. Various other approaches have been developed in the literature, Bootstrapping which is a non-parametric approach (Willemain et al., 2004); Neutral networks proposed by Kourentzes (2013) is another approach which is also a non-parametric tool for intermittent forecasting demand. This approach allows the interaction between the non-zero demand and the demand to be captured. Judgmental forecasting is good tool for intermittent forecasting demand as it is often used to adjust quantitative derived forecasting has been proved to improved forecast accuracy (Syntetos et al., 2009).

Babiloni (2012) gives a review on forecast demand, while Boylan (2010) provide a literature on spare part forecasting demand. Both are based historical demand data which are time series methods. Hu, Boylan, Chen, and Labib (2017) framework is for operational in spare part management; His paper considers other factors than time series data, it considers the failure rate of the asset and also the operational environment impact on the asset. The paper is a reliability-based forecasting approach with studies the impact of different maintenance strategies.

Most of the methods and techniques are based on time series which is based on historical pattern of the spare parts and it does not consider other factors like conditional factors and variables that might affect the series (Stevenson, 2012). There are many sources of information, that might enable firms or organizations to generate forecasts such as items or installed based products reliability characteristics and maintenance policy. The items reliability data and information are usually collected by service department or service engineers or maintenance engineers. Number of literatures that discussed the use of the installed base information for spare parts forecasting. The common drivers for the discussion in the literatures are maintenance policy, the age and size of the installed based products (Stormi et al., 2018) and the spare part failure probability (Si et al., 2017, Barabadi, 2012;).

To avoid unavailability of spare part, it is important to group the spare parts based on their criticality and to have an effective planning. Spare part classification is way to control stock levels because it helps to identify the critical key parts whose unavailability may affect the production.

Spare parts classification facilitates the decisions making process because it enables organization to identify the critical part on the most important asset. The important items are those which their unavailability may cause critical and severe consequences for the plant (Syntetos et al. 2009). In inventory management, important items could be those which have high holding costs and those with high demand.

Following characteristics should be considered when identifying critical maintenance spare parts.

- control criticality and process: process critically happened due to the unavailability of the parts; for instance, down time costs. Control criticality is about the probability of the failure of the part, availability of the part, repair time. Usually, inventory control is on the local inventory and not the whole supply chain.
- specificity: maintenance parts can be categorized into generic and unique. For the generic (standard), usually there are many suppliers but for unique (specialized) spare parts, it is difficult as it is usually from few or one supplier (lead time may be longer).
- demand patterns: it is about demand volume and predictability. There might be spare parts with very low volume demand but with high critically and price but as it is low volume demand, supplier might not be attracted to offer service for it. Predictability is about the estimation of the failure pattern of the part.

- commodity value: Keeping spare parts in stock does not create value, even though it might reduce downtime costs.
- beside those characteristics, there are other critical characteristics like lead time, quality. reliability, price and holding cost.

The risk in supply chain management is so important that a poor or non-effective risk mitigation plan, will lead to a mismatch in the demand and the supply (disruptions). A proper risk mitigation strategy should be established to reduce effectively the impact on the whole systems (Rajesh, 2017). This cannot be done easily due to the uncertainties in decision making processes. There are many risks:

- lead-time related risks, for instance the delays, forecast risks, and errors due to wrong or inadequate quantitative forecasting (Chopra and Sodhi, 2012).
- flexibility risks, which are capacity and supply chain design risks.Without the flexibility of supply chain design, it is sometimes difficult to accommodate to the markets or customers changes (Klibi et al., 2010).
- integration related risks, which are related to technologies and systems risks. With good technologies, it is easy to integrate the new or recent technology to the supply chains, wrong systems or application can also affect negatively the whole supply chains (Tomlin, 2006)
- sourcing risks which are related to procurement, supply chain sources cost, stability and commitment (Xu, 2010).

Spare part can be classified into qualitative (ABC), quantitative (DEMATEL) or the combination of the two (AHP). Those models are often based on mathematical or qualitative models which are linear programming, dynamic programming. Even though some of the models are easy to implement and mostly used the industries, they lack in considering many features or criteria (Braglia et al. 2004, p. 55-56).

The thesis identifies and evaluates key factors and criteria that could be used to ensure the availability of the plant (choosing the right supplier, parts and so on) and this could be done by using decision making tools to support management.

In the past decades, the service requirement and level has changed, and it is obvious that even though spare parts classification is important, it is challenging because of diverse set of spare parts which implies the multi-criteria approach. The classification of inventory item, spare parts is essential part of the inventory control of the spare parts (Shahin and Gholami, 2014).

Many theoretical models for multi criteria classification approach and several multi criteria decision making (MCDM) models exist (Dalia Streimikiene, and Deepak Sharma, 2018); Activity Based Costing (ABC) Analysis, AHP (Analytic Hierarchy Process), Fuzzy AHP, Fuzzy TOPSIS, ELECTRE (Elimination and et Choice Translating Reality), PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation), TOPSIS (Technique for Order Reference by Similarity to Ideal Solution), ISM (interpretive structural modeling) (Dhawale, A., 2019), grey-DEMATEL (Decision Making Trial and Evaluation Laboratory) (Shrinath Manoharan, Venkata Sai Kumar Pulimi, Golam Kabir, Syed Mithun Ali. ,2022).

ABC Analysis is widely used in practice and in the industries, but it is more useful when items are rated, ranked in terms of only one criterion, the cost.

ABC is not only used in manufacturing or production but in R&D, marketing as so on. It was introduced 1988 to address intra-firm supply chain issues (Cooper & Kaplan, 1988). It cannot be implemented without identifying the resources and the activities involved (Uskonen & Tenhiälä, 2012).

The application of ABC is simple and easy to use, that’s the reason it is widely used. ABC Analysis is used to classify spare parts using the demand value for an electronic manufacturer (Syntetos et al.2009). ABC Analysis even though widely is not used successfully in industries, due to the heterogenous aspect of the spare parts.

2.5 Study Gap

There are many studies related to the availability of equipment and different plants systems but not for Waste-to-energy plant. Waste-to-energy got attention of academics, researchers but they focus mostly on the treatment of waste, different waste treatment methods, but there is a big gap, lack of study about the maintenance of Waste to energy plant. The thesis tackles this gap by identifying the critical factors that enable the availability of waste-to-energy plant.

3. STUDY METHODOLOGY

Research design is covered in this part, as well as the data collection, the sample and the population. Besides the primary source of information, secondary source of data is used. The data is collected from relevant institutional resources. The secondary data collection methodology is adopted because of the ease in data collection, simplicity of analysis, reliability of findings and the comparison of the findings from different researchers (Maxwell, 2012). Few maintenance program professionals (4 to 5) were interviewed, to compare the theoretical findings and the practical findings.

3.1 Population and Sample

The population are Waste-to-Energy maintenance manager, professionals, service provider and suppliers from all around the world. The samples were selected using different sources, search on LinkedIn and google, company websites. Random selection was used to select the target groups (respondent groups). There were approximatively 25 respondents from the number of research population that was about 150 WtE professionals.

Out of 25 returned responses, 5 were not considered, due to the fact those respondents were not WtE professionals based on the background study. So, a valid sample of 20 respondents were considered, which constitutes a response rate of 12% of the target population. The respondents comprise of 4 maintenance planners, 5 service engineers, 4 technicians, 4 supervisors, 3 maintenance equipment spare part suppliers and 5 maintenance managers. Table 3 below shows the background of the interviewees and their experience in the field in terms of years.

Table 3: Interviewees' background

Title / position	Number of respondents	Years of experience
Maintenance planners	3	[4; 10]
Service engineers	4	[3;12]
Technicians	4	[2;10]
Supervisors	3	[5;15]
Spare part suppliers	2	[3;15]
Maintenance managers	4	[8;20]

3.2 Research Design

Qualitative and quantitative method are used. It is called a mixed methodology according to Amaratunga et al. (2002.). The adoption of a mixed research method (qualitative and quantitative) provide a better understanding of the research topic and aid to draw better conclusion (Obiajunwa, 2010).

It is based on a survey and secondary data from literature. The reason why the quantitative approach is used is that, its emphasis the closed-end questions. The research approach is deductive, it focuses on the collected data to prove and test a theory. In this research data is collected to test the funding from the literature (Cresswell 2014). With quantitative approach, the relationship of different variables is measured and analyzed using statistical techniques. The quantitative approach demands more economical resources where qualitative approach takes much more time. Qualitative method helps to understand many unclear phenomena. In quantitative research, questions are usually "What", "How many" or "How often" while in qualitative research, questions are "Why" or "How". Lewis & Thornhill (2016) stated that the main advantage of online survey is that, it can reach many people regardless their geographical region.Qualitative method is used to give the opportunity for the respondents to give their own opinions about the challenges they have experienced and then analyze the open questions or comments.

In addition to primary data, the secondary data and a semi-interview is conducted, even though it is considered as time consuming data collection techniques (Tuten & Urban 2001). It is useful because besides the standard interview structures, the interviewees provide information from their experiences, from lessons learnt. By interviewing, the researcher can gain richness in data through open discussion. As most of the plants are distant from the logistic, a model based on DEMATEL, decision making tool is used to support spare part selection decision making. The motivation behind the choice of DEMATEL methodology is that it is can be used with a small sample, and it help to find the interdependency of the criteria, barriers or factors in the process of decision-making. The subjective nature of the factors and criteria makes the decision difficult sometimes, that is the reason DEMATEL is used to provide a certain quantitative value to the criteria for analysis.

3.3 Data collection method

There are different ways of collecting or gathering empirical data: case study, survey, experiment, and this master's degree thesis uses a survey. Survey is one of the practical means of reaching out respondents for a research.

There are three types of surveys: factual, inferential and exploratory (Easterby-Smith et al. (2012). The inferential survey identifies connection between different variables and concepts using a sample population. Factual survey is fact-based data used for market surveys or polls by companies and to develop different models, exploratory surveys are used (Easterby-Smith et al. 2013). Online questionnaire which is an inferential survey is the method used in this thesis. The questionnaire can be defined as a method with a pre-determined question that respondents can answer.

Questionnaire was constructed in English using Webropol 3.0 online survey platform. The results were transferred from Webropol to Microsoft Excel for quantitative analysis. Some of the questions were multi-indicators, items scale which were measured using unbalanced six-point Likert scale.

Six-point Likert scale is suitable for subjective statement measurement, to measure the internal feeling about a statement.

According to Bonometti & Tang (2006), a valid survey required five different steps:

- Designing the survey questionnaire
- Determining the target group to answer the survey
- Selecting suitable distribution methodology
- Collecting the data submitted by the respondents
- Analyzing collected data

This approach was followed in this study from survey questionnaire designing to the last phase, which is data analysis.

The scale ranged is as follows:

- 1 as “No opinion”
- 2 as “Does not affect”
- 3 as “Slightly affect”
- 4 as “Affect”
- 5 as “Strongly affect”
- 6 as “Extremely affect”.

The questionnaire was constructed in a structured order and covers three main subjects: the WtE availability factors, the maintenance planning and scheduling, and the spare part selection criteria. Based on the research questions and theoretical framework, the questionnaire was designed and sent to the respondents.

The survey was sent to the respondents, after making changes suggested by the thesis supervisor and the contact person of the company.

Questionnaire was same for all the respondents. There were 13 multiple-choice questions and 4 questions open comment questions.

3.4 Reliability and Validity

Reliability is important in a research. Reliability in qualitative research means the possibility of reproducing the same results while in quantitative research, it means similar conclusion will be reach using the same sample and methods (Lowhorn 2007). Reliability is used to ensure consistency, accuracy, steadiness, and compatibility of data.

The aim of the reliability is to ensure the measurement of the quality of any data.

Validity means the capability of the instrument used to rate the defined target in a research or the credibility or the trustworthiness of the collected data and the methods used (Lowhorn, 2007). The factors that enable high availability of the WtE plant were measured in this thesis.

3.5 Analysis Implementation

The background information of the respondents was the first covered to verify if all the respondents fulfilled the requirements. The respondents were then classified in different groups: spare part supply provider, maintenance manager, maintenance planning and schedule manager, maintenance project manager and maintenance technician group. 6 of the respondents was deleted because they didn't fulfill the requirements, criteria.

Below is the Figure 3 showing respondents groups and number of respondents.

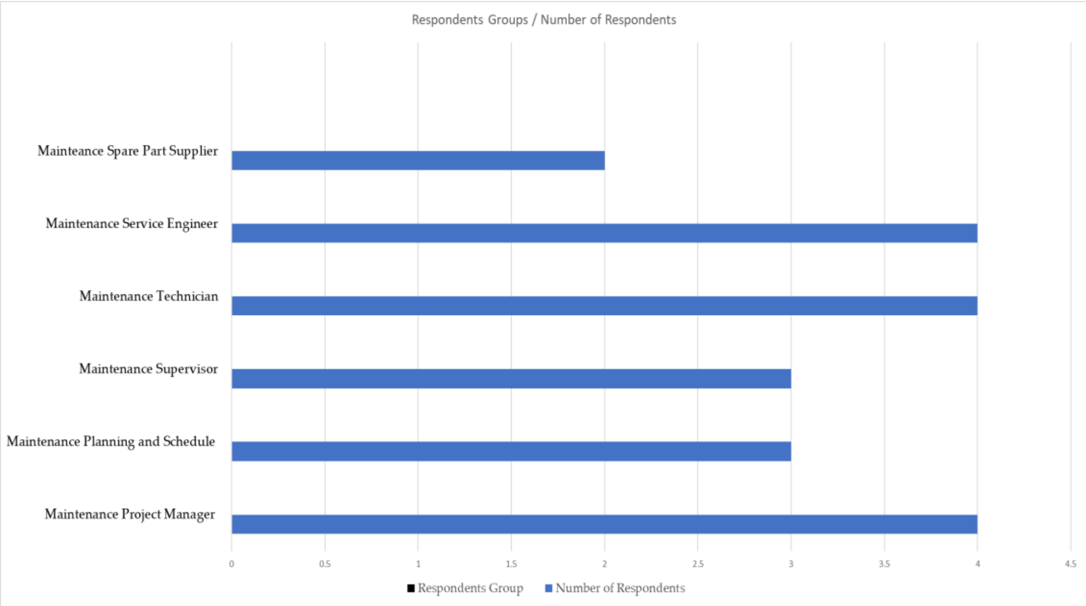

Figure 3: Respondent groups and numbers

3.6 Background Information of Respondents

The respondents provided their background information to ensure that the requirements were fulfilled, and they are part of the target groups. Also, it helps to understand their answers and make a better analysis.

The respondents are in different countries, in Europe, in Africa as well as in Asia and America. (UK, Germany, India, China, Finland, Denmark, Ethiopia). The location of the respondents could affect their answers to the survey, as it depends on the country's legislation, company's culture, organizational structure.

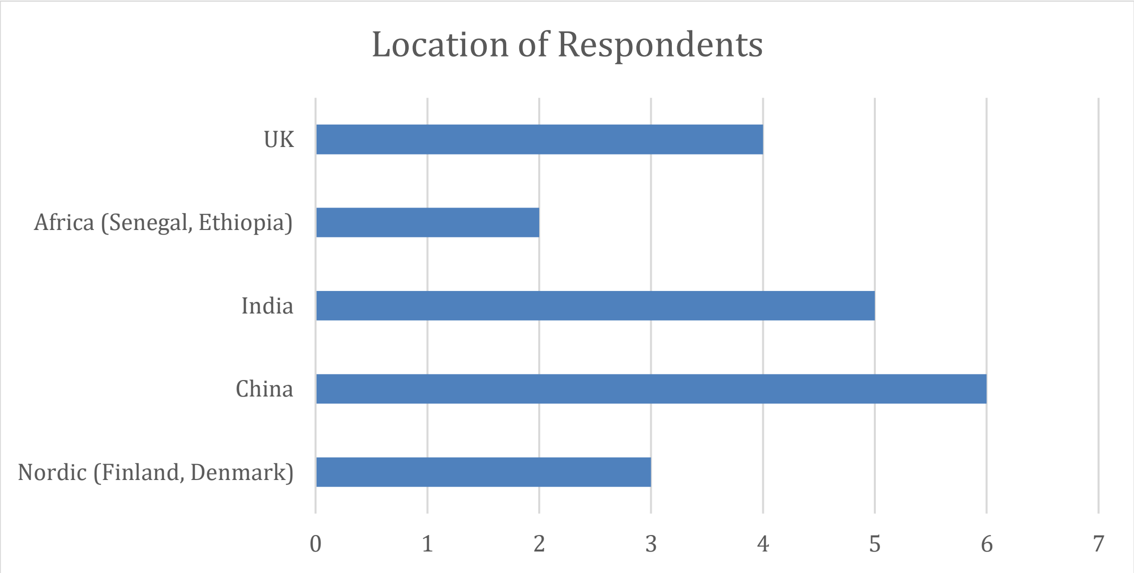

Figure 4: Respondents location

3.7 Decision Making methods

In this thesis, DEMATEL method is used to analyze the critical criteria. There are used because both consider and help to solve the vague and incoherent information that can be result sometimes in human judgement when using most decision-making tools.

3.7.1 DEMATEL Method

DEMATEL is a structural, mathematical method modelling (Gabus and Fontela, 1972), which analyzes the interdependencies relationship and influential effects of different factors by using the cause and effect diagram (Lin, 2013). This method has been used by many researchers; supplier selection (Chang et al., 2011). It is used as a multicriteria method to evaluate the KPI of the maintenance in food processing industries (Shahin, A., Masoomi, B. and Shafie, M.A. 2019; Si, S.L., You, X.Y., Liu, H.C. and Zhang, P. 2018).

It has been used in spare part chain risk mitigation knowledge management implementation (Wu, 2012) and human resources (Chou et al.,2012) etc.

The DEMATEL framework has been also used for instance to access the decisive factors in supply chain management (Wu et al., 2015). A carbon management model of supplier selection in GSCM has been developed using DEMATEL (Hsu et al.,2013). In Manila, it has been used in municipal solid waste management to analyze the cause-effect relationship. It has been used in the construction sites (Seker and Zavadskas, 2017). It has been used to identify the influential indicators towards sustainable supply chain adoption in the auto components manufacturing sector (Y.B. Li, K. Mathiyazhagan, 2018).

The objective of DEMATEL is to evaluate the interdependency, interrelationship among criteria or factors to solve complex problems, in complex system (Si et al., 2018).

The visual representation of graph theory is the result of DEMATEL method (Tzeng et al., 2007) which is easy to interpret, and it helps identifying better solutions in a structural way (Hsu et al., 2013; Lin, 2013). DEMATEL approach can be used with limited sample.

DEMATEL steps are:

- **step 1:** Initial relation matrix “A”

The initial relation matrix is setup using decisions makers’ rating over given criteria. The experts are asked to rate the factors or key criteria to create a direct relationship using their rating. The scale designed has five levels: [0,0] = No opinion, [0, 1] = Very low influence, [1, 2] = Slight influence, [2, 3] = Influence, [3, 4] = Strong influence and [4, 5] = Extremely influence. The matrix is as shown in equation (1).

$$A = \begin{vmatrix} 0 & a_{12} & a_{13} & \cdots & a_{1(n-1)} & a_{1n} \\ a_{21} & 0 & a_{23} & \cdots & a_{2(n-1)} & a_{2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{(n-1)1} & a_{(n-1)2} & a_{(n-1)3} & \cdots & 0 & a_{(n-1)n} \\ a_{n1} & a_{n2} & a_{n3} & \cdots & a_{n(n-1)} & 0 \end{vmatrix} \quad (Equation\ 1)$$

Equation 1: *Initial relation matrix*

- **step 2:** Set up normalized direct-relation matrix "X"

Equations (2) and (3) are applied to obtain the normalized relation matrix and the elements lies between 0 and 1.

$$K = \frac{1}{\max\limits_{1 \le i \le n} \sum_{j=1}^{n} a_{ij}} \ (Equation\ 2)$$

Equation 2*: Normalized factor*

$$X = K * A \ (Equation\ 3)$$

Equation 3: The normalized direct relation matrix

X is the normalized direct relation matrix

K is the normalization factor

A is the initial relation matrix

- **step 3:** Setup total relation matrix "T"

The normalized relation matrix is processed to obtain the total relation matrix by using the Equation (4).

$$T = N(I - N)^2 \quad (Equation\ 4)$$

Equation 4:*Total Relation matrix*

"I" is the identity matrix.

- **step 4:** Sum of the all the rows and all the columns

D (sum of the rows) and R (sum of the columns) are obtained using the Equation (5) and (6).

$$D = \left[\sum_{j=1}^{n} m_{ij}\right]_{n \times 1} \quad (Equation\ 5)$$

Equation 5: *Sum of the rows (D)*

$$R = \left[\sum_{i=1}^{n} m_{ij}\right]'_{n \times 1}$$

Equation 6: *Sum of the columns (R)*

- **step 5:** Develop a causal diagram

The causal diagram is obtained by means of the dataset (D+R, D-R). D+R, also called "Prominence" is the horizontal axis vector and D-R, called "Relation" is the vertical axis vector. Generally, criteria with negative values of (D - R) is grouped into effect group while criteria with positive value of (D - R) is, grouped into cause group (Tseng, 2009).

4. DESCRIPTION OF THE CASE COMPANY

WOIMA Corporation is a Finnish modular waste-to-energy power plant supplier with the aim to mitigate waste-related problems in developing countries. It is a company which was founded in 2017. WOIMA Corporation offers a turn-key solution that simultaneously significantly reduces waste landfilling, delivers a variety of energy commodities and cuts down waste logistics costs. Their solutions mitigate environmental, social and health problems caused by waste and offer sustainable growth to waste management companies, energy sector, investors and local population alike (WOIMA corporation, 2018).

Different sizes of containers are used to build the modular power plant. The size is 20' and 40' and those are transportable, which make the installation easy.

Their aim to design robust, low operations costs, high efficiency, good tolerance, strict emission plant for the users.

The company aim to reduce the environmental, social, and health problems due to municipal solid waste and to provide circular economy solutions.

Waste-to-Energy plant called "wasteWOIMA®" was the first modular plant designed by the company. wasteWOIMA® uses different waste streams; Municipal Solid Waste (MSW), RDF, bio, gas, etc.) and produces saturated steam, electricity, thermal energy and/or potable water. It can be interconnected to create larger configurations (up to 4).

Each wasteWOIMA® line incinerates roughly 150 tons of waste/day to generate 3.5 MWe of electrical power or 2.0 MWe / 10 MW thermal energy, 200 m3 of potable water daily.

The optimal expected operation of the plant during its lifecycle can be ensured by identifying the critical factors that affect the availability of the plant and the best criteria that can be used when choosing the supplier of spare part of the plant.

Picture 1: Modular waste incineration plant WasteWOIMA® (WOIMA Corporation 2018a)

The waste incineration plant has five blocks as shown in Figure 5: waste incineration, heat radiation and cooling, waste heat recovery, air pollution control and power generation.

5. RESULTS ANALYSIS

This chapter covers data collection and the results analysis. It presents the answers to the survey questions as well as the analysis of each question. The last chapter of this section shows a summary of the results.

5.1 Employee/ Labor Factors

The responses in the Figure 6 below show that the employee involvement and commitment (70%), personal skills (60%), training and teamwork (55%) are important factors to ensure high availability of the plant.

The more the engineer knows how to operate the machine efficiently, the better will be the availability of the machine/plant. Besides that, when the engineer/operator knows how to perform the basic maintenance of the machine, it helps the machines to operate smoothly. Engineer / Operator's training is also an important factor to consider. Engineer / Operator needs to continuously update his/her knowledge.

The respondents reveal that employee's involvement and empowerment are effective only when after receiving a formal, and systematic training in basic maintenance and plant operating activities (Ahire et al., 1996). The training and education are vital in achieving the high availability of the plant as well as for a successful maintenance. Each person involved in the chain, must understanding the importance and the objectives behind the quality management which is related to the maintenance and the availability of the plant. Working as a team, improve all the processes to achieve the high availability of the plant.

Teamwork is the keys to achieve organizational goals and teams are the majors' part of the plant maintenance and the availability of the plant. More than half of the respondents think that teamwork is the condition to achieve a quality maintenance work.

From the Figure 6, communication is also important as it is a factor that holds all the teams to operate efficiently and effectively. In order to incorporate, necessary changes to ensure a high availability, and to convey good ideas to the all the stakeholders, thus a good feedback, report and communication are needed (Sanders, 1994).

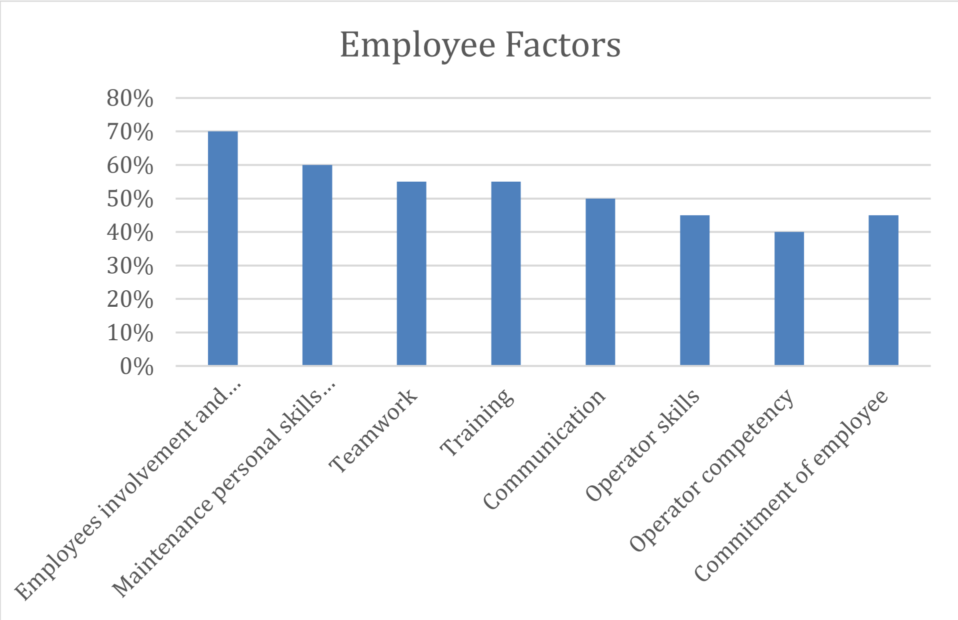

Figure 5: Employee factors (according to respondents)

5.2 Economic Factors

Costs can be grouped into indirect costs (loss of revenue) and direct cost. Direct ones are operating costs (salaries, labor costs, spare parts, storage, training, subcontracting) and those directly related to maintenance costs.

From the figure 7 below, the direct costs extremely affect the availability of the plant. About 37% of the respondents stated that the direct cost is a critical factor also to consider when planning a maintenance. Maintenance equipment cost affects as well as the availability of the plant.

Maintenance equipment costs (according to the respondents 33%) are critical for the efficiency of the maintenance tasks. The right equipment and tools for maintenance make the maintenance itself easier, the precision of the work and the quality required and expected.

Spare part costs affect significantly (20% based on to the Figure 7) the maintenance activity it depends on the availability of the pare part, the quality of the spare part and the suppliers.

Indirect costs are the costs for renewal, overwork costs, the loss of profit, production loss during planned or unplanned, poor quality cost due to maintenance deficiency or reduction in sale volume (Järviö, 2017). The costs include all the sssssindirect and direct costs involved in the inhouse and outhouse maintenance activities (outsourcing). (Waeyenbergh and Pintelon, 2002).

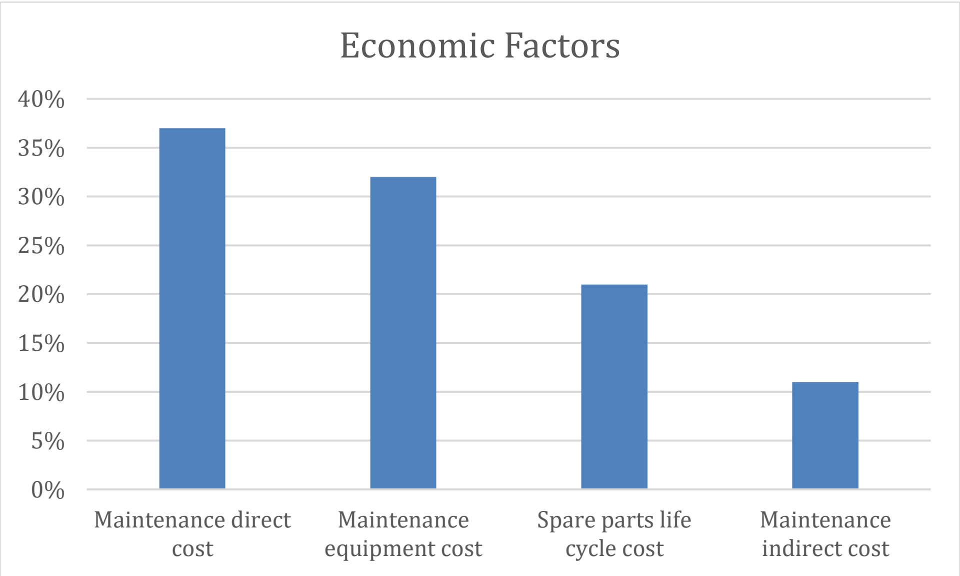

Figure 6: Availability of financial factors (according to respondents)

5.3 Management Commitment and Leadership Factors

When employee, or people who need to achieve organizational goals, receive support or confidence from their manager, they

Leadership is the attitude to support or give configure to those needed to achieve organizational goals (Hackett & Spurgeon 1998, Sheet,199). Management plays a key role in the availability of the plant.

The managers are responsible for establishing operating and maintenance policies, guidelines and strategic objectives of the plants and providing the direction of the quality management within the organization.

Based on the Figure 8, the top management's commitment (50%), resources commitment (55%) and process quality management (50 %) are the most critical factors.

The commitment of the top and middle management is essential for the resource's allocation, for the plant operator and all the people involved in the maintenance.

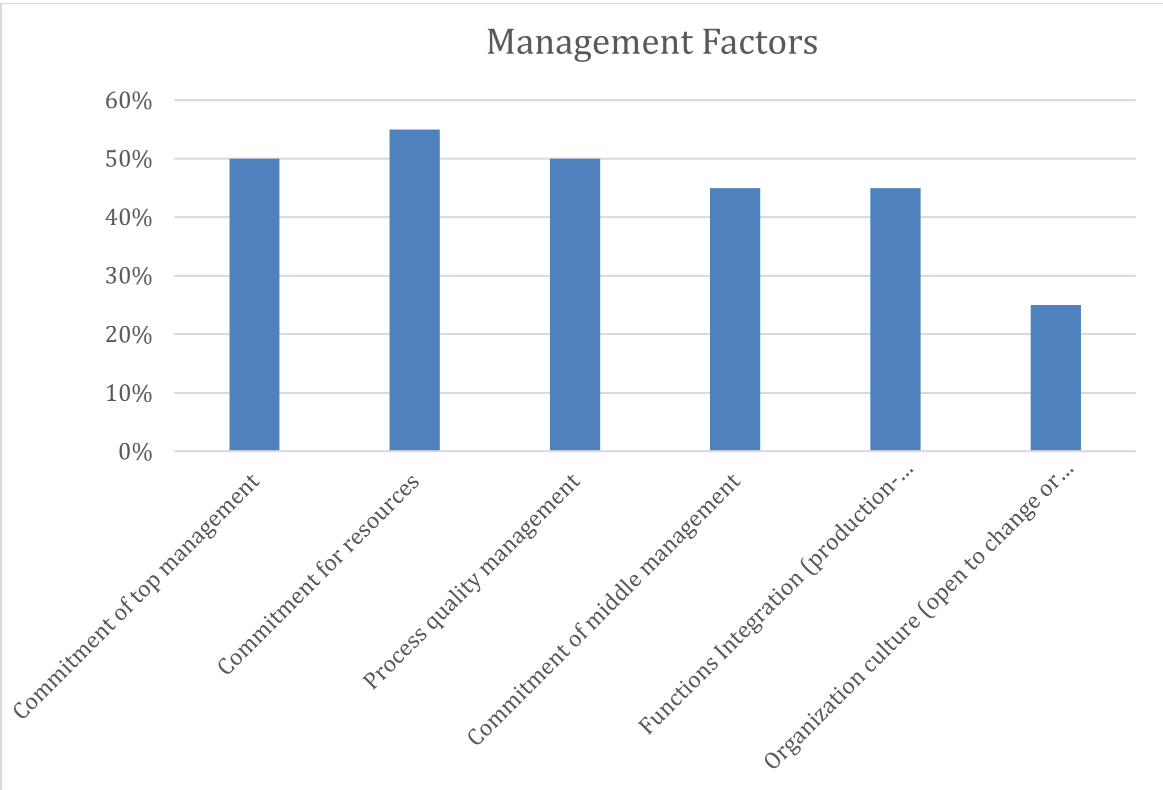

Figure 7: Management factors (according to the respondents)

5.4 Spare part factors / Logistic / Procurement

From the Figure 9 below, the most critical factors to ensure high availability depends on the quality of the spare part, the reliability and availability as well as the lead times, which related to delay.

The answers presented in the figure 9 shows that, 15 respondents, which is 75% of the respondents pointed out the importance of the spare part quality and functionality. The cost of holding an inventory is high but the availability and the accessibility of the critical spare part determine the downtime.

The aim of the parts inventories is to help execution the maintenance task efficiently to avoid longer down time that might occur due to order lead time.

Figure 9 reveals that spare part reliability (68%), quality, spare part availability (60%) and functionality (70%) are important factors to consider for higher availability of the plant. The better the quality is, the shorter is the downtime, hence the mean time between failure (MTBF) will be longer.

The lead times is related to the process of spare part inventory and maintenance and therefore influence the downtimes (Dohi et al., 1998). Even though the downtime is also influenced by the response time of the internal or external maintenance engineer to some extend (Haugen and Hill, 1999), the availability of the tool's influences also the downtime (Patankar et al., 2009).

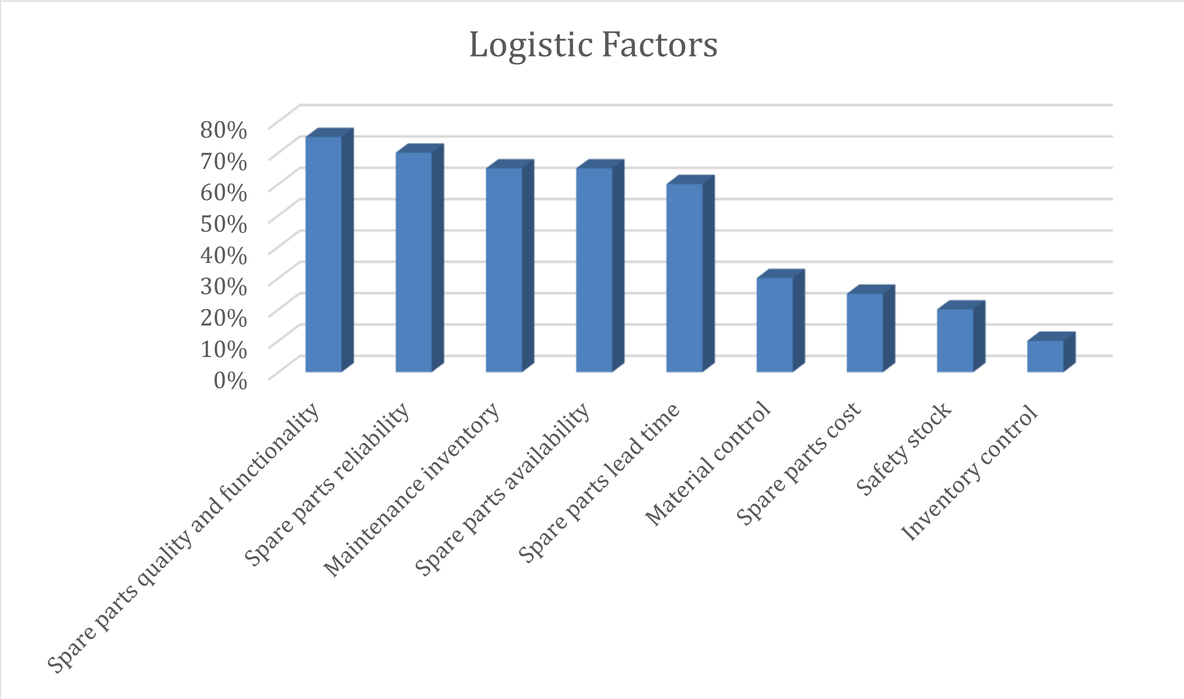

Figure 8: Logistic factors (according to respondents)

5.5 Maintenance Factors

More than 70% of the respondents, pointed out the importance of the maintenance planning and scheduling, as well as the tools and the maintenance equipment. The planning and scheduling involve the labor, tools and equipment and the timing to do the maintenance. The right timing for the maintenance needs to be taken into account to avoid long downtime.

Over 40% of the responses (Figure 10) also think that good operating procedures and practices facilitate the maintenance works and improve the quality of the maintenance, thus enable the high availability of the plant.

Decision making tools and a good management system support the operating and the maintenance team from the top management to the operator, thus enable high availability.

Figure 10 reveals that maintenance planning (80%) and scheduling (75%) are the most critical factors. Besides that, operating procedures and practices (55%), Mean Time to Repair (MTTR) are crucial for the efficiency and effectiveness of the maintenance.

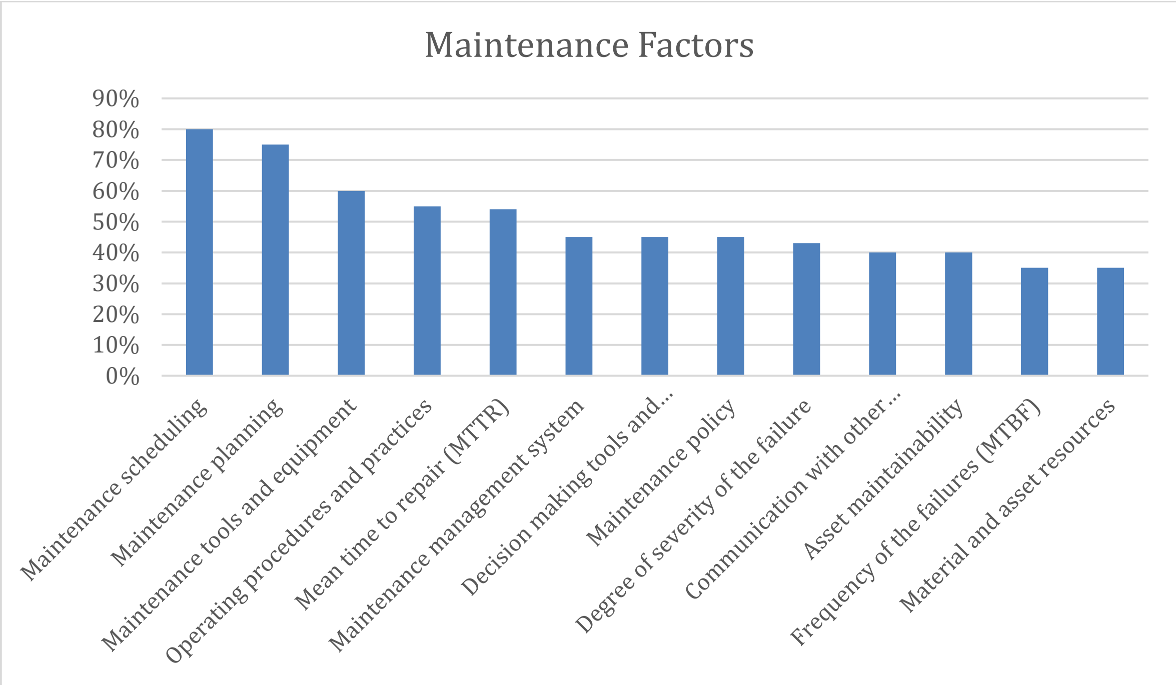

Figure 9: Maintenance factors (according to respondents)

5.6 Environmental Factors

Country regulation affect one way or another WTE plant. Rigid is the regulatory compliance in the country, better the environment is done effectively. Based on the responses showing in Figure 11, regulation compliance (50%), corrosion (40%), humidity (25%) and dust (15%) affect the availability of the plant. These factors need to be considered especially the temperature when the plants are in countries with tropical temperatures or seasons.

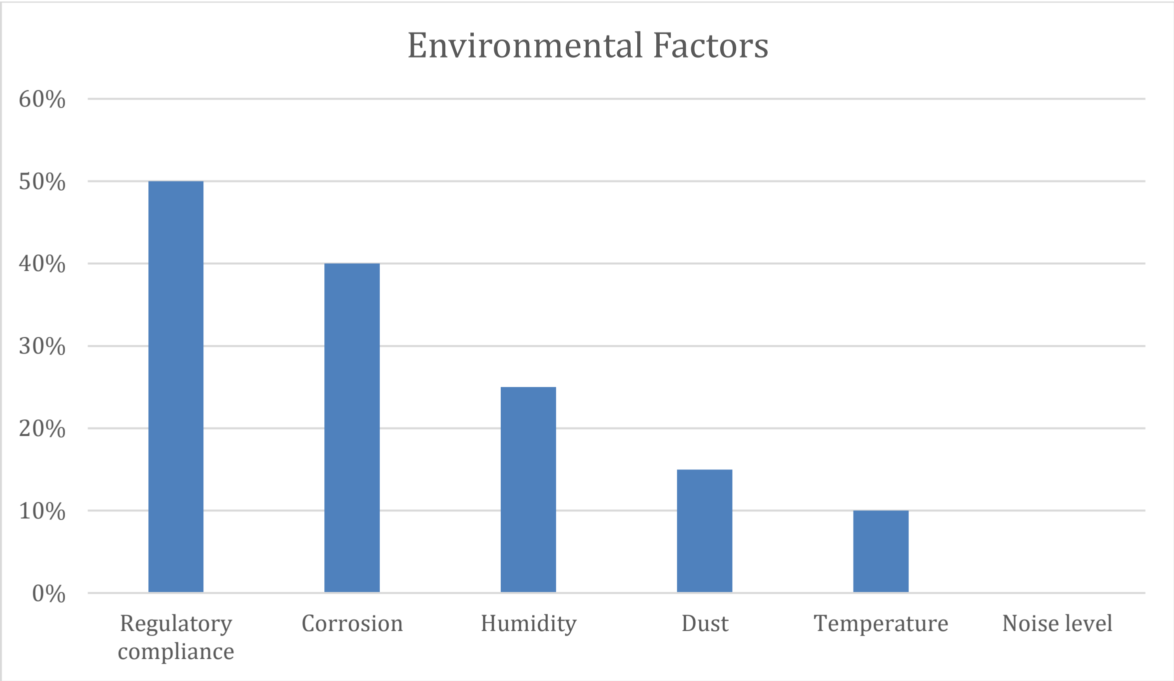

Figure 10: Environmental factors (according to the respondents)

5.7 Outsourcing Factors

About 80% of the respondents outsource the special skills, so that the company focuses more on their core competencies. Over 50 % of them also says that, they outsource their maintenance function or the work during outage or the shutdown.

It can be seen also from the figure 12 that, less than 20% outsource their spare part, which explain the importance of the spare part in the availability of the plant or the maintenance activities of the plant.

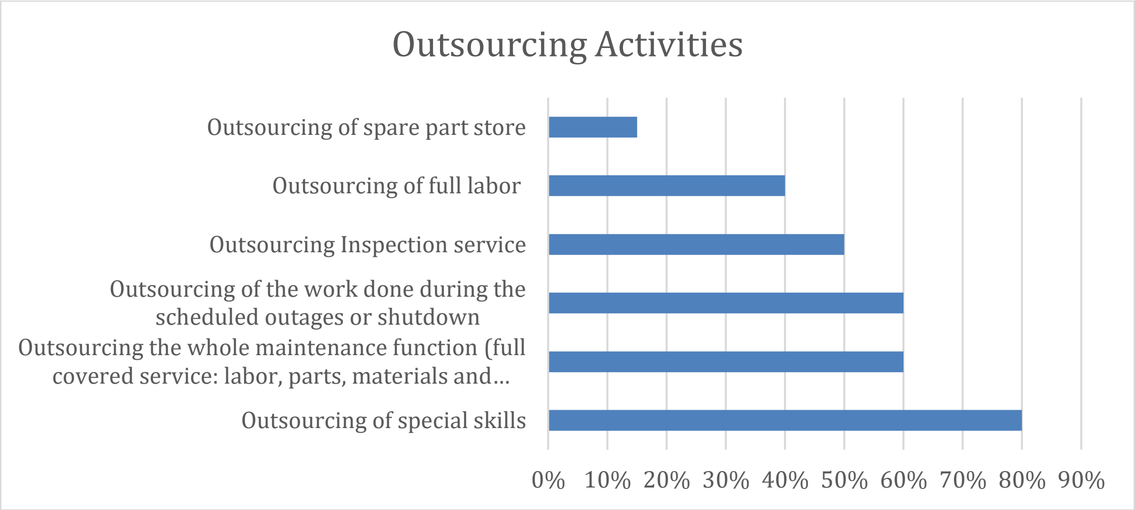

Figure 11: Outsourcing Activities (according to the respondents)

5.8 Spare Part Criteria Analysis

DEMATEL method is used in this part of the analysis. Cause-effect relationship among criteria is established, and spare part is prioritized for a better part selection while using DEMATEL method (Tang HWV, 2018).

- Step 1: **Initial relation matrix "A"**

The respondents result for spare part criteria has been set in an excel file. The averages of all the rating of each criteria is called Initial direct influence matrix A (showing in Table 4). It is obtained using the equation (1) and expert methods. The influence of a criteria on itself is 0.

Table 4 presents the average of the scores given on each factor by respondents (experts). As it can be seen in the table 4, the diagonal element of each factor is 0.

Table 4: The matrix A displays a direct relationship of factors.

	Critically	Specificity	Predictability	Maintainability	Inventory cost	Availability of the market	Order lead time	Price	Volume of the spare part	Quality	Severity of its failure	Availability of support	SUM
Critically	0	5	2	4	2	5	4	3	3	4	5	2	39
Specificity	3	0	4	3	3	5	2	3	1	4	3	1	32
Predictability	2	3	0	4	3	5	4	5	2	2	4	3	37
Maintainability	3	2	4	0	3	4	3	3	3	3	2	2	32
Inventory cost	1	1	4	2	0	2	3	2	4	2	3	3	27
Availability of the market	1	2	2	3	2	0	4	3	3	3	2	2	27
Order lead time	5	4	5	5	4	5	0	5	4	5	5	5	52
Price	2	3	4	4	5	4	5	0	5	3	5	4	44
Volume of the spare part	2	1	2	2	4	2	2	2	0	2	2	3	24
Quality	5	5	4	5	5	4	3	5	5	0	5	5	51
Severity of its failure	3	4	2	4	5	4	5	2	4	3	0	5	41
Availability of support	1	2	1	3	2	4	4	2	2	7	2	0	30
												Max	52

- Step 2: **Normalization of the direct-relation matrix X**

The normalized direct relation matrix has been calculated based on Equation 2 and Equation 3 and presented in Table 5.

In this step, all the respondents rating, has been divided by the Max value which is the sum of the row for each criterion. Matrix X is also called the direct influence matrix.

Resultant matrix X showing in Table 5.

For example, the direct influence value of “Quality” on “Failure Severity” is 0.096.

Table 5: Matrix X displays a normalized direct relation of factors

Critically	0	0.096	0.038	0.077	0.038	0.096	0.077	0.058	0.058	0.077	0.096	0.038
Specificity	0.058	0	0.077	0.058	0.058	0.096	0.038	0.058	0.019	0.077	0.058	0.019
Predictability	0.038	0.058	0	0.077	0.058	0.096	0.077	0.096	0.038	0.038	0.077	0.058
Maintainability	0.058	0.038	0.077	0	0.058	0.077	0.058	0.058	0.058	0.058	0.038	0.038
Inventory cost	0.019	0.019	0.077	0.038	0	0.038	0.058	0.038	0.077	0.038	0.058	0.058
Availability of the market	0.019	0.038	0.038	0.058	0.038	0	0.077	0.058	0.058	0.058	0.038	0.038
Order lead time	0.096	0.077	0.096	0.096	0.077	0.096	0	0.096	0.077	0.096	0.096	0.096
Price	0.038	0.058	0.077	0.077	0.096	0.077	0.096	0	0.096	0.058	0.096	0.077
Volume of the spare part	0.038	0.019	0.038	0.038	0.077	0.038	0.038	0.038	0	0.038	0.038	0.058
Quality	0.096	0.096	0.077	0.096	0.096	0.077	0.058	0.096	0.096	0	0.096	0.096
Severity of its failure	0.058	0.077	0.038	0.077	0.096	0.077	0.096	0.038	0.077	0.058	0	0.096
Availability of support	0.019	0.038	0.019	0.058	0.038	0.077	0.077	0.038	0.038	0.135	0.038	0

- Step 3: **Estimation of Total Relationship Matrix (T)**

Using Equation 4, the Total Relationship Matrix (T) was determined and shown in Table 9. Before that, different intermediate calculations have been done and presented in Table 6, 7 and 8.

Table 6: Identity Matrix

Identity Matrix	1	0	0	0	0	0	0	0	0	0	0	0
	0	1	0	0	0	0	0	0	0	0	0	0
	0	0	1	0	0	0	0	0	0	0	0	0
	0	0	0	1	0	0	0	0	0	0	0	0
	0	0	0	0	1	0	0	0	0	0	0	0
	0	0	0	0	0	1	0	0	0	0	0	0
	0	0	0	0	0	0	1	0	0	0	0	0
	0	0	0	0	0	0	0	1	0	0	0	0
	0	0	0	0	0	0	0	0	1	0	0	0
	0	0	0	0	0	0	0	0	0	1	0	0
	0	0	0	0	0	0	0	0	0	0	1	0
	0	0	0	0	0	0	0	0	0	0	0	1

Next is to calculate Matrix (I-X) values as showing in Table 4. It is basically, the subtraction of matrix of identity matrix and the matrix X.

Table 6: Matrix (I-X)

Critically	1	-0.0962	-0.0385	-0.0769	-0.0385	-0.0962	-0.0769	-0.0577	-0.0577	-0.0769	-0.0962	-0.0385
Specificity	-0.0577	1	-0.0769	-0.0577	-0.0577	-0.0962	-0.0385	-0.0577	-0.0192	-0.0769	-0.0577	-0.0192
Predictability	-0.0385	-0.0577	1	-0.0769	-0.0577	-0.0962	-0.0769	-0.0962	-0.0385	-0.0385	-0.0769	-0.0577
Maintainability	-0.0577	-0.0385	-0.0769	1	-0.0577	-0.0769	-0.0577	-0.0577	-0.0577	-0.0577	-0.0385	-0.0385
Inventory cost	-0.0192	-0.0192	-0.0769	-0.0385	1	-0.0385	-0.0577	-0.0385	-0.0769	-0.0385	-0.0577	-0.0577
Availability of the market	-0.0192	-0.0385	-0.0385	-0.0577	-0.0385	1	-0.0769	-0.0577	-0.0577	-0.0577	-0.0385	-0.0385
Order lead time	-0.0962	-0.0769	-0.0962	-0.0962	-0.0769	-0.0962	1	-0.0962	-0.0769	-0.0962	-0.0962	-0.0962
Price	-0.0385	-0.0577	-0.0769	-0.0769	-0.0962	-0.0769	-0.0962	1	-0.0962	-0.0577	-0.0962	-0.0769
Volume of the spare part	-0.0385	-0.0192	-0.0385	-0.0385	-0.0769	-0.0385	-0.0385	-0.0385	1	-0.0385	-0.0385	-0.0577
Quality	-0.0962	-0.0962	-0.0769	-0.0962	-0.0962	-0.0769	-0.0577	-0.0962	-0.0962	1	-0.0962	-0.0962
Severity of its failure	-0.0577	-0.0769	-0.0385	-0.0769	-0.0962	-0.0769	-0.0962	-0.0385	-0.0769	-0.0577	1	-0.0962
Availability of support	-0.0192	-0.0385	-0.0192	-0.0577	-0.0385	-0.0769	-0.0769	-0.0385	-0.0385	-0.1346	-0.0385	1

(I-X) the inverse of matrix is in the Table 8.

Table 7: Inverse of Matrix (I-X)

Critically	1.1188	0.2213	0.1786	0.2316	0.1943	0.2667	0.2307	0.1988	0.2036	0.2262	0.2423	0.1822
Specificity	0.1512	1.1098	0.1893	0.1876	0.1838	0.2365	0.1707	0.1759	0.1444	0.1973	0.1833	0.1399
Predictability	0.1465	0.1772	1.1338	0.2225	0.2026	0.2564	0.2243	0.2250	0.1793	0.1838	0.2168	0.1923
Maintainability	0.1495	0.1441	0.1874	1.1307	0.1822	0.2167	0.1856	0.1740	0.1773	0.1797	0.1641	0.1562
Inventory cost	0.0996	0.1086	0.1683	0.1471	1.1091	0.1588	0.1652	0.1372	0.1754	0.1437	0.1602	0.1572
Availability of the market	0.1042	0.1297	0.1390	0.1684	0.1498	1.1256	0.1846	0.1582	0.1620	0.1645	0.1471	0.1422
Order lead time	0.2398	0.2424	0.2704	0.2960	0.2744	0.3192	1.2086	0.2760	0.2658	0.2899	0.2888	0.2774
Price	0.1646	0.1956	0.2262	0.2454	0.2611	0.2642	0.2636	1.1574	0.2532	0.2238	0.2560	0.2329
Volume of the spare part	0.1070	0.0982	0.1230	0.1338	0.1674	0.1442	0.1353	0.1245	1.0924	0.1322	0.1310	0.1444
Quality	0.2333	0.2516	0.2470	0.2869	0.2842	0.2932	0.2550	0.2672	0.2752	1.1942	0.2807	0.2695
Severity of its failure	0.1733	0.2032	0.1811	0.2329	0.2469	0.2514	0.2500	0.1834	0.2233	0.2151	1.1552	0.2367
Availability of support	0.1176	0.1444	0.1349	0.1847	0.1647	0.2138	0.1988	0.1560	0.1602	0.2490	0.1621	1.1198

Total Relationship Matrix T is obtained by applying the Equation (6). Ri (sum of the rows) and Ci (sum of the columns) are also presented as shown in Table 9.

$$T = X * (I - X)^{-1} \ (Equation\ 6)$$

Table 8: Relationship Matrix T

Relationship Matrix T= X*inv(I-X)												
Critically	-0.03957	0.059911	-0.00592	0.030325	-0.01146	0.045488	0.031805	0.014793	0.013683	0.032914	0.054734	-0.00629
Specificity	0.030695	-0.03624	0.044749	0.017751	0.02034	0.055843	-0.0037	0.02108	-0.02145	0.044749	0.018861	-0.01886
Predictability	0.005917	0.022189	-0.04327	0.033654	0.013314	0.049186	0.031805	0.060651	-0.00629	-0.00777	0.035873	0.017012
Maintainability	0.031435	0.005547	0.045488	-0.04216	0.02071	0.035503	0.018861	0.02182	0.02182	0.022189	-0.00185	0.002219
Inventory cost	-0.00592	-0.00851	0.052515	0.004808	-0.0355	0.001109	0.025518	0.007766	0.049556	0.006287	0.027737	0.026997
Availability of the market	-0.00888	0.011095	0.006657	0.024778	0.003328	-0.03957	0.047707	0.027737	0.026627	0.026627	0.004808	0.005917
Order lead time	0.055843	0.025888	0.046228	0.035873	0.016642	0.027367	-0.06953	0.043269	0.019601	0.038092	0.038092	0.043269
Price	-0.00111	0.016642	0.032175	0.026257	0.046967	0.01997	0.046967	-0.05067	0.050296	0.005917	0.050296	0.028846
Volume of the spare part	0.019231	-0.00518	0.012944	0.009615	0.052145	0.006287	0.008136	0.012944	-0.02996	0.009246	0.009985	0.032175
Quality	0.058432	0.051036	0.025888	0.039571	0.039941	0.008506	-0.00592	0.047337	0.043639	-0.06472	0.04105	0.046228
Severity of its failure	0.022929	0.04105	-0.0074	0.030695	0.053624	0.023669	0.052515	-0.00703	0.034024	0.005917	-0.04956	0.056583
Availability of support	-0.01479	0.004808	-0.01849	0.018861	-0.00111	0.038462	0.044379	0.00074	-0.00037	0.106879	0	-0.0392

Table 9: Sum of the all the rows and all the columns

Relationship Matrix T= X*inv(I-X)													Ri
Critically	-0.03957	0.059911	-0.00592	0.030325	-0.01146	0.045488	0.031805	0.014793	0.013683	0.032914	0.054734	-0.00629	0.220414
Specificity	0.030695	-0.03624	0.044749	0.017751	0.02034	0.055843	-0.0037	0.02108	-0.02145	0.044749	0.018861	-0.01886	0.173817
Predictability	0.005917	0.022189	-0.04327	0.033654	0.013314	0.049186	0.031805	0.060651	-0.00629	-0.00777	0.035873	0.017012	0.212278
Maintainability	0.031435	0.005547	0.045488	-0.04216	0.02071	0.035503	0.018861	0.02182	0.02182	0.022189	-0.00185	0.002219	0.181583
Inventory cost	-0.00592	-0.00851	0.052515	0.004808	-0.0355	0.001109	0.025518	0.007766	0.049556	0.006287	0.027737	0.026997	0.152367
Availability of the market	-0.00888	0.011095	0.006657	0.024778	0.003328	-0.03957	0.047707	0.027737	0.026627	0.026627	0.004808	0.005917	0.136834
Order lead time	0.055843	0.025888	0.046228	0.035873	0.016642	0.027367	-0.06953	0.043269	0.019601	0.038092	0.038092	0.043269	0.320636
Price	-0.00111	0.016642	0.032175	0.026257	0.046967	0.01997	0.046967	-0.05067	0.050296	0.005917	0.050296	0.028846	0.272559
Volume of the spare part	0.019231	-0.00518	0.012944	0.009615	0.052145	0.006287	0.008136	0.012944	-0.02996	0.009246	0.009985	0.032175	0.137574
Quality	0.058432	0.051036	0.025888	0.039571	0.039941	0.008506	-0.00592	0.047337	0.043639	-0.06472	0.04105	0.046228	0.330991
Severity of its failure	0.022929	0.04105	-0.0074	0.030695	0.053624	0.023669	0.052515	-0.00703	0.034024	0.005917	-0.04956	0.056583	0.257027
Availability of support	-0.01479	0.004808	-0.01849	0.018861	-0.00111	0.038462	0.044379	0.00074	-0.00037	0.106879	0	-0.0392	0.140163
Ci	0.154216	0.18824	0.191568	0.23003	0.218935	0.27182	0.22855	0.200444	0.201183	0.226331	0.23003	0.194896	2.536243

- Step 5: **Develop a causal diagram**

Table 10 shows the two groups: cause group and effect group. The term “Ri + Ci” is measures the importance of the factor and the strength of the influence on and by the factor on another.

Positive “Ri – Ci” is means the factor influences other factors than it is influenced by them, then it belongs to the cause groups.

Negative “Ri - Ci” means the factors is influenced by others that it influences itself, thus the factor belongs to the “Effect group”.

The values of “Ri - Ci” in Table 10 are positives for A, C, G, H, J and K. The values demonstrate that these are in “Cause” group.

Dataset “Ri - Ci” and “Ri + Ci” are shown in Table 10 and the causal diagram is plotted as in Figure 13.

In Figure 13 and Table 10, the highest position indicator value “Ri + Ci” is obtained by Quality (J), which meant it has the strongest association with other criteria. Quality is the most critical criterion with the highest value of 0.56. The following criteria follows the Quality in the ranking: Order lead time (G), Severity of the failure (K) and Price (H).

The lowest position value is the availability of the support (L). “Ri – Ci” is the parameter used to know the influence of the criteria on all the others. Quality (J) with the highest positive value (0.10), has a dominating influence on other perspectives.

The highest negative value on the relation indicator is obtained by Availability of the market (F), it means that it receives the biggest influence from the other criteria.

Table 10: Cause & Effect group of the factors

		Ri	Ci	Ri+Ci	Ri-Ci	Identity
Critically	A	0.22	0.15	0.37	0.07	Cause
Specificity	B	0.17	0.19	0.36	-0.02	Effect
Predictability	C	0.21	0.19	0.40	0.02	Cause
Maintainability	D	0.18	0.23	0.41	-0.05	Effect
Inventory cost	E	0.15	0.22	0.37	-0.07	Effect
Availability of the market	F	0.14	0.27	0.41	-0.13	Effect
Order lead time	G	0.32	0.23	0.55	0.09	Cause
Price	H	0.27	0.2	0.47	0.07	Cause
Volume of the spare part	I	0.14	0.2	0.34	-0.06	Effect
Quality	J	0.33	0.23	0.56	0.10	Cause
Severity of its failure	K	0.26	0.23	0.49	0.03	Cause
Availability of support	L	0.14	0.19	0.33	-0.05	Effect

The cause cluster includes A, C, G, H, J and K. The effect cluster is composed of B, D, E, F, I and L.

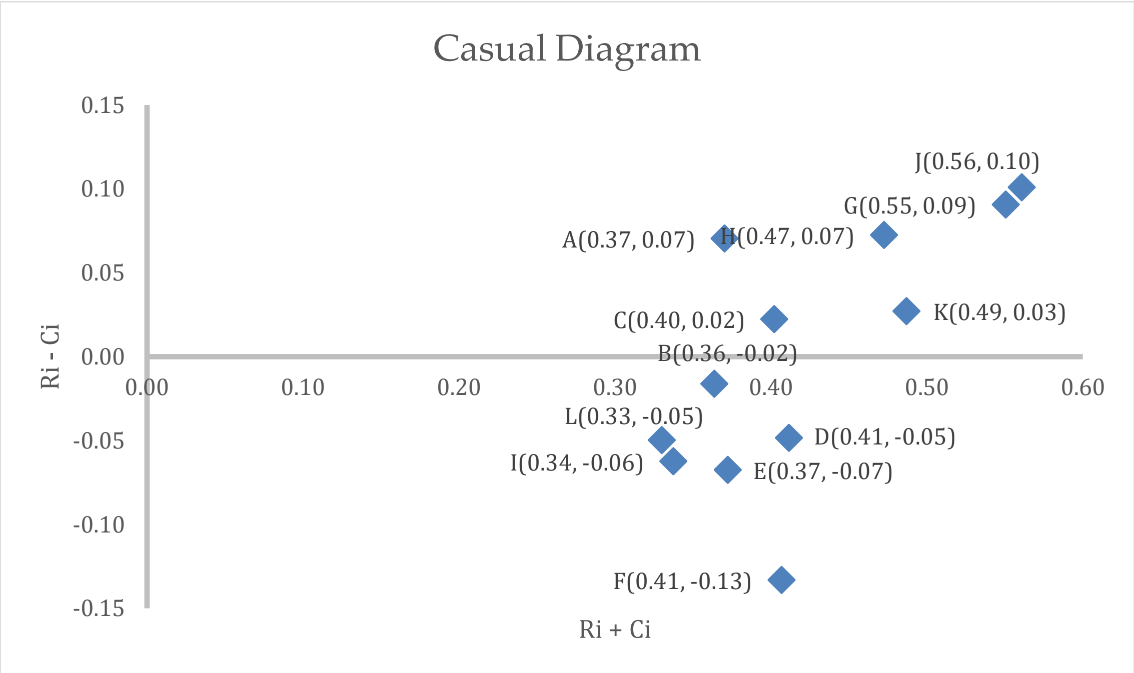

Figure 12:Casual Diagram of the factors

The values in bold are those above the threshold as shown in Table 11.

Table 11: T- Matrix

	Critically	Specificity	Predictability	Maintainability	Inventory cost	Availability of the market	Order lead time	Price	Volume of the spare part	Quality	Severity of its failure	Availability of support
Critically	-0.040	0.060	-0.006	0.030	-0.011	0.045	0.032	0.015	0.014	0.033	0.055	-0.006
Specificity	0.031	-0.036	0.045	0.018	0.020	0.056	-0.004	0.021	-0.021	0.045	0.019	-0.019
Predictability	0.006	0.022	-0.043	0.034	0.013	0.049	0.032	0.061	-0.006	-0.008	0.036	0.017
Maintainability	0.031	0.006	0.045	-0.042	0.021	0.036	0.019	0.022	0.022	0.022	-0.002	0.002
Inventory cost	-0.006	-0.009	0.053	0.005	-0.036	0.001	0.026	0.008	0.050	0.006	0.028	0.027
Availability of the market	-0.009	0.011	0.007	0.025	0.003	-0.040	0.048	0.028	0.027	0.027	0.005	0.006
Order lead time	0.056	0.026	0.046	0.036	0.017	0.027	-0.070	0.043	0.020	0.038	0.038	0.043
Price	-0.001	0.017	0.032	0.026	0.047	0.020	0.047	-0.051	0.050	0.006	0.050	0.029
Volume of the spare part	0.019	-0.005	0.013	0.010	0.052	0.006	0.008	0.013	-0.030	0.009	0.010	0.032
Quality	0.058	0.051	0.026	0.040	0.040	0.009	-0.006	0.047	0.044	-0.065	0.041	0.046
Severity of its failure	0.023	0.041	-0.007	0.031	0.054	0.024	0.053	-0.007	0.034	0.006	-0.050	0.057
Availability of support	-0.015	0.005	-0.018	0.019	-0.001	0.038	0.044	0.001	0.000	0.107	0.000	-0.039

Threshold alpha Value 0.0176

Below is relationship mapping diagram.

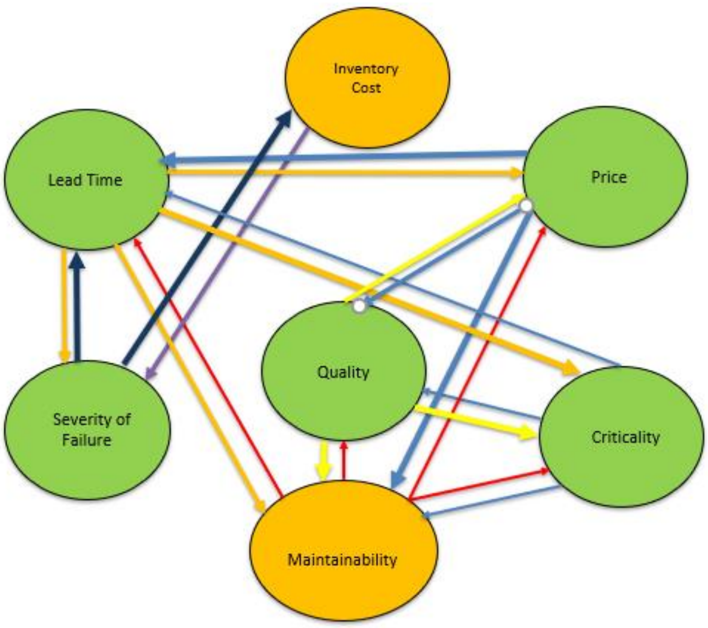

Figure 13: Cause-effect relationship diagram

From the figure, some criteria affect each other's. Quality, Price and Lead time have huge impact on other criteria.

Quality has huge impact on the Maintainability and the Criticality. A better quality can lead to a better maintainability of the spare part. The Quality and Price affects each other. Even though the Price does not guarantee quality. Severity of the failure may affect the Inventory costs, because when the Severity is high, the downtime might be longer if the spare part is not available for maintenance, thus it is important to have the spare available in the warehouse.

Lead time is an important factor that affects the Price. This factor needs to have a special attention when the critical spare part is not available or kept in the warehouse or when the spare part needs to be ordered abroad, or in different continent than the power plant. In developing countries, lead time might be longer, and make the downtime longer, thus huge loss.

5.9 Study Limitation

Limitation of the thesis is related to the amount of the data collected, the number of the respondents. The findings can be used globally but it is done with a low sample, the error rate should be considered. The survey encounters probably the lack of cooperation from respondents as the study was not directly done from their companies.

6. FINDINGS

The human, economic, equipment and tools, management and environment factors have important impact on the maintenance in general and the availability of the WtE plant.

Maintenance should be part of the whole company or firm's strategies. Corrective maintenance (CM) cannot be avoided totally handled and thinking about other alternative maintenance strategies could reduce repetitive failures. Preventive maintenance (PM) is the best way to ensure better availability for the plant and besides that, a Reliability Centered Maintenance (RCM) can be in place for a better planning and schedule of the maintenance. As this maintenance relies on the history data of the plant, system or device, it might be difficult to achieve for new established plant. In this case, an alternative can be the Condition Based Maintenance (CBM).

Without a proper planning and scheduling, and good operation procedures, there will be many interruptions of the production due to failures.

Good maintenance policies need to be elaborated, and it should be part of management responsibility to make it followed by all the stakeholders. It can only be effective by taking actions, and by knowing all the required tools and methods required for the maintenance in advance (Basri et al., 2014). It is important that all the actions of preventive maintenance are done in proven, proper, normalized and standardized way.

It is important to provide good guidelines and better understanding of the policies to those involved in the maintenance chain; this improves the quality of the maintenance.

The selection of the KPI (Key performance indicators) is one of the success factors, because it provides the level of current performance, it helps to set the desired performance. Thus, it helps identifying the needed actions for performance improvement.

The maintenance strategy will be only effective and efficient if the human factors are taken into account. Human error is a failure to execute a task. It can lead to the damage of plant items, equipment or disruption of operations. Human error can occur, due to different reasons; insufficient skill, training of the manpower involved, inadequate lighting in the work area, improper maintenance tools, high noise levels and poorly written operating and equipment maintenance procedures (Dhillon and Liu, 2006).

From the survey, it can be seen clearly that the employee skills and competences impact the availability of the plant. An employee / operator with the needed skills, operates the system the system well. Communication and Teamwork are two keys factors to ensure better availability of the plant. A continuous improvement can only be achieved with an effective employee, engineer involvement. Employee involvement also impact the quality of the of plant and it is a solutions enabler. Hence, it indeed creates a climate of confidence and trust in the company. Employee involvement is a good factor to consider for a continuous improvement. It goes as well for the maintenance engineers. Roles and responsibilities need to be defined for all the maintenance actors.

In any organization, training and education should have special attention (John & Amrik, 1989).

Performance effectiveness and efficiency can be achieved by selection the right man power, personnel, labor with needed capabilities, and by having a clear and better policies that each person can understand, apply and follow. Health, safety and environment should be should also be considered; safety protocols and guidelines should be elaborated for workers for emergency and crisis management.

A committed management is required, and it is a the key driver of the performance. The factor highly affect the plant availability and it shows the management involvement in setting the direction of the maintenance and the culture about the maintenance, and in the innovation changes.

It is important to analyze the capital cost and the benefit to the organization, all the costs should be included; the logistics costs, spare part costs, cost for repair and replacement, tools and equipment costs, as well as the labor costs. It includes the cost of downtime as well.

The deterioration of the plant system and the high costs of the maintenance can be reduced by identifying and implementing a proper maintenance policy. It also maintains stable production capabilities.

The maintenance policy should include a proper and effective maintenance planning and scheduling. Unscheduled maintenance can be costly and make the downtime longer if the issue cannot be solved immediately (Papakostas et al., 2010).

The maintenance costs can be reduced by improving the scheduled maintenance. For a successful implementation of the maintenance policy, decision-making tools and methodologies are required. The decision-making tools and methodologies are supportive tools that help identifying the maintenance items and their related consequences (reliability and risk management), but also the right timing to perform the maintenance.

Without these supportive tools and methodologies, the decisions are suggestive, experiences-based and even conservative, and this leads to unnecessary actions and maintenances, and it does not enable innovative working environment.

Maintenance task can be improved by reporting regularly the tasks related to maintenance but also any status related to the items, systems and machines.

The report tracks the record and monitor the progress of maintenance program. It should be done for each maintenance task.

Machine record keeping, historical data are essential or effective maintenance. Data management is an enabler for a better decision-making. Nowadays, the best way is to use a Computerized Maintenance Management System (CMMS), because it improves the reliability of the item by continuously tracking the maintenance assets. When digitalization is involved, cyber security needs to get a special attention to tackle security related issues.

Outsourcing is a good way to gain flexibility by outsourcing the non-core activities; though a better us of internal resources. The survey result confirmed this statement. It can be clearly seen that the companies outsource less of their spare part management since the spare part is vital for the availability of the plant, especially during the maintenance of the plant.

Figure 13 shows the cause-effect casual diagram, and, factors can be divided into two groups: cause and effect factors.

A special attention is required for the cause factors, because it helps identifying the critical factors.

In Figure 13, Quality (J) has the highest (Ri - Ci) value (0.10) amount all the factors in cause group, which ca be deduced that that Quality influences the availability of the plant. Furthermore, from influential impact point of view, Quality (J) has the highest Ri; meaning it has a notable impact among all the others.

Order Lead time (G), is ranks second place with the value 0.09. Order Lead time (G), has the second highest Ri (0.32). Therefore, it has the second important influence on the availability of the plant.

The third factor is Price (H) since its Ri - Ci value ranks third place (0.07). In other hand, apparently, it has the third rank when comparing the influential impact.

Criticality (A) is the fourth factor as the value Ri – Ci is 0.07. Even though it is fifth from Ri value, its impact cannot be ignored.

Severity of its failure (K) and Predictability (C) have reasonable impact on the availability of the plant their respective Ri -Ci values are 0.03 and 0.02. Severity of its failure (K) in other hand cannot be ignored as it has the fourth highest Ri value (0.26) from the influential impact degree point of view.

Effect factors are impacted and influenced by other factors, so ignoring these factors may impact negatively and lead to serious consequences. The analysis of these factors is critical for the selection of the spare part, thus the availability of the plant.

From the casual diagram, the highest Ri-Ci is for Maintainability (D). Moreover, its influenced impact index (Ci) and its degree of influential impact index (Ri) values are (0.23, 0.18) high among effect factors group. Its Ri – Ci is quite low. Therefore, Maintainability (D) significantly impact the other factors. Availability in the Market (F) and Inventory Cost (E) have second and third highest Ri + Ci values (respectively 0.41 and 0.37). However, the Ri – Ci value of Availability in the Market (F) is very low compared to other criteria. This means that It is affected easily by other criteria.

In the light of above findings, Quality (J), Order lead time (G), Price (H), Critically (A), Maintainability (D), Inventory cost (E), and Availability of the market (F) are critical criteria for selecting spare part to improve, and to enable the availability of WtE plant.

The findings correlate with the theoretical framework, review. The availability of the WtE plant depends a lot on the quality for the spares part. The better, the quality, smaller is the downtime. As suggested by Montanari, Braglia and Grassi (2004), the spare part impact the availability and required fast delivery (lead time).

The lead time is an important criterion as well. Especially in the case that some of the WtE plant operate in distant locations from main logistic centers. This needs a special attention for the plants located in developing countries for instance, because the lead time can be much longer as the supplier in the country might place order from a different continent because the spare part needed might not be available and take longer time based on country regulation and so on.

One objective of the maintenance is to reduce costs in general and spare part costs. But spare part price shouldn’t compromise the quality and the reliability of the spare part.

The critically and the maintainability are directly influenced by the quality of the spare part. The consequences of the breakdown of some spare part could lead to a longer downtime and the higher costs when quantified.

Critically of a part can be considered as the consequence caused by that part failure in case the replacement is not immediately available. There are different ways to measure or evaluate the critically of a part; it could be in term of cost of downtime which is sometime difficult to measure. However, one approach is to relate it to the time, for instance:

1- The spare part should be provided, and failure corrected immediately
2- Until the spare part is provided, failure for a short time of period be postponed or tolerated if possible.
3- Non-critical failure for the operations can be corrected and longer lead time for the spare part

The spare part needs to be categorized to know which ones are critically or special (specialized and unique parts) for the availability and reduce the costs. Usually, the generic spare parts supply is easy and there are many suppliers. The risks of non-supply is low and these are usually available. these spares are available the risk of non-supply is low. Unique and specialized and parts required a special because these usually have unique, single or limited number of suppliers and their lead time might be erratic.

A list of the maintainable spare part should be done to know which ones should be done at site, or at different location.

The mentioned criteria previously can never be effective if the reliability of the machinery is not considered. Replacing the old aged machinery is the best way to reduce the cost effectively, to keep the downtime to a minimum and to improve the reliability of the existing machines.

Outsourcing the spare parts can be one way to reduce inventory cost but it is advisable to outsource the key, unique, specialized spare parts because their availability can be problematic as such parts might not be available when needed. These could be store at site if possible. For those that could not be stored at site, having a centralized warehouse for those could be used by considering the lead time.

7. CONCLUSION

The thesis has two objectives; the first is to find the critical factors enabling high availability of WtE plant. The second is to research the best criteria while selecting spare part for WtE plant. The objectives were broken into different research questions.

The thesis discusses the concept of different maintenance strategies by researching different factors that affect the availability of the WtE plant; management, human, economical, procurement, equipment and tools, maintenance, environmental factors. It identified also the best criteria when selecting spare parts for the plant items.

Survey and theoretical review were used in the research. The literature review as theoretical framework shows that maintenance of WtE plant has not been researched that much even though maintenance in general is a known topic that got academic and researchers' attention.

The thesis explains different critical factors affecting the availability of the WtE plant and the existing maintenance strategies. The literature review and the survey results represent a solid understanding of the maintenance in general and especially WtE maintenance.

Based on the literature review, an interesting finding is that the corrective maintenance can never be avoided completely. But it is worth to reduce repetitive maintenance by adopting a good maintenance strategy. The best solution is to combine a preventive, conditional and corrective maintenance.

Total Productive Maintenance (TPM) could be used to enhance employee involvement, thus enable the availability of the WtE plant. Reliability Centered Maintenance (RCM), well-known systematic way to analyze and to improve the standard maintenance plans to prevent unexpected failures and to optimize asset availability, thus to improve the productivity of the plant. The key success of the RCM is to use real time monitoring, collecting data which will be processed and analyzed to track the performance of the asset, equipment.

Based on the survey answers, it can be clearly seen that different factors impact the availability of WtE plant, human factors, which are the skills, competencies, training, communication; economic factors, which are referred to costs (indirect and direct) involved in maintenance; Management roles and factors impact the effectively of the maintenance; management involvement and commitment. The spare part factors have an important impact on the maintenance and the availability of the plant.

DEMATEL method is used to provide a smart and systematic decision-making approach for spare part selection by grouping them into effect and cause groups. The method helps enabling and coping with vague and imprecise judgement in decision-making. Key criteria are identified and the link between them has been associated with a visual diagram.

DEMATEL method is chosen over the other methods for the pragmatic methodology used to construct and analyze the structural model involving causal relationship between multiple factors. It also integrates different expert knowledge that helps to investigate internal relationship and significance degrees of all the chosen factors. One advantage is that it can present a derived relationship through a cause-effect diagram. Critical factors through a visual structural model can be found, as well as the interdependent relationship amount factors are identified and evaluated while using DEMTEL.

Key findings of the thesis revealed that human, economic, equipment and tools, management and environment factors have important impact of the effectiveness of the maintenance and the availability of the WtE plant, whatever the maintenance strategies from preventive to corrective maintenance through the condition maintenance. Quality, Lead time, Price and severity of spare part failure are keys criteria to consider while selecting spare part for WtE plant.

Limitation of the thesis is related to the amount of the data collected. Qualitative and quantitative data collected from experienced WtE engineers have been used in this thesis. The sample was 20 from a population of 150 WtE professionals from different continents.

It would be interesting to do further research of the topic by using data from different plants operated by the case company, to make the research more objective. This will help the case company knowing real issues their plants face. It could be interesting to do further research by focusing for instance on different locations and population because different climatic and environment factors may influence the failure rate of the plants items; dust, humidity, cultural factors.

Plant item, part that requires more maintenance or attention, or parts that often fail in the plants designed by the case company could be an interesting subject for further research. That way, a proper and more objective maintenance programs, strategies can be implemented.

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APPENDICES

Appendix 1: Interview Questions

Waste-to-Energy Plant (WtE)

OPTIMAL MAINTENANCE PROGRAM

Hello,

I am Alassani Fousseni Igodo, Master's Degree student in Industrial Systems Analytics at University of Vaasa.

Currently I am working on my final thesis on the topic:

''OPTIMAL WtE PLANT MAINTENANCE PROGRAM''.

The aim of the study is to develop optimal plant lifetime maintenance program for a modular waste-to-energy power plant. The objectives of the paper are to identify the critical factors that enable high availability of the WtE plant, to identify the best criteria for the spare part selection.

By answering the questions below, it would help to improve the availability of the WtE plant and, to reduce the costs of the maintenance and mitigate the risks related to maintenance, thus it will improve customer satisfaction and the quality of the service provided in many sites.

Please answer the questions below.

1.Personal information (Not compulsory)

First name & Last name	
Email	
Company	
City	
Country	
Position / Role	

A- Waste-to-Energy Plant Lifecycle Availability

2. Please on the scale of 1 to 6, rate the factors (by importance) affecting WtE plant life cycle availability.

	No opinion	Does not affect	Slightly affect	Affect	Strongly affect	Extremely affect
Operator skills	☐	☐	☐	☐	☐	☐
Maintenance personal skills and competency	☐	☐	☐	☐	☐	☐
Operator competency	☐	☐	☐	☐	☐	☐
Communication	☐	☐	☐	☐	☐	☐
Training	☐	☐	☐	☐	☐	☐
Teamwork	☐	☐	☐	☐	☐	☐
Employees involvement and participation	☐	☐	☐	☐	☐	☐
Commitment of employee	☐	☐	☐	☐	☐	☐

3. Economic Factors

	No opinion	Does not affect	Slightly affect	Affect	Strongly affect	Extremely affect
Spare parts life cycle cost	☐	☐	☐	☐	☐	☐
Maintenance equipment cost	☐	☐	☐	☐	☐	☐
Maintenance direct cost	☐	☐	☐	☐	☐	☐
Maintenance indirect cost	☐	☐	☐	☐	☐	☐

4. Management Factors

	No opinion	Does not affect	Slightly affect	Affect	Strongly affect	Extremely affect
Commitment of top management	☐	☐	☐	☐	☐	☐
Commitment of middle management	☐	☐	☐	☐	☐	☐
Commitment for resources	☐	☐	☐	☐	☐	☐
Organization culture (open to change or not)	☐	☐	☐	☐	☐	☐
Process quality management	☐	☐	☐	☐	☐	☐
Functions Integration (production-purchasing, procurement, maintenance, work in conjunction (communication)	☐	☐	☐	☐	☐	☐

5. Procurement Factors

	No opinion	Does not affect	Slightly affect	Affect	Strongly affect	Extremely affect
Spare parts availability	☐	☐	☐	☐	☐	☐
Spare parts quality and functionality	☐	☐	☐	☐	☐	☐
Spare parts lead time	☐	☐	☐	☐	☐	☐
Spare parts reliability	☐	☐	☐	☐	☐	☐
Inventory control	☐	☐	☐	☐	☐	☐
Spare parts cost	☐	☐	☐	☐	☐	☐
Maintenance inventory	☐	☐	☐	☐	☐	☐
Safety stock	☐	☐	☐	☐	☐	☐
Material control	☐	☐	☐	☐	☐	☐

6. Maintenance Factors

	No opinion	Does not affect	Slightly affect	Affect	Strongly affect	Extremely affect
Maintenance planning	☐	☐	☐	☐	☐	☐
Maintenance scheduling	☐	☐	☐	☐	☐	☐
Human resources	☐	☐	☐	☐	☐	☐
Material and asset resources	☐	☐	☐	☐	☐	☐
Maintenance tools and equipment	☐	☐	☐	☐	☐	☐
Communication with other functions	☐	☐	☐	☐	☐	☐
Operating procedures and practices	☐	☐	☐	☐	☐	☐
Frequency of the failures (MTBF)	☐	☐	☐	☐	☐	☐
Mean time to repair (MTTR)	☐	☐	☐	☐	☐	☐
Degree of severity of the failure	☐	☐	☐	☐	☐	☐
Maintenance policy	☐	☐	☐	☐	☐	☐
Lack of maintenance management system	☐	☐	☐	☐	☐	☐
Asset maintainability	☐	☐	☐	☐	☐	☐

	No opinion	Does not affect	Slightly affect	Affect	Strongly affect	Extremely affect
Tools and support equipment	☐	☐	☐	☐	☐	☐

7. Environmental Factors

	No opinion	Does not affect	Slightly affect	Affect	Strongly affect	Extremely affect
Temperature	☐	☐	☐	☐	☐	☐
Humidity	☐	☐	☐	☐	☐	☐
Noise level	☐	☐	☐	☐	☐	☐
Dust	☐	☐	☐	☐	☐	☐
Corrosion	☐	☐	☐	☐	☐	☐
Regulatory compliance	☐	☐	☐	☐	☐	☐

8. Information System

	No opinion	Does not affect	Slightly affect	Affect	Strongly affect	Extremely affect
Lack of CMMS	☐	☐	☐	☐	☐	☐
Lack of historical data	☐	☐	☐	☐	☐	☐
Condition monitoring technologies	☐	☐	☐	☐	☐	☐

B. Maintenance Planning & Scheduling

9. What are the issues when planning and scheduling simple failures or critical failures?

____

____

____

____

____

10. Does previous (historical) maintenance information availability and sharing, affect the effectiveness of the maintenance?

C. Spare Part Selection Criteria

11. What are the best criteria for spare part selecting? Please list, if missing.

	No opinion	Not at all important	Slightly Important	Important	Very Important	Extremely Important
Critically	◯	◯	◯	◯	◯	◯
Specificity	◯	◯	◯	◯	◯	◯
Predictability	◯	◯	◯	◯	◯	◯
Maintainability	◯	◯	◯	◯	◯	◯
Inventory cost	◯	◯	◯	◯	◯	◯
Availability of the market	◯	◯	◯	◯	◯	◯
Order lead time	◯	◯	◯	◯	◯	◯
Price	◯	◯	◯	◯	◯	◯
Volume of the spare part	◯	◯	◯	◯	◯	◯
Availability of support	◯	◯	◯	◯	◯	◯
Availability of the spare part information	◯	◯	◯	◯	◯	◯
Severity of its failure	◯	◯	◯	◯	◯	◯
Quality	◯	◯	◯	◯	◯	◯
	◯	◯	◯	◯	◯	◯
	◯	◯	◯	◯	◯	◯
	◯	◯	◯	◯	◯	◯
	◯	◯	◯	◯	◯	◯

12. How do you deal with critical spare parts supply chain? Do you store them always on site?

D- Outsourced Maintenance

13. What are the main issues when outsourcing the maintenance?

14. What is the level of outsourcing?

	Yes	No
Outsourcing the whole maintenance function (full covered service: labor, parts, materials and emergency service)	○	○
Outsourcing of the work done during the scheduled outages or shutdown	○	○
Outsourcing of special skills	○	○
Outsourcing of system function or equipment	○	○
Outsourcing of spare part store	○	○
Outsourcing of full labor	○	○
Outsourcing Inspection service	○	○

15. Are outsourced personnel hired when needed or are they only on demand?

E- Operators, Maintenance Documentation

16. During Maintenances what are the most common causes for issues:

	Yes	No
Unclear work scope	◯	◯
Unskilled personnel	◯	◯
Bad Planning and scheduling	◯	◯
Inadequate documentation or manuals	◯	◯
Contractual issues	◯	◯
Available tools	◯	◯
Lack of spare parts	◯	◯

17. Is HSE (Health, safety and environment) considered in the maintenance program?

18. Free Text / Suggestion