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ORIGINAL PAPER

Optimal maintenance for a waste-to-energy plant using DEMATEL: a case study

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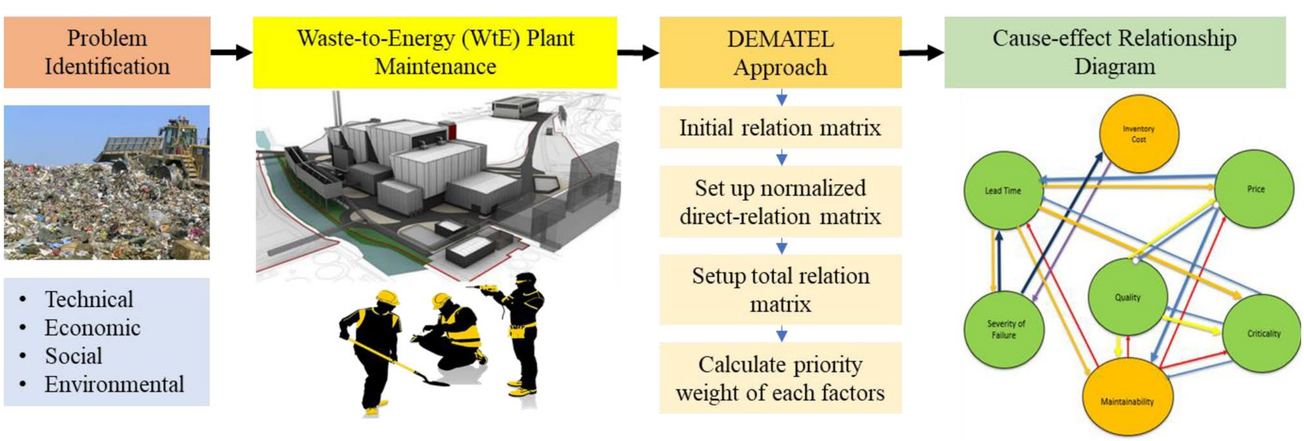
Abstract

Waste-to-energy (WtE) plants are complex systems that requiring different types of maintenance to be reliable and available in functionality. The inadequacies of WtE plant lifetime maintenance may increase the production costs and negatively affect the competitiveness and the availability of WtE plants. To keep the efficiency of all the plant systems high and operating as expected during their lifetime, it is important to maintain them. This study focuses on the maintenance of WtE plants by analyzing the operating procedures at a case company. In the study, a multi-criterion decision-making method (MCDM) named Decision-Making Trial and Evaluation Laboratory (DEMATEL) is used to evaluate the weight and rank of twelve identified criteria for spare parts of the case WtE company. The empirical part of this study consists of a qualitative study, where data were collected from an open-ended questionnaire survey and case company data from existing documents. The respondents' rate from the questionnaire survey was 20%. Key findings from the study show that human, economic, equipment and tool related, management, and environmental factors have an important impact on the effectiveness of the maintenance and availability of the WtE plant. The study also shows that quality, lead time, price, and the severity of spare part failure are the key criteria to consider when selecting spare parts for the WtE plant. The study recommends several initiatives to improve the availability of WtE plant and spare parts which will help to reduce the costs of maintenance as well as mitigate the risks related to the maintenance.

Graphical Abstract



Keywords DEMATEL MCDM · Municipal solid waste (MSW) · Multi-criteria decision-making (MCDM) · Waste-to-energy (WtE) · Maintenance program · Corrective maintenance · Optimization · Maintenance strategy

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Introduction

In recent decades, the rapid growth of municipal solid waste (MSW) has endangered human health and the environment. The rapid growth is due to the increase in population, urbanization, and energy or resource consumption (Bello et al. 2022). By 2050, the total amount of MSW in the whole world is expected to be about 3.4 billion tons (Munir et al. 2021), but it varies from one country to another (Noufal et al. 2020). The management of a huge amount of waste is a challenge for our generation and future generations. Excessive use of fossil fuels causes serious issues for the environment (Farhang et al. 2021). The only viable way to minimize a large amount of material waste is by recycling or reusing it. All the materials cannot be recycled, and energy recovery is a suitable method to treat undesirable remains from recycling (Solheimslid et al. 2015). The energy recovery method helps in treating 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 municipal solid waste into energy. Conventional techniques such as composting and landfilling are generally used to manage MSW (Christensen et al. 2020). Common technologies such as biochemical conversion (composting, vermicomposting, anaerobic digestion/bio methanation), thermal conversion, and chemical conversions are also used to manage MSW (Kalyani and Pandey 2014). The thermal conversion method includes incineration, combustion (Escamilla-García et al. 2020), gasification (Prasertcharoensuk et al. 2019), pyrolysis (Kwon et al. 2019), and refuse-derived fuel (RDF) (Kalyani and Pandey 2014). Incineration is the most widely used technology for MSW treatment (Giro-Paloma et al. 2020; Afrane et al. 2021).

Waste-to-energy (WtE) incinerators are one of the important technologies used for MSW (Ali et al. 2021). Incineration is a waste treatment technique of burning organic waste and other components into heat, and the resulting heat from the process is converted into steam or electricity (Bandarra et al. 2021). There are three different incineration technologies: fluidized bed, moving grate, and rotary kiln. Moving grate is the most widely used technology (Xia et al. 2020). In Europe, waste incineration is often used due to the speed of the process, the significant amount of waste destruction, and its energy production potential (Setyan et al. 2017). Waste-to-energy solves many issues and problems such as waste management, greenhouse gas emissions, and energy consumption (Afrane et al. 2021). It is therefore essential to install globally as many WtE plants as possible to manage MSW successfully. A WtE plant is a complex system that requires different types of maintenance to be reliable and available in its full functionality.

Not only installing WtE plants, but also their proper maintenance is extremely important. Maintenance has a crucial impact on the performance, availability, and reliability of WtE plant. It is essential for regular maintenance of equipment and items in a power plant for it to run smoothly without any component failures and to improve overall efficiency, availability, and reliability. Due to technological limitations and costs, it is difficult if not impossible to design maintenance-free systems. To keep the efficiency of all the plant systems high and operating as expected during their lifetime, it is important to maintain them. Both extended periods of downtime for planned maintenance and unplanned outages because of the malfunctions of WtE plants result in a mix of lower revenue and greater expenses. At least a 90% level of plant availability is preferred (Fordham et al. 2003). Poor plant maintenance results in lower efficiency, which causes less amounts of energy to be recovered, as well as a higher rate of pollution due to unburnt wastes causing higher emissions into the environment.

Various factors affect the plant's performance, reliability, and ultimately energy output and efficiency. Some of the reasons are (i) poor plant design elements, (ii) selection of boiler material, (iii) composition of the waste, (iv) control of the combustion process, (v) flue gas compositions, (vi) repair method, and (vii) frequency and mode of plant cleaning. Such plant performance can be improved by adopting proper strategies such as (i) removing as much water content from the waste as possible by drying, (ii) separating and removing non-combustible components like glass, metal, and stones, (iii) avoiding the use of untreated waste, (iv) adopting eco-friendly WtE technologies, etc. Studies have shown that incineration can be used to reduce MSW by 80–90% which saves a substantial amount of land needed for trash disposal (Malav et al. 2020). Moreover, MSW can also be used as a renewable energy source to produce power by various WtE technologies.

Effective maintenance programs can ensure the use of WtE plants with a higher level of availability, which ultimately improves the efficiency of the plant and contributes toward maintaining environmental sustainability. Additionally, there is great potential to increase the availability and profitability of the plant by improving the operations and maintenance strategy (Jonge and Scarf 2020). However, several criteria or factors affect the proper maintenance ofWtE plants to ensure higher availability, and identification and prioritization of such factors contribute substantially to ensuring their optimum maintenance. Although in the literature various studies have focused on installing WtE power plants globally, little research has been carried out on maintaining them efficiently (Gholizadeh et al. 2021; Shahsavar et al. 2022). Considering this gap in the research and its potential b, this study identifies three research questions, which are as follows:

RQ 1: What are the critical factors that enable a high level of plant availability?

RQ 2: What are the best criteria when choosing maintenance-critical spare parts?

RQ 3: How can the WtE plant maintenance program be optimized?

The rest of the article is organized as follows: Relevant literature on MSW uses in WtE, the maintenance of WtE, various factors that influence WtE maintenance, and the importance of spare parts in maintenance are discussed in Sect. "Literature framework". Sect. "Study methodology" explains the study methodology, where justification for the use of DEMATEL and its concept and detailed methodology are elaborated, along with the data collection approach. Sect. "Description of the case company" describes the case company, while Sect. "Results analysis" focuses on data collection and analysis of the results and identifies the factors that affect the maintenance and thus the availability of the WtE plant. The DEMATEL method is also used in this section to ascertain the criteria for spare parts. Sect. "Study analysis and findings" presents the conclusions and findings of the study and future research directions.

Literature framework

WtE plants to manage MSW for environmental sustainability

According to a broad definition, MSW can be identified as a waste stream that includes recyclables, hazardous materials, and domestic and industrial trash (Mojtahedi et al. 2021). Rapid urbanization, population increase, global industrial and material transition, and an explosion in the production of municipal solid garbage are the major sources of MSW in recent decades (Shahsavar et al. 2021). Due to the rapid development of towns, the management of MSW is in crisis in many jurisdictions. It is often very difficult to dispose of MSW due to the complexity of the transportation network (Asefi and Lim, 2017), rising sensitivity to the costs of environmental impact (Fathollahi-Fard et al. 2019), the practical constraints that frequently govern where to locate processing facilities (Fathollahi-Fard et al. 2019), the origin of waste streams, recycling options, and the difficulties of transportation management (Wang et al. 2018).

Several studies have been conducted to manage such MSW in more sustainable and environment-friendly ways (Yong et al. 2019; Hoang and Fogarassy 2020). These studies have identified that it is possible to manage MSW through landfilling and incineration process through waste-to-energy (WtE) plants (Istrate et al. 2020; Tisi et al. 2023). These WtE technologies have the advantage of reducing the enormous amount of waste that would put in landfill and minimizing the negative environmental impact. Additionally, there are numerous uses for the energy generated by the waste-to-energy process. WTE technology can achieve higher reuse and recycling rates without compromising the ability to build synergies with the generation of energy and climate policy. In WtE, the amount of garbage to be burned with energy recovery is determined by a strategic analysis that considers several methods based on the amounts of unsorted waste, waste that is landfilled, and separately collected waste, respectively. As a result, a WTE plant's viability as a landfill substitute for a particular area is assessed (Cucchiella et al. 2017).

Maintenance and its implication in WtE plants

Maintenance is described as the combination of technical and related administrative responsibilities needed to maintain, keep, preserve, or restore anything to a state where it can perform its intended, expected function, (ISO 14224, 2006). At least four main critical points were underlined in the definition: maintenance (meaning the asset needs to be maintained), restoration (meaning to correct a default), intended function (meaning to represent the asset's full potential), and optimal cost. The purpose of maintenance is to guarantee asset or plant availability. Maintenance of the life cycle of any asset is crucial. The variety and nature of the equipment, assets, and goods have altered how maintenance has traditionally been carried out because the differing items require a variety of maintenance methods and approaches. The goal of maintenance is to guarantee that the assets, goods, and equipment will be readily available at a reasonable cost. According to Dhillon (2002), maintenance is the collection of procedures used to bring back a machine or component to the point where it can once again carry out its intended functions. The deficiencies of WTE plant lifetime maintenance may raise production expenses, which further harms the organization's competitiveness and raises all kinds of dangers, including lengthier downtimes and frequent failures.

In general, two types of maintenance are available, namely corrective maintenance or failure-based maintenance, and preventive maintenance or non-failure-based maintenance. When something breaks down or a fault is discovered and the asset needs to be repaired, failure-based maintenance, also known as corrective maintenance, is carried out. Preventive maintenance is a planned strategy that entails carrying out various tasks to prolong the life of equipment by reducing impairment and excessive depreciation. Figure 1

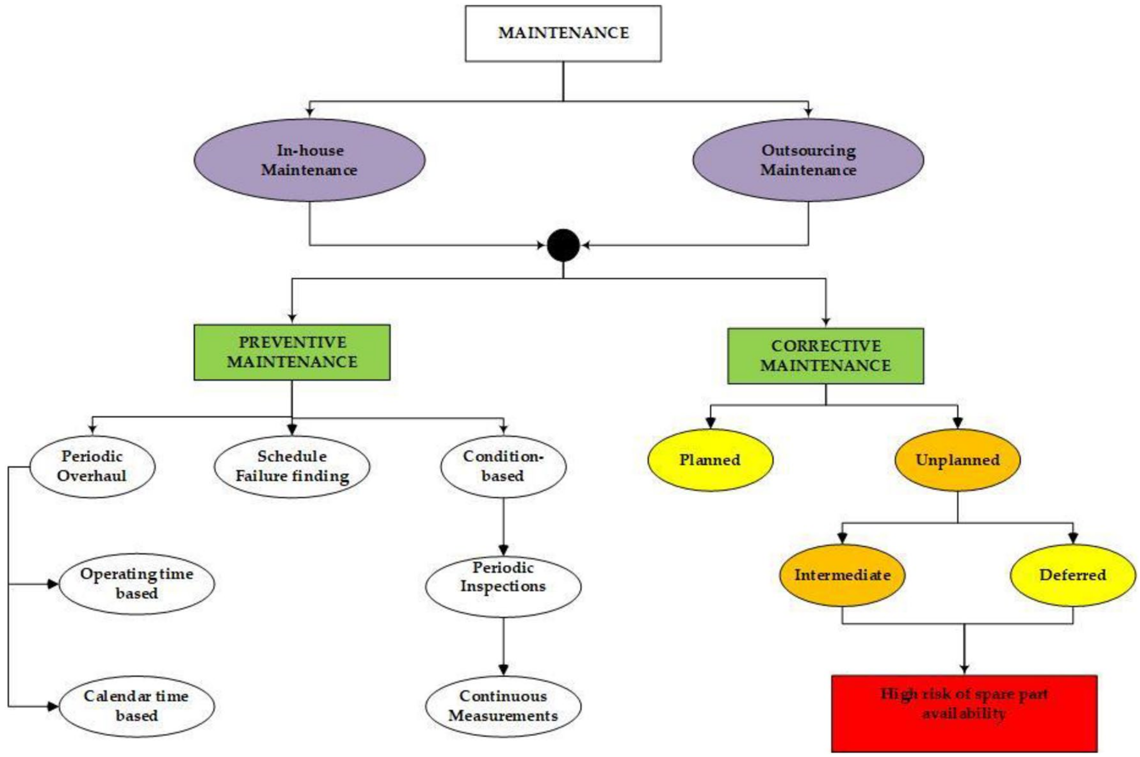


Fig. 1 Various types of commonly available maintenance

shows that maintenance can also be divided into in-house and outsourced maintenance. In-house maintenance refers to a situation where the maintenance operations are carried out inside the organizational premises, whereas transferring the internal activities and operations of a business or organization to an outside service provider is known as outsourcing maintenance (Handley 2008). Both preventative and corrective maintenance is also divided into several sub-types as also seen in Fig. 1. Figure 1 shows that preventive maintenance is subdivided into periodic overhaul, schedule failure finding, and condition-based maintenance, while corrective maintenance has planned and unplanned maintenance. Other sub-divisions of maintenance types are also visible in Fig. 1. In WtE plants, both preventive and corrective maintenance are employed, depending on the situation.

Various critical factors related to the availability of WtE plants

The ability of an asset to carry out its needed function within a predetermined window of time defined by the maker is known as availability (IEC, 1990, CEN, 2010). Availability is constantly correlated with maintainability, reliability, and upkeep (IEC, 1990, CEN, 2010). When an asset fulfills its intended purpose under a specific circumstance, it is called reliability (IEC, 1990), while an asset maintained under specified conditions, within a predetermined time frame, and using predetermined resources and methods, is known as maintainability (IEC, 1990). Factors affecting plant availability are those that contribute to efficient plant operations. These factors are essential for the plant's productivity. Different factors that have an impact on the plant's availability and reliability are presented in Table 1. Table 1 shows that there are five types of basic factors, namely human factors, management factors, equipment factors, financial factors, and logistics/supply chain factors, which influence plant availability.

Importance of spare parts for maintenance of WtE plants

Good spare part demand forecasting is necessary for a successful maintenance plan or management, and it also incorporates effective spare part demand inventory planning and control to prevent excessive spare part shortage and holding costs. The biggest challenge in maintenance and material management is managing spare parts. Previous studies have demonstrated that a lack of spare parts negatively affects maintenance management by lengthening outages and causing more downtime (Ali et al. 2010; Muniz et al. 2021). The productivity of the plant may be compromised, and supply times may lengthen if the asset or facility is unavailable. A

Table 1 Plant availability factors with necessary references

Factors	Sub-factors	Authors
Human	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)
	Teamwork	Hudson (2007)
	Technician behavior	Shaafstal, Schraagen, and van Berlo (2000)
Management	Human error management	Reason and Hobbs (2003)
	Communication, tasks	Konogiannis (1999), Larkin (1994)
	Communication, feedback system	Fitch & Sanders (1994)
	Leadership	Hackett and Spurgeon 1998
Equipment	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	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)
Logistics / Supply chain	Spare parts, ABC method	Uskonen, J. and Tenhiälä, A. (2012)
	MCDM	Ilangkumaran, M. and Kumanan, S. (2009),
	Spare parts	Willemain TR, et al. (2004)
	Spare parts inventory	Shahin and Gholami (2014)
	Availability & lead time	Braglia, Grassi, & Montanari (2004)
	Spare parts Management	Boylan (2010)
	Lead times	Dohi et al. (1998)
	DEMATEL	Tang HWV, (2018)

spare part is used either in preventative maintenance to keep an asset from going down or in corrective maintenance to replace a part. To prevent a scarcity of spare parts, it may be necessary for a company or organization to retain extra items or spare parts from Waste-to-Energy plant components (safety stocks) (Altay & Erdal 1998). The upkeep of inventory, maintenance, and repairs can account for up to 40% of an organization's procurement costs (Donnelly, 2013).

By maintaining high quality and safety standards,2001 spare parts management enhances and enables a better availability of spare parts at the right time, at the right location, in the right amount, at the right price, and at the lowest cost. Ineffectiveness results from the employment of normal inventory stock management techniques for maintenance spare parts inventory management, according to Huiskonen (), who states that the inventory of maintenance spare parts needs to be unique because typical inventory methods ignore the control features of the spares. In contrast to typical end products, which are more rapidly moving and have independent demand, spare parts are distinct. When an installed part or component fails or needs to be replaced in advance, spare parts are necessary (Fortuin & Martin, 1999). It is crucial to group spare parts according to how significant they are and to have good planning if you want to prevent spare part shortages. The classification of spare parts is a method for managing stock levels because it helps to identify the crucial components, whose absence could influence production.

The classification of spare parts helps organizations make decisions since it makes it possible to pinpoint the crucial component of the most valuable asset. Important items are those whose absence could have serious and adverse effects on the plant (Boylan and Syntetos 2010). Items with high holding costs and high demand could be considered crucial in inventory management. There are different types of spare parts, including qualitative (ABC), quantitative (DEMATEL), and combinations of the two (AHP). These models frequently rely on linear programming or dynamic programming, which are mathematical or qualitative concepts. Even if some models are widely used in sectors and are simple to apply, they do not take many features or criteria into account (Braglia et al. 2004, p. 55–56). By employing decision-making tools to support management, this study identifies and assesses important elements and criteria that might be used to ensure the plant's availability (choosing the best supplier, components, and so forth).

Identified research gaps

There are many studies related to the availability of equipment and different plant systems, but few studies have focused on waste-to-energy plants. The study of waste-to-energy plants has received attention from academics and researchers for many decades but they have focused mostly on the treatment of waste, different waste treatment methods, challenges, etc. However, there have been only a limited number of studies performed on the maintenance of WtE plants, which is considered to be a research gap and considered in this study. In addition, this study also identifies alack of proper investigation related to the importance of spare parts in the program of plant' maintenance, which is also taken into consideration in the present study. Moreover, various critical factors that foster the availability of waste-to-energy plants through proper and regular scheduled maintenance are also considered in this study.

Study methodology

This study adopts both a case study approach and a questionnaire survey, which are based on a qualitative study. The qualitative research approach is deductive, which is focused on collected data to prove and test a theory. In this research study, the necessary data were collected to test findings from the literature (Creswell 2014a, b). In the study, the primary source of data was collected by interviewing experts working in WtE, while secondary data were collected from the case company's documents/reports. Secondary data collection methodology was adopted because of the ease of data collection, simplicity of analysis, reliability of findings, and the ability to compare the findings of different researchers (Maxwell 2012).

Population and sample

The population of the study consisted of various professionals from WtE plants such as maintenance managers, professionals, service providers, and suppliers from all around the world. The study samples were selected using different social media sources such as LinkedIn, Google, and from different WtE companies' websites around the world. Random sampling was chosen to select the respondent groups. The developed survey questionnaires were sent to 100 various professionals in WtE plants globally through emails. Due to the pandemic situation and busy schedule of the professionals, the responses were come out in low number. In total, 25 respondents answered the questionnaire, of which of 5 were not considered, due to the fact that those respondents were not WtE professionals based on the background study. Therefore, a valid sample of 20 respondents was considered, which constitutes a response rate of 20% of the target population, which is an acceptable number for the case study sample. The 20 respondents consisted of 3 maintenance planners, 4 service engineers, 4 technicians, 3 supervisors, 2 spare part suppliers, and 4 maintenance managers, as presented in Table 2. Table 2 also shows the background of the interviewees and their experience in the field in terms of years.

Data collection method

There are different ways of collecting or gathering empirical data such as case studies, surveys, and experiments. In this study, data were collected by survey. A survey is one of the practical means of reaching out to respondents for research. A questionnaire was constructed in English using the Webropol 3.0 online survey platform, and is presented in Appendix 1. The results were transferred from Webropol to

Table 2 Interviewees' background

Title/position	Number of respondents	Average years of experience
Maintenance planners	3	8
Service engineers	4	7
Technicians	4	8
Supervisors	3	9
Spare part suppliers	2	9
Maintenance managers	4	10

Microsoft Excel for quantitative analysis. Some of the questions were multi-indicators, item scales that were measured using an unbalanced? six-point Likert scale. A six-point Likert scale is suitable for subjective statement measurement, to measure the internal feeling about a statement.

The scale range is as follows: "1: No opinion," "2: Does not affect," "3: Slightly affects," "4: Affects," "5: Strongly affects," and "6: Extremely affects." The questionnaire was the same for all the respondents. There were 13 multiple-choice questions and 4 s open-comment questions.

Analysis of the implementation

The background information of the respondents was first covered to verify whether all the respondents fulfilled the requirements. The respondents were then classified into different groups: spare part supply provider, maintenance manager, maintenance planning and schedule manager, maintenance project manager, and maintenance technician group. Six of the respondents were excluded because they did not fulfill the requirements and criteria. Figure 2 shows the respondents' groups and the number of respondents.

Background information of respondents

The respondents provided their background information to ensure that the requirements were fulfilled and that they were part of the target groups. Also, this helped to understand their answers and make a better analysis. The respondents are in different countries in Europe, Africa, as well as in Asia and America, as seen in Fig. 3. The location of the respondents could have affected their answers to the survey, as the location affects the country's legislation, and the company's culture and organizational structure.

Decision-making methods

There are several methods available to study MCDM methods. For instance, Afrane et al. (2021) used the fuzzy TOPSIS method to study four different WtE technologies to identify the alternative with the most techno-economic advantage for investment in Ghana. Afrane et al. (2021) also evaluated four WtE technologies against twelve selection criteria for energy recovery from waste in Ghana using an integrated AHP-fuzzy TOPSIS method. Ali Shah et al. (2021) used fuzzy DEMATEL, fuzzy ANP, and fuzzy VIKOR multi-criteria decision-making methods for the evaluation of an energy trilemma-based decision support

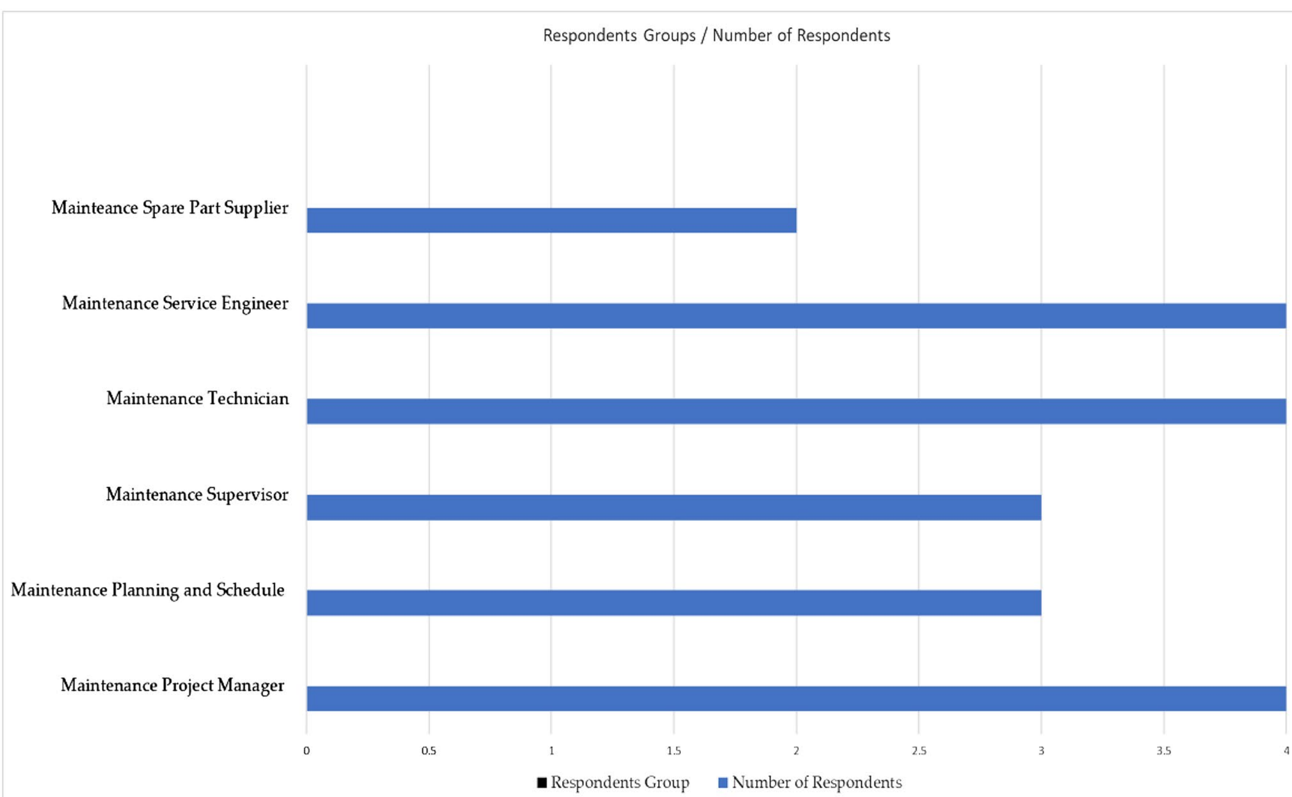


Fig. 2 Respondents' groups with numbers

Fig. 3 Respondents' location with numbers

framework to minimize uncertainty in the results. Hoang et al. (2019) deployed a multi-objective decision-making (MODM) method to offer an extensive debate and consensus among decision-makers over the effective waste flow allocation and the ideal capacity of disposal facilities. Shahsavar et al. (2022) proposed a new integrated MCDM approach that includes the Shannon entropy (SE), ordered weighted aggregation (OWA), analytic hierarchy process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and, ELimination Et Choice Translating REality (ELECTRE) systems in an intelligent way for a biorecovery of municipal different plastic waste management.

In this study, the DEMATEL method was used to analyze the critical criteria and to make the decision. The motivation behind the choice of DEMATEL methodology is that it can be used with a small sample, and it helps to find the interdependency of the criteria, barriers, or factors in the process of decision-making (Ahmadzadeh et al. 2021; Ignacio et al. 2020; Yadav and Singh., 2020). The subjective nature of the factors and criteria usually makes the decision-making rather difficult, which is why DEMATEL is used to provide a certain quantitative value to the criteria for analysis (Drumond et al. 2022; Sotoudeh-Anvari, 2022). This method is also used because it considers and helps to solve vague and incoherent information that can result sometimes in human judgment when using most decision-making tools (Acuña-Carvajal et al. 2019; Mao et al. 2023).

DEMATEL is a structural, mathematical method of modeling, which analyzes the interdependencies relationship and influential effects of different factors by using a cause and effect diagram (Lin 2013; Sharma et al. 2020; Yuan et al. 2022). This method has been used by many researchers (Bhatia and Srivastava 2018). It has been used in spare part chain risk mitigation knowledge management implementation (Wu and Tsai 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 and Chang., 2015), and a carbon management model of supplier selection in GSCM (Hsu et al. 2013). Environmental sustainability enablers have been analyzed by Goyal et al. (2019) using fuzzy DEMATEL. In Manila, it has been used in municipal solid waste management to analyze the cause-effect relationship. It has been used to identify the influential indicators toward sustainable supply chain adoption in the auto components manufacturing sector (Li and Mathiyazhagan 2018).

DEMATEL steps are

Step 1: Initial relation matrix "A"

The initial relation matrix is set up using decision-makers' ratings over given criteria. The experts are asked to rate the factors or key criteria to create a direct relationship using their ratings. 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 as shown in Eq. (1) is an initial relation matrix.

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

Step 2: Set up normalized direct-relation matrix "X."

Equations (2) and (3) are applied to obtain the normalized factor and the normalized direct-relation matrix, respectively, where the elements lie between 0 and 1.

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

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

where X is the normalized direct relation matrix, K is the normalization factor, and 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 Eq. (4).

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

where "I" is the identity matrix

Step 4: The sum of all the rows and all the columns are calculated using Eq. (5) and Eq. (6), respectively, where D represents the sum of the rows and R represents the sum of the columns.

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

$$R = \left[\sum_{i=1}^{n} m_{ij} \right]'_{n \times 1} \quad (6)$$

Step 5: Developing a causal diagram

The causal diagram is obtained using 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) are grouped into the effect group, while criteria with a positive value of (D–R) are grouped into the cause group (Tseng, and Lin., 2009).

Description of the case company

The studied case company is a modular WtE power plant manufacturer in Finland aiming to mitigate waste-related problems in developing countries. It is a company that was founded in 2017 and offers a turn-key solution that simultaneously significantly reduces waste landfilling, delivers a variety of energy commodities and cuts down waste logistics costs. The solutions from the case company promote the mitigation of environmental, social, and health problems caused by municipal solid waste and offer sustainable growth to waste management companies including the energy sector, investors, and local population.

The case company was the first to design a modular power plant from WtE that is easy to install. The design of the plant is considered robust, with low operational costs, high efficiency, good tolerance, and strict low emission plant for users and providing circular economy solutions. This plant uses different waste streams: MSW, RDF, biogas, etc., and produces saturated steam, electricity, thermal energy, and/or potable water. It can also be interconnected to create larger configurations. Each of the case company's plants is capable of incinerating roughly 150 tons of waste per day to generate 3.5 MWe of electrical power or 2.0 MWe / 10 MW thermal energy, and 200 m^3 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 parts for the plant. The waste incineration plant has five blocks, namely waste incineration, heat radiation and cooling, waste heat recovery, air pollution control, and power generation.

Results analysis

This section covers data collection and the analysis of the results. It presents the answers to the survey questions as well as an analysis of each question. At the end of this section, a summary of the results is presented.

Employee/labor factors

Figure 4 shows the responses to various employee factors according to the interview participants. Figure 4 shows that the level of employees' involvement and empowerment are 70%, maintenance of personal skills 60%, training and teamwork 55%, and so on. The operator's training and teamwork are important factors to consider. They are vital in achieving a high level of availability of the plant as well as for successful maintenance. An operator needs to continuously update his/her knowledge. Figure 4 shows that communication is also an important factor to ensure that all the team members operate efficiently and effectively.

Economic factors

Costs can be grouped into indirect costs (loss of revenue) and direct costs. Direct costs comprise operating costs (salaries, labor costs, spare parts, storage, training, subcontracting)

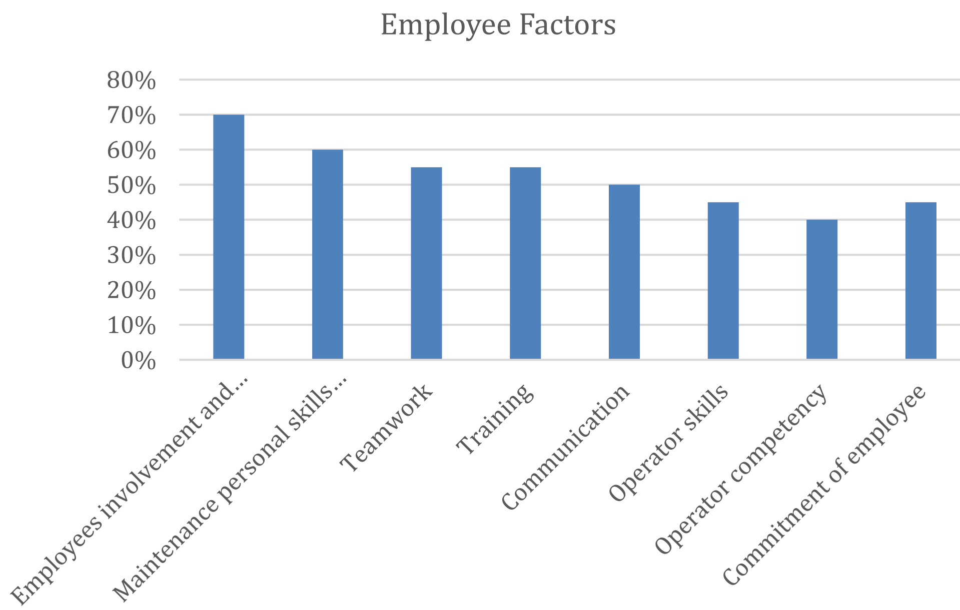


Fig. 4 Employee/labor factors according to the interview respondents

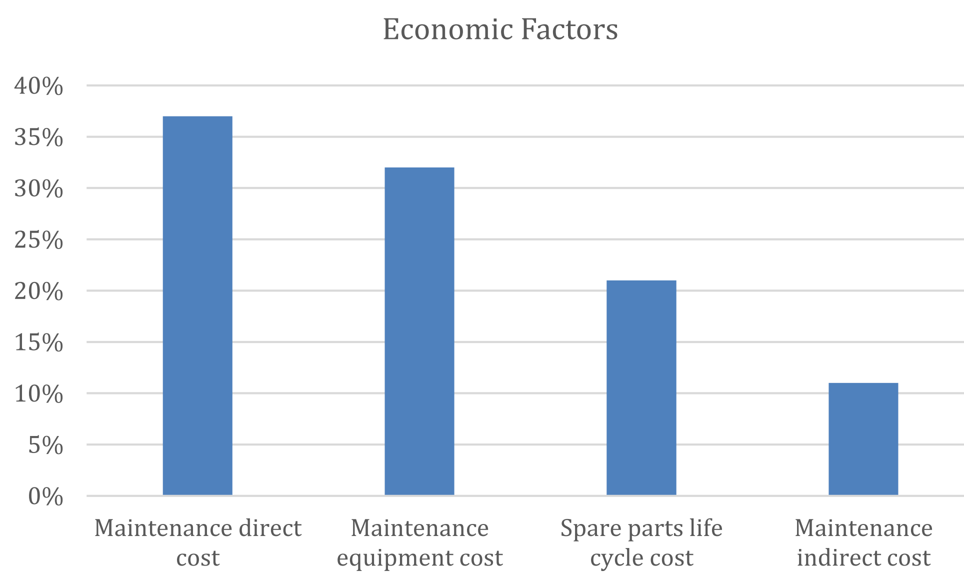


Fig. 5 Financial factors according to the interview respondents

and those directly related to maintenance costs. Figure 5 shows that about 37% of the respondents stated that direct costs are a critical factor, while planning maintenance and maintenance equipment costs comprise about 33%, and these are critical for the efficiency of the maintenance tasks. The right equipment and tools for maintenance make the maintenance itself easier. Figure 5 also shows that spare part costs comprise 21% and these significantly affect the maintenance activity.

Management commitment and leadership factors

Leadership provides support to or actualizes the factors needed to achieve organizational goals (Hackett and Spurgeon 1998). 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 quality management within the organization. As shown in Fig. 6, the top management's commitment (50%), resource commitment (55%), and process quality management (50%) are the most critical factors.

Logistics factors

Figure 7 reveals that the quality of the spare parts, reliability and availability, as well as the lead times, are the most critical spare part factors in ensuring high availability. The

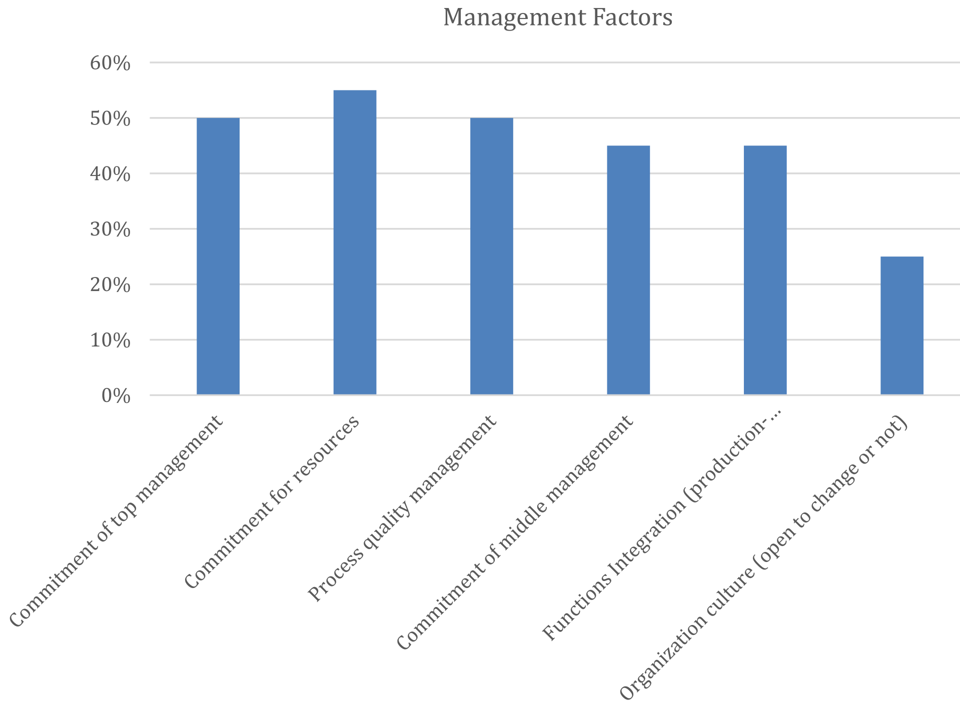


Fig. 6 Management factors according to the interview respondents

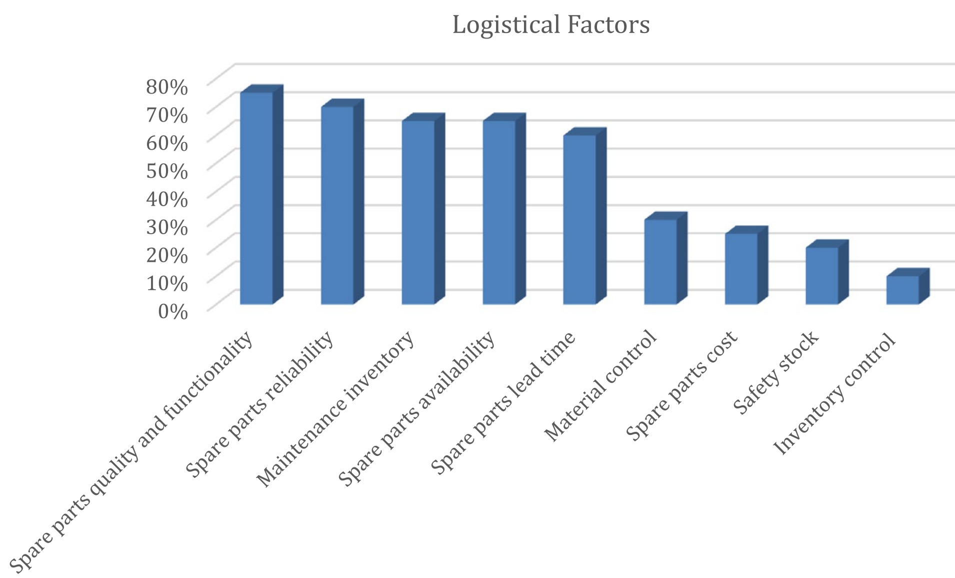


Fig. 7 Logistical factors according to the interview respondents

answers presented in Fig. 7 show that 15 respondents (75% of the total) pointed out the importance of the spare part quality and functionality. Figure 7 also shows that spare part reliability (68%), quality, spare part availability (60%), and functionality (70%) are important factors to consider regarding higher availability of the plant. The lead time is related to the process of spare part inventory and maintenance and therefore influences the downtimes (Tadashi et al. 2000).

Maintenance factors

More than 70% of the respondents pointed out the importance of maintenance planning and scheduling, as well as the tools and maintenance equipment. The planning and scheduling involve the labor, tools, equipment, and timing of the maintenance. Over 40% of the responses (Fig. 8) also think that good operating procedures and practices facilitate the maintenance work and improve the quality of the maintenance. Decision-making tools and a good management system support the operating and maintenance team from top management to operator. Figure 8 reveals that maintenance planning (80%) and scheduling (75%) are the most critical factors. Besides that, operating procedures and practices (55%) and mean time to repair

Fig. 8 Maintenance factors according to the interview respondents

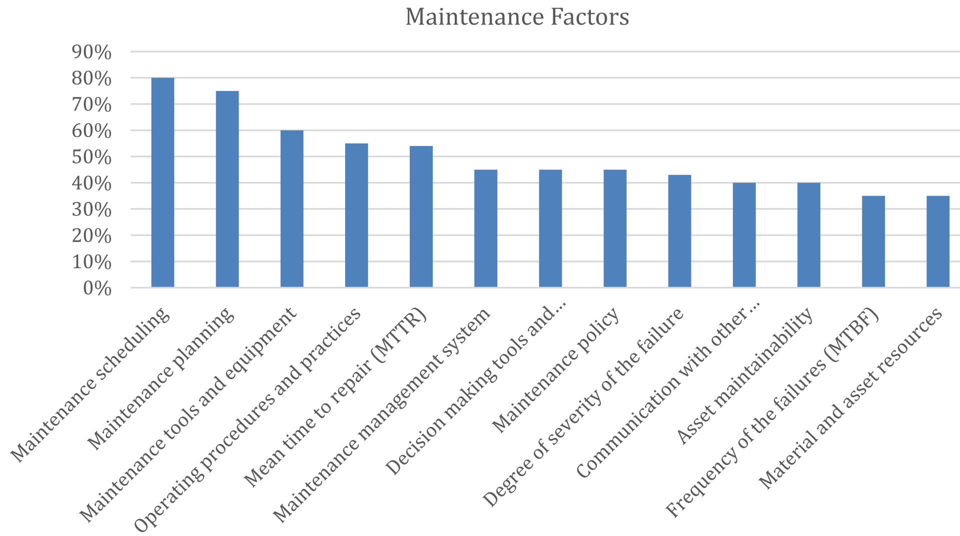


Fig. 9 Environmental factors according to the interview respondents

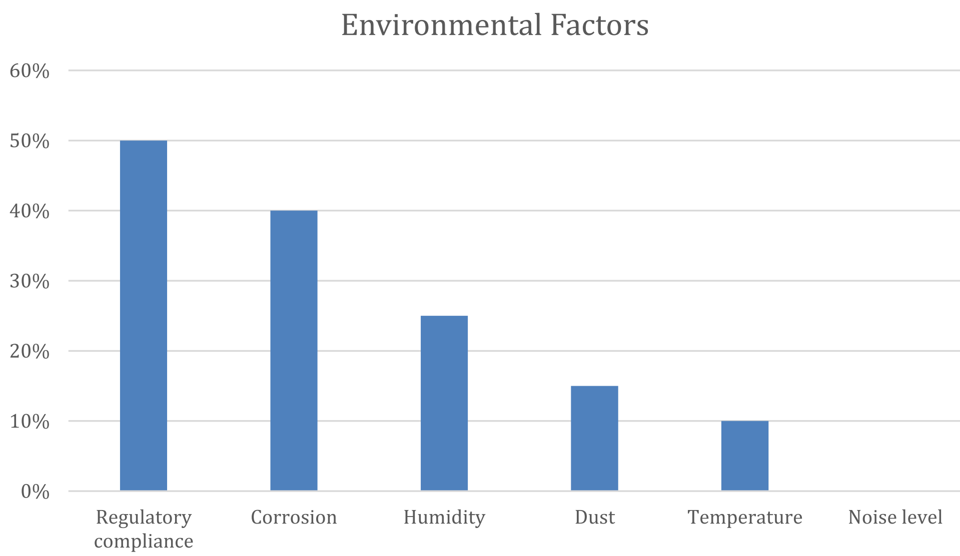
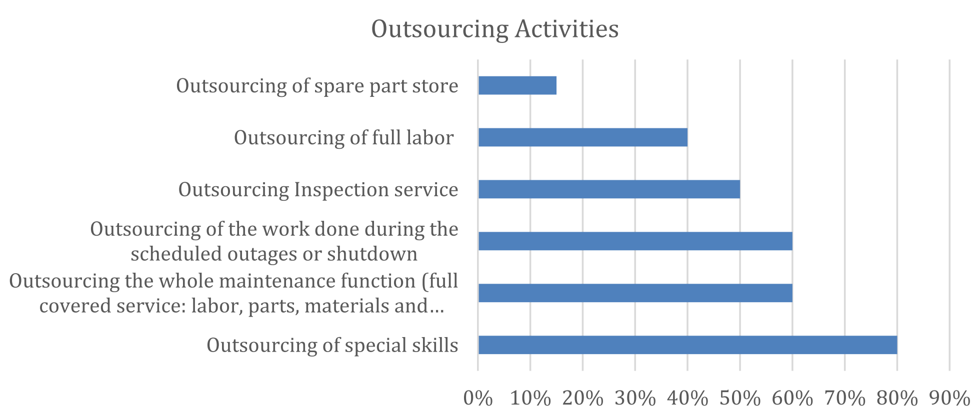


Fig. 10 Outsourcing factors according to the interview respondents



(MTTR) (55%) are crucial for the efficiency and effectiveness of the maintenance.

Environmental factors

Country regulation affects the WtE plant in one way or another. Based on the responses shown in Fig. 9, regulation compliance (50%), corrosion (40%), humidity (25%), dust (15%), and temperature (10%) affect the availability of the plant. These factors need to be considered, and especially the temperature when the plants are in countries with tropical temperatures or seasons.

Outsourcing factors

From the study findings highlighted in Fig. 10, it can be seen that the case company outsourced 80% of special skills, which allowed the company to focus more on its core competencies. Figure 10 also shows that the company outsources the whole maintenance function, outsources the work done during scheduled outages or shutdowns, outsources the inspection service, as well as outsourcing full labor and spare parts at 60%, 60%, 50%, 40%, and 15%, respectively.

Spare part criteria analysis

The DEMATEL method is used in this part of the analysis. The cause-effect relationship between the criteria and the spare part is prioritized for a better part selection while using the DEMATEL method (Tang 2018).

Step 1: Initial relation matrix "A"

The respondents' result for spare part criteria was put into an Excel file. The averages of all the ratings of each criterion are called initial direct influence matrix A (shown in Table 3). It is obtained using Eq. (1) and expert methods. The influence of a criterion on itself is 0. Table 3 presents the average of the scores given for each factor by the respondents (experts). As can be seen in Table 3, the diagonal element of each factor is 0.

Step 2: Normalization of the direct-relation matrix X

The normalized direct relation matrix has been calculated based on Eq. 2 and Eq. 3 and is presented in Table 4. In this step, all the respondents' ratings have been divided by the maximum value, which is the sum of the row for each criterion. Matrix X is also called the direct influence matrix and the resultant matrix X is shown in Table 4. For example, the direct influence value of "Quality" on "Failure Severity" is 0.096.

Step 3: Estimation of total relationship matrix (T) By using Eq. 4, the total relationship matrix (T) was determined and is shown in Table 09. Before that, different intermediate calculations were done and are presented in Tables 5, 6, 7 and 8.

Table 3 Matrix A displays direct relationships among the 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
Criticalitly	**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 the 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

Table 4 Matrix X displays a normalized direct relation of factors

Criticalitly	**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 M	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 S. P	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 the 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 S	0,019	0,038	0,019	0,058	0,038	0,077	0,077	0,038	0,038	0,135	0,038	**0**

Table 5 Identity matrix (I)

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**

Table 6 Matrix (I-X)

Criticalitly	**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 M	– 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 S. P	– 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 the 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 S	– 0.0192	– 0.0385	– 0.0192	– 0.0577	– 0.0385	– 0.0769	– 0.0769	– 0.0385	– 0.0385	– 0.1346	– 0.0385	**1**

@Table 7 displays the inverse matrix of (I-X) as presented in Table 6

Table 7 Inverse of matrix (I-X)

Criticalitly	1.119	0.221	0.179	0.232	0.194	0.267	0.231	0.199	0.204	0.226	0.242	0.182
Specificity	0.151	1.110	0.189	0.188	0.184	0.236	0.171	0.176	0.144	0.197	0.183	0.140
Predictability	0.146	0.177	1.134	0.223	0.203	0.256	0.224	0.225	0.179	0.184	0.217	0.192
Maintainability	0.150	0.144	0.187	1.131	0.182	0.217	0.186	0.174	0.177	0.180	0.164	0.156
Inventory cost	0.100	0.109	0.168	0.147	1.109	0.159	0.165	0.137	0.175	0.144	0.160	0.157
Availability of the market	0.104	0.130	0.139	0.168	0.150	1.126	0.185	0.158	0.162	0.164	0.147	0.142
Order lead time	0.240	0.242	0.270	0.296	0.274	0.319	1.209	0.276	0.266	0.290	0.289	0.277
Price	0.165	0.196	0.226	0.245	0.261	0.264	0.264	1.157	0.253	0.224	0.256	0.233
Volume of the spare part	0.107	0.098	0.123	0.134	0.167	0.144	0.135	0.124	1.092	0.132	0.131	0.144
Quality	0.233	0.252	0.247	0.287	0.284	0.293	0.255	0.267	0.275	1.194	0.281	0.270
Severity of the failure	0.173	0.203	0.181	0.233	0.247	0.251	0.250	0.183	0.223	0.215	1.155	0.237
Availability of support	0.118	0.144	0.135	0.185	0.165	0.214	0.199	0.156	0.160	0.249	0.162	1.120

Table 8 Relationship matrix T

Relationship matrix T = X*inv (I-X)												
Criticaitlly	− 0.04	0.06	− 0.01	0.03	− 0.01	0.05	0.03	0.01	0.01	0.03	0.05	− 0.01
Specificity	0.03	− 0.04	0.04	0.02	0.02	0.06	0.00	0.02	− 0.02	0.04	0.02	− 0.02
Predictability	0.01	0.02	− 0.04	0.03	0.01	0.05	0.03	0.06	− 0.01	− 0.01	0.04	0.02
Maintainability	0.03	0.01	0.05	− 0.04	0.02	0.04	0.02	0.02	0.02	0.02	0.00	0.00
Inventory cost	− 0.01	− 0.01	0.05	0.00	− 0.04	0.00	0.03	0.01	0.05	0.01	0.03	0.03
Availability of the market	− 0.01	0.01	0.01	0.02	0.00	− 0.04	0.05	0.03	0.03	0.03	0.00	0.01
Order lead time	0.06	0.03	0.05	0.04	0.02	0.03	− 0.07	0.04	0.02	0.04	0.04	0.04
Price	0.00	0.02	0.03	0.03	0.05	0.02	0.05	− 0.05	0.05	0.01	0.05	0.03
Volume of the spare part	0.02	− 0.01	0.01	0.01	0.05	0.01	0.01	0.01	− 0.03	0.01	0.01	0.03
Quality	0.06	0.05	0.03	0.04	0.04	0.01	− 0.01	0.05	0.04	− 0.06	0.04	0.05
Severity of the failure	0.02	0.04	− 0.01	0.03	0.05	0.02	0.05	− 0.01	0.03	0.01	− 0.05	0.06
Availability of support	− 0.01	0.00	− 0.02	0.02	0.00	0.04	0.04	0.00	0.00	0.11	0.00	− 0.04

Table 9 Sum of the all the rows and columns

Relationship matrix T = X*inv (I-X)	Ri												
Criticalitly	− 0.04	0.06	− 0.01	0.03	− 0.01	0.05	0.03	0.01	0.01	0.03	0.05	− 0.01	0.22
Specificity	0.03	− 0.04	0.04	0.02	0.02	0.06	0.00	0.02	− 0.02	0.04	0.02	− 0.02	0.17
Predictability	0.01	0.02	− 0.04	0.03	0.01	0.05	0.03	0.06	− 0.01	− 0.01	0.04	0.02	0.21
Maintainability	0.03	0.01	0.05	− 0.04	0.02	0.04	0.02	0.02	0.02	0.02	0.00	0.00	0.18
Inventory cost	− 0.01	− 0.01	0.05	0.00	− 0.04	0.00	0.03	0.01	0.05	0.01	0.03	0.03	0.15
Availability of the market	− 0.01	0.01	0.01	0.02	0.00	− 0.04	0.05	0.03	0.03	0.03	0.00	0.01	0.14
Order lead time	0.06	0.03	0.05	0.04	0.02	0.03	− 0.07	0.04	0.02	0.04	0.04	0.04	0.32
Price	0.00	0.02	0.03	0.03	0.05	0.02	0.05	− 0.05	0.05	0.01	0.05	0.03	0.27
Volume of the spare part	0.02	− 0.01	0.01	0.01	0.05	0.01	0.01	0.01	− 0.03	0.01	0.01	0.03	0.14
Quality	0.06	0.05	0.03	0.04	0.04	0.01	− 0.01	0.05	0.04	− 0.06	0.04	0.05	0.33
Severity of the failure	0.02	0.04	− 0.01	0.03	0.05	0.02	0.05	− 0.01	0.03	0.01	− 0.05	0.06	0.26
Availability of support	− 0.01	0.00	− 0.02	0.02	0.00	0.04	0.04	0.00	0.00	0.11	0.00	− 0.04	0.14
Ci	0.15	0.19	0.19	0.23	0.22	0.27	0.23	0.20	0.20	0.23	0.23	0.19	2.54

Table 10 Cause and effect group of the factors

		Ri	Ci	Ri + Ci	Ri–Ci	Identity
Criticalitly	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 the 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 next step is to calculate the Matrix (I-X) values, as shown in Table 5. This is basically the subtraction of the matrix of an identity matrix (Table 5) and the matrix X (Table 4).

Total relationship matrix T is obtained by applying Eq. (6). Ri (sum of the rows) and Ci (sum of the columns) are also presented in Table 9.

$$T = X * (I - X)^{-1} \tag{7}$$

Step 5: Developing a causal diagram

Table 10 shows the two groups: the cause group and the effect group. The term "Ri + Ci" measures the importance of the factor and the strength of the influence on and by the factor on others. Positive "Ri – Ci" means the factor influences other factors more than it is influenced by them, and then it belongs to the cause groups. Negative "Ri–Ci" means the factors are influenced by others more than it influences itself, and 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 the cause group. Datasets "Ri–Ci" and "Ri + Ci" are shown in Table 9, and the causal diagram is plotted in Fig. 11.

In Fig. 11 and Table 10, the highest position indicator value "Ri + Ci" is obtained by quality (J), which means it has the strongest association with other criteria. Quality is the most critical criterion with the highest value of 0.56. The following criteria follow quality in the ranking: order lead time (G), severity of the failure (K), and price (H). The lowest position value is the availability of 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), which means that it receives the biggest influence from the other criteria (Fig. 12).

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

The values in bold are those above the threshold, as shown in Table 10.

Quality has a huge impact on maintainability and criticality. Better quality can lead to better maintainability of the spare part. Quality and price affect each other, even though the price does not guarantee quality. The severity of the failure may affect the inventory costs because when the severity is high, the downtime might be longer, especially when the spare part is not available for maintenance.

Lead time is a significant element that influences price. When a key spare (item) part is needed but cannot be found, stored, or ordered from a foreign country or other continent than the power plant, extra consideration must be given to this factor. Lead times may be higher in poorer nations, which would lengthen downtime and result in a significant loss (Table 11).

Study analysis and findings

The human, economic, equipment and tools, management, and environmental factors have an important impact on the maintenance in general and the availability level of the WtE plant. Maintenance should be part of the whole company or firm's strategies. Corrective maintenance (CM) cannot be avoided totally, and thinking about other alternative maintenance strategies could reduce repetitive failures. Preventive maintenance (PM) is the best way to ensure better availability of the plant, and besides that, reliability centered maintenance (RCM) can be implemented for better planning and scheduling of the maintenance.

Good maintenance policies need to be employed, and it should be part of the management's responsibility to ensure they are followed by all the stakeholders. This can only be effective by acting, and by knowing all the required tools and methods required for maintenance in advance (Basri et al. 2017). All the actions of preventive maintenance must be performed in a proven, proper, normalized, and standardized way. Human

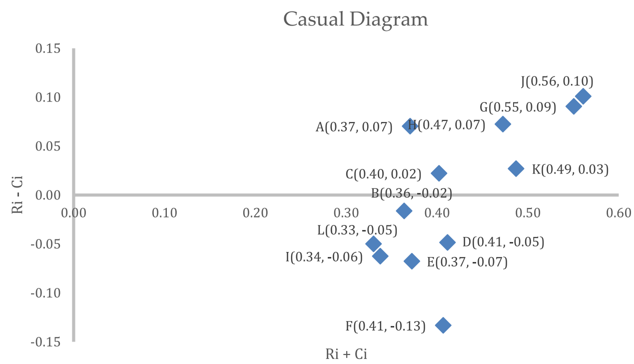


Fig. 11 Causal diagram of the factors

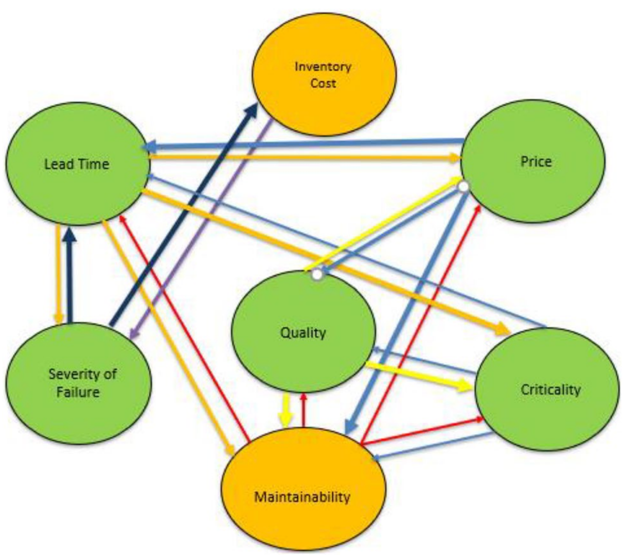


Fig. 12 Cause-effect relationship diagram

error can occur, for 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).

Communication and teamwork are two key factors in ensuring better availability of the plant. Continuous improvement can only be achieved through the involvement of effective operators. The maintenance operators' roles and responsibilities need to be defined for all the maintenance actors. In any organization, training and education should have special attention (Oakland and Amrik, 1989). It is important to analyze the capital cost and the benefit to the organization, and all the costs should be included: the logistics costs, spare part costs, costs of repair and replacement, tools and equipment costs, as well as labor costs. The cost of downtime must also be included.

The maintenance policy should include 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 decision-making tools and methodologies are supportive tools that help identify the maintenance items and their related consequences (reliability and risk management), but also the right timing to perform the maintenance. The findings correlate with the theoretical framework and review. The availability of the WtE plant depends a lot on the quality of the spare parts. The lead time is also an important criterion, especially when some WtE plants operate in distant locations away from the main logistic centers. This needs special attention for plants located in developing countries, for instance, because the lead time can be much longer as the supplier in the country might place an order from a different continent.

The criticality of a part can be considered as the consequence caused by that part's failure in case the replacement is not immediately available. There are different ways to measure or evaluate the criticality of a part: It could be in terms of the cost of downtime, which is sometimes difficult to measure. The spare part needs to be categorized in order to know which ones are critical or special (specialized and unique parts in terms of) availability and to reduce costs. Usually, the supply of generic spare parts is trouble-free and there are many suppliers. The risks of non-supply are low and these parts are usually available. Unique and specialized parts require special consideration because these usually have a unique, single, or limited number of suppliers, and their lead time might be erratic. A list of maintainable spare parts should be made in order to know which ones should be kept at the site, or at different locations.

Conclusions and future research direction

The management of MSW is a significant environmental issue. MSW can be a useful source of energy through various waste-to-energy (WtE) technologies. Such technologies can contribute to producing a significant amount of energy from waste, which ultimately reduces MSW management. Lack of efficient management of MSW can cause harmful environmental effects as well as enhancing the risk to public health, and it raises some other socio-economic issues that are worth discussion. It is, therefore, crucial to efficiently manage the handling of waste collection, segregation, and safe disposal. Waste-to-energy

Table 11 T- matrix

	Critically	Specific-ity	Predict-ability	Maintain-ability	Inventory cost	Availability of the market	Order lead time	Price	Volume of the spare part	Quality	Severity of its failure	Availability of support
Criticalitly	− 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 M	− 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 S. P	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 the 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									

(WtE) technologies can perform proper use and manage the MSW through various treatments such as pyrolysis, gasification, incineration, and biomethanation, which can convert MSW into an appropriate source of renewable energy.

This study has elaborated on the applicability as well as availability of WtE technologies to minimize the overall negative impacts of waste. It also highlighted various aspects of the availability of WtE plants with special focus on maintainability and the proper supply of spare parts. In the research, surveys and a theoretical review were used. Although maintenance in general is a well-known subject that has attracted academic and research interest, the literature study used as the theoretical framework reveals that the maintenance of WtE plants has not been well explored. In addition, this study explains various crucial elements that have an impact on the availability of WtE plants as well as the current maintenance approaches. A comprehensive understanding of maintenance in general, and in particular WtE maintenance, is drawn from the literature research and survey data. An intriguing result from the literature analysis is that corrective maintenance is never fully avoidable. However, by implementing a sound maintenance approach, recurring maintenance can be reduced. Combining preventive, conditional, and corrective maintenance is the optimum approach to ensure tha availability of WtE plants.

This study identified three research questions, which are answered within the scope of this study. The first research question, which was 'what are the critical factors that enable high plant availability?' was answered by investigating several factors which were collected through a review of the scientific literature and opinions of the interviewees, who are professionals engaged in WtE. In addition, the second research question, which was 'what are the best criteria when choosing maintenance-critical spare parts?' was also identified by the respondents and analyzed using the DEMATEL method. It was revealed that maintenance planning (80%) and scheduling (75%) are the most critical factors in the maintenance program in WtE plants. Additionally, operating procedures and practices (55%) and mean time to repair (55%) are crucial for the efficiency and effectiveness of the maintenance.

Moreover, the third research question, which was 'how to optimize the WtE plant maintenance program?' was answered by adopting the cause and effect approach within DEMATEL methodology. The study explores different critical factors affecting the availability of WtE plants and their existing maintenance strategies. The literature review and survey results offered a solid understanding of maintenance in general and WtE maintenance in particular. Based on the literature review, an interesting finding is that corrective maintenance can never be avoided completely. But it is worth reducing repetitive maintenance by adopting a good maintenance strategy. The best solution is to combine preventive, conditional, and corrective maintenance. Management roles and factors impact the effectiveness of the maintenance, namely management involvement and commitment. The spare part factors have an important impact on the maintenance and availability of the plant.

The DEMATEL method was used to provide a smart and systematic decision-making approach for spare part selection by grouping them into cause and effect groups. The method helps to deal with vague and imprecise judgment in decision-making. Key criteria are identified, and the link between them has been associated with a visual diagram. Key findings of the study revealed that human, economic, equipment and tools, management, and environmental factors have an important impact on the effectiveness of the maintenance and availability of the WtE plant, whatever the maintenance strategies: from preventive to corrective maintenance through to the condition maintenance. Quality, lead time, price, and severity of spare part failure are key criteria to consider when selecting a spare part for the WtE plant.

It would be interesting to carry out further research on the topic by using data from different plants operated by the case company in order to make the research more objective. This would help the case company better know the real issues their plants face. It would be interesting to perform further research by focusing, for instance, on different locations and populations, because different climatic and environmental factors may influence the failure rate of the plant's equipment: dust, humidity, and cultural factors.

Appendix 1

Questionnaires survey as used in this study.

Waste-To-energy plant (WtE) optimal maintenance program

Hello,

The aim of the study is to develop an 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 WtE plant, and to identify the best criteria for the spare part selection.

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

Please answer the questions below.

Personal information (not compulsory)

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

A- waste-to-energy plant lifecycle availability

On a scale of 1 to 6, please rate the factors (by importance) affecting WtE plant life cycle availability. (commitment of employees)

	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	☐	☐	☐	☐	☐	☐

slightly affects, affects, affects, strongly affects, extremely affects

Economic factors add "S" to "affect"

	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	☐	☐	☐	☐	☐	☐

Management factors ditto (add S to affect)

	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)	☐	☐	☐	☐	☐	☐

Procurement factors (add "S" to affect)

	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	☐	☐	☐	☐	☐	☐

Maintenance factors (add "S" to affect)

	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	☐	☐	☐	☐	☐	☐

Environmental factors (add "S" to affect)

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

Information system (add "S" to affect)

	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 and scheduling

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

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

C. spare part selection criteria

What are the best criteria for spare part selecting? Please list any missing

do you mean criticality rather than critically?severity of THE failure

	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	○	○	○	○	○	○
	○	○	○	○	○	○
	○	○	○	○	○	○
	○	○	○	○	○	○
	○	○	○	○	○	○

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

D- outsourced maintenance

What are the main issues when outsourcing the maintenance?

What is the level of outsourcing? fullY covered service during outages (not THE outages); inspection with lower case "i"

	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	○	○

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

E- operators, maintenance documentation

During maintenances what are the most common causes for issues

planning with lower case "*p*"

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

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

Free text / suggestion

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