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USAMA ALI

INTEGRATION OF THE PROMETHEE II METHOD WITH A DELAY TIME MODEL FOR DEFINING AN INSPECTION POLICY FOR ELECTRICAL WIRING SYSTEMS´ COMPONENTS

Recife

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Dissertation presented to the Post-Graduate Program of Production Engineering of the Federal University of Pernambuco, to obtain the Master´s Degree in Production Engineering.

Concentration Area: Production Management.

Advisor: Prof. Dr. Cristiano Alexandre Virgínio Cavalcante.

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ABSTRACT

In the past, maintenance was seen as a necessary evil that generates only industrial costs and its function was only focused on the "broke, fix" policy. However, this view has changed, since the advantages of adopting maintenance strategies have gained increasing visibility, mainly due to the importance of preserving the functional state of an item, the main outputs from maintenance concept development which collaborates to prevent failures and to prevent industrial accidents, both of which could generate consequences of magnitudes, which go beyond economic impacts. Thus, due to the need to establish maintenance strategies in the midst of a competitive market for electrical wire systems, this thesis proposes a model for evaluating inspection policies based on two criteria called *Cost – Q(T)* and Mean Time Between Operational Failure – *MTBOF(T)* in order to determine the interval between inspections for the electrical wiring systems, considering the delay-time concept for modelling the failure process of components. In addition, the proposed model is constructed from a multicriteria perspective, considering the PROMETHEE II method for dealing with the conflict in a decision-maker's objectives. The application shows, how the model can be used to support decisions in real contexts that allow not just to find a recommendation for time between inspections *(T)*, but also gives the decision-maker the possibility of choosing the best time for the inspection. This arises because the model gives besides the first most preferable alternative, an order with the preferable alternatives.

Keywords: maintenance policy; delay-time model; PROMETHEE II method.

RESUMO

No passado, a manutenção era vista como um mal necessário que gerava apenas custos industriais e sua função era voltada apenas para a política de "quebrou, conserta". Porém, essa visão mudou, uma vez que as vantagens da adoção de estratégias de manutenção têm ganhado cada vez mais visibilidade, principalmente devido à importância de se preservar o estado funcional de um item, principais saídas do desenvolvimento do conceito de manutenção que colabora para prevenir falhas e prevenir acidentes industriais, ambos podendo gerar consequências de magnitudes, que vão além dos impactos econômicos. Assim, devido à necessidade de estabelecer estratégias de manutenção em meio a um mercado competitivo de sistemas de fiação elétrica, esta dissertação propõe um modelo de avaliação de políticas de inspeção com base em dois critérios denominados Custo - Q (T) e Tempo Médio Entre Falhas Operacionais - MTBOF (T) para determinar o intervalo entre as inspeções dos sistemas de fiação elétrica, considerando o conceito do delay time para modelagem do processo de falha de componentes. Além disso, o modelo proposto é construído em uma perspectiva multicritério, considerando o método PROMETHEE II para lidar com o conflito nos objetivos do tomador de decisão. A aplicação mostra como o modelo pode ser utilizado para apoiar decisões em contextos reais que permitem não só encontrar uma recomendação de tempo entre as inspeções (T), mas também dá ao decisor a possibilidade de escolher o melhor momento para a inspeção. Isso ocorre porque o modelo dá, além da primeira alternativa mais preferível, uma ordem com as alternativas preferíveis.

Palavras-chave: política de manutenção; modelo delay time; Método PROMETHEE II.

LIST OF FIGURES

LIST OF GRAPHS

LIST OF TABLES

LIST OF ABBREVATIONS

CDF	Cumulative Density Function
CM	Corrective Maintenance
DTM	Delay Time Model
INS (T)	Best Inspection Time
IoT	Internet of Things
MCDA	Multi-Criteria Decision Aiding or Multi-Criteria Decision Analysis
MCDM	Multi-Criteria Decision Making
MTBOF	Mean Time between Operational Failures
PDF	Probability Density Function
PdM	Predictive Maintenance
PM	Preventive Maintenance
SA	Sensitivity Analysis

TABLE OF CONTENTS

1 INTRODUCTION

Like any scientific research built upon the groundwork of science and technology, this thesis begins with the role of maintenance in the modern world. As Wang and Hwang (2004) stated, in modern manufacturing, maintenance plays a vital role, and it is also important that firms accept maintenance as an element of generating profit. Reason (2000) argued that maintenance is a function in which repairs are carried out by a certain period in order to increase the life of any machine and to keep it in the previous condition so as to continue using its old capacity.

The literature shows that when maintenance was first discussed long ago, it was, as stated by Pintelon and Parodi-Herz (2008) regarded as a necessary evil for organizations to engage in, but now Maintenance is viewed as a value-adding activity. As Horenbeek et al. (2011) explain, firms now identify that maintenance can provide value to their business and they also explain that the lack of applications and academic models is a gap from a business specific perspective and that this is also the greatest problem encountered in the field of maintenance optimization.

In the light of all the background of maintenance discussed above, noteworthy attention has been paid in recent years to minimizing the negative impacts caused by failures of electrical wire. When this is done, it can be often considered as producing cost savings due to better maintenance. As stated by Lee et al. (2018), the material properties of wire can worsen because of the stress of the working load and because of the environmental factors that can cause the wire to fall into bad, faulty and failed conditions, which can lead to electrical connection failures within the power distribution system.

The electrical power distribution system can be considered as the foremost operating system to operate the systems that run on electricity. The steady growth in the wiring network has exceeded the normal level in past three decades, and this has increased the complexity of dealing with and maintaining the wire below hazard levels since increasing the wiring raises electricity loads and supply voltages Millet (2014).

Failures in electrical wiring systems can have critical consequences for society and for the environment, in addition to causing huge economic losses. The failure of wire due to, for example Arcing and Cut-off, affect the data communication in any facility and lead to system down time and critical consequences such as accidents that may occur. These may cause a blackout, a fire in the system because of arcing, and losses of life as a consequence of accidents, etc. Such occurrences can lead to an increase in the waste of resources, time and money. Gartner

(2013) relates that the down-time of data communication in a facility costs around 5,600-US$ per min, which amounts to an average of more than 300,000-US$ per hour.

Tang et al. (2015) affirms that Predictive Maintenance PM approaches can save approximately 18% of maintenance costs because they provide real-time information which in this case is simply that inconsistent wire should be replaced. Consequently, monitoring is required so as to eliminate unplanned downtime because wiring has failed and, therefore when a system is monitored and inconsistent wiring is identified, this wiring should be replaced prior to failures.

In the light of the above discussions, considering that electrical wires are vital components of the infrastructure for transmitting electrical energy, this thesis proposes a maintenance policy for these components which, to be more specific should be applied in the context of inspections for the best performance, based on the assumption that a correct maintenance policy has a strategic and valuable role for companies.

1.1 DESCRIPTION OF THE PROBLEM

The components of an electrical wiring system such as wire start deterioration as soon as it is installed. This introduces the hazard of arcing and explosion. If the deterioration is not attended to properly, it can cause electrical malfunctions and failures (GILL, 2020) and that leads to the unavailability of energy in homes and in industries.

In the late '90s, the world was already familiar with the fact that Electrical Energy will play a vital role in increasing socioeconomic growth. The total consumption of energy was expected to grow by 57 per cent from 2004 to 2030 since energy is now the backbone of economic growth of any part of the world (Khan and Qayyum, 2009). Although developing countries’ share of the demand is only 30 per cent, it is also expected to increase to 40 per cent due to the increase in population (Raiz, 2008).

The constant supply of electrical energy in any sector of the world cannot be negligible. The increasing demand for electricity places a heavy load on the components whether a single component or multiple components, especially those that are connected to the electrical wire. According to Naqvi and Rahbar (2009) a significant portion of accidents that leads to death has been reported as follows: 42% of events were caused due to contact with bad electrical lines between 1992 and 2002. This percentage shows the need to develop a maintenance policy for the electrical wiring systems that reduces the death ratio.

Blackouts, fire, bad transmitting of electricity can destroy many components and things connected with the wire. To keep the wire maintained, to avoid the risks and hazards of losing life and money and also considering the impacts of failures that adversely affect financial aspects, it is necessary to keep the wire maintained.

In all the scenario explained above which is associated with the lack of maintenance that causes accidents, the unavailability of electricity in homes and in industries due to the failure of wire can affect the economic growth of a country. Thus, these are the main problems addressed in this thesis. It is emphasized that maintenance actions need to develop and start functioning as soon as the wire is installed to ensure the maximum security against a) accidents due to the failure of wire and b) the adverse effect on economic growth due to the unavailability of electrical energy.

1.2 JUSTIFICATION AND RELEVANCE

In today´s world, the electrical energy area faces serious issues, e.g. to increase and make progress in delivering electrical energy to different sectors of the world by economically and socially acceptable means. As stated by Khan and Qayyum (2009), these issues will need a package of policies designed to meet the world's energy needs. In many developing countries of the world, the most significant barrier to economic growth is an unreliable supply of electricity (Grainger and Zhang 2019).

In the modern world, electricity is an important input for most business but an unreliable supply can interrupt an organization's production. Several studies have shown the impacts of electricity shortages on firms' production, such as Fisher-Vanden et al. (2015) in which the productivity and environmental effects of electricity shortages in China is measured against a huge lack of production due to the shortage of electricity, and so it is essential that organizations seek to adopt maintenance policies. In particular, the planning of maintenance activities has great applicability. For example, it supports managers to observe the condition of resources and to understand the economic aspects associated with maintenance costs (WU; COOLEN; LIU, 2017).

The day-by-day increase in demand for electricity has been rising sharply which constantly requires the construction and use of new poles to supply electrical energy. As the demand for electricity involves every organization from large industries to residential condominiums, a large amount of highly conducted electrical wire on poles are positioned in areas or in places with possible access to houses. This increases the risk of accidents and there is always a chance of a disaster occurring as the supplier transformers are also interconnected with the poles and wire. Therefore, the above scenario motivates us to research and proposed a new inspection model based on the delay time and PROMETHEE II method in order to overcome the shortages, the unreliable supply of the electricity and to reduce the hazards and risks.

Keeping in mind the need to provide a reliable amount of electricity according to its use, to avoid fluctuations and other forms of negative impact on the transmission of electricity and to avoid risk from its production and supply, a maintenance model that integrates the Delay Time Model and the PROMETHEE II method will be able to obtain better results based on multiple criteria. It is developed to bring two main benefits to society, namely:

Benefit-1: This research is cost-effective because it will prevent the unnecessary maintenance of the electrical wire. This research will be used to mitigate the unreliable supply of the electricity considering the two criteria e.g. *Cost – Q(T)* and Mean Time Between Operational Failure – *MTBOF(T)* that are being measured.

Benefit-2: The benefits of applying a multicriteria model based on the PROMETHEE II method in a realistic context enable not only a recommendation to be found for the best time between inspections *(T)*, but also gives the DM to choose among the most preferable times for the inspection, since the model provides an order of the alternatives based on the DM's preferences.

1.3 OBJECTIVES

This section presents the general objective and specific objectives of the research.

1.3.1 General Objective:

The general objective of this thesis is to propose a model based on delay time and on PROMETHEE II for the inspection of electrical wiring systems with some alternatives of the time to carry out inspections.

1.3.2 Specific Objectives:

- Investigate the particularities of maintenance in service delivery systems and on the relevant aspects of poles, wire, transformers etc;
- Specify what the relevant criteria to be modeled are;
- Perform mathematical modeling incorporating to find the Cost – Q(T) and Mean Time Between Operational Failure – MTBOF(T);
- Build a multicriteria model to support the maintenance policy, considering the research problem.

1.4 METHODOLOGY

The following steps have been taken in-order to develop this work:

- In any research, the preliminary step to start the work is the bibliographic review, starting with a bibliographic review of the fundamental concepts. This strategy was applied in this research and a review of the literature on the fundamental concepts of maintenance, on the delay time method and on the PROMETHEE II method was undertaken.
- Secondly, it was decided to choose the delay time model and the PROMETHEE II method to perform the modelling, as the delay time model represents, according to (Christer & Waller 1984) a useful tool for modelling maintenance in the context analysed and in the delay time of a fault i.e., in the lapse of time from when a defect is noticed for the very first time until the time when it is repaired since it can be delayed no longer because of unacceptable consequences. Therefore, the repair may be made at any time during this period. The PROMETHEE II method does not presume the presence of a single best alternative. As stated by (AMARAL; COSTA, 2014), it is a method that has proven to be a tool that is rational in order to support the decision-making for the selection of best alternatives. The PROMETHEE II method is interactive and it is used to classify and order the complex and difficult alternatives. It is well-known for its three main characteristics, namely, that it is simple, clear and stable.
- After gaining brief knowledge of maintenance in services and in the relevant aspects of the maintenance of electrical wire, etc., the relevant criteria were identified and modelled.
- Subsequently, a mathematical model was developed for a simple component, focusing on obtaining better results for the system based on multiple criteria. The maintenance policy, which uses the delay time model, is operationalized by observing the three states of the electrical wire (Good, Defective and Failed). Thus, starting with the construction of a model and based on the results obtained from the modelled equations, an ideal inspection policy is determined.
- Finally, a sensitivity analysis was performed to verify the robustness of the model.

2 THEORETICAL FRAMEWORK AND LITERATURE REVIEW

In this chapter, the aim is to present the theoretical framework and the review of the literature. Initially, conceptualization, dedications and other characteristics are addressed related to maintenance in general and then it is more about the *delay time* model and the multicriteria decision method, highlighting the PROMETHEE II method.

2.1 MAINTENANCE

This section covers some aspects of maintenance, which are: Definition, Importance, Objective and Functions, Growth of Maintenance, Classifications, Strategies, Cost.

2.1.1 Definition

The term Maintenance is well defined in the literature. Many authors define maintenance only as the way in which companies try to stop failures from happening at their physical facilities. According to Reason (2000) maintenance goes beyond this, as maintenance can further be defined as the arrangement of all mechanical, managerial and professional actions.

According to Parida et al. (2011), what cannot be measured, cannot be managed during the life cycle of an object which it is intended to be retained, or to be restored to a state in which it can perform the required tasks and the normal functions for which that object was introduced effectively. In order for operations managers to be able to manage the processes of maintenance and their own resources, it is necessary to measure the contribution of maintenance to business goals.

The above description clarifies the objective of maintenance and can help us to understand what part of an organization is, somehow, devoted to maintenance.

2.1.2 Importance

Maintenance plays a vital role in the context of production systems of an operating industrial plant with the means to monitor and to prevent or correct the defects and failures in the system. This operation provides results that favour a better competitive business positioning. In this scenario, the importance of maintenance can be verified in operational and strategic terms (Santos 2019).

According to Singh et al. (2019), strategies that are good in maintenance play a vital role in the efficacy of industrial processes, and help to avoid unnecessary or ineffective actions in organizations. With the rising competition in the industrial sector, maintenance industries are becoming energetically and technologically advanced, as well as constantly determined to meet changing market demands. The employer of maintenance is now required to evolve strategies to manage larger capacity with faster speed, and more refined machinery systems. All the favourable technological advances come with different drawbacks of which the most dominant is that of adopting new technologies.

Almeida and Souza (2001) state that maintenance management in a competitive way has always been a concern of scholars on the subject and progressively for companies. The management of the maintenance of production systems must focus on its impacts and on competitiveness.

2.1.3 The growth of maintenance in past decades

Just like today, in the mid-1960s, maintenance studies became more and more frequent, as industry professionals and academic researchers came to realize the benefits that good maintenance policies can bring. According to Moubray (1997) the evolution of maintenance can be divided into three generations:

- (1940-50) – This is the era that is commonly known as the 1st generation of the maintenance. In this era, maintenance was carried out in failure situations.
- (1950-70) – This is the era of maintenance that is known as the 2nd generation, in which preventive maintenance was taken into account by understanding the criteria that any failure in the system can interrupt production.
- (1970s) – This is the era of 3rd generation of maintenance when changes in the industrial sector took place, as DMs began to show more concern about the availability of equipment, safety and the environment.
- In 2013 in Germany, Industry 4.0 was announced. This is regarded as the main contribution in the current 4th generation of maintenance in industries that are currently revolutionizing the manufacturing sector.

Wang (2012) stated that maintenance concepts all include arrangements which can pay to keep plant assets in working condition. Dunn (2003) had begun to try to define possible practices for the fourth generation of maintenance, which, as he explained, would probably focus on reducing the probability of failures, by fostering a more proactive culture rather than a reactive one.

The inclusion of technologies such as the Internet of Things – IoT (DER MAUER et al., 2019) and augmented reality (SCURATI et al., 2018) facilitate the identification of the real state of the machines and hidden failures that could interrupt production processes and generate adverse costs. Making use of technologies like these to prevent component failures shows an increasingly insightful maintenance management, which seeks to guarantee both the availability of assets and the maximization of production.

2.1.4 Objectives and functions

A proper management of maintenance needs technical assistance, procedures and methods to properly use the resources for factories, power plants, vehicles, equipment and machines. The key objective of maintenance is to guarantee the functioning of the system (availability, efficiency and product quality), the life of the system (asset management) and its reliability and safety. Poorly maintained machines or equipment may lead to random breakdowns, thereby causing the unavailability of the system for production or service. As stated by Simeu-Abazi and Sassine (2010), the main purpose of maintenance engineering is to reduce the adverse effects of breakdown and to increase the availability of the system at a low cost, in order to increase its performance and to improve its dependability level.

Taking into account the affirmation of Pintelon and Parodi-Herz (2008) that the key objective of maintenance management is to obtain “total asset life cycle optimization” e.g., increasing the availability of plant/equipment and the reliability of these assets in order to achieve operational/business objectives. Therefore, maintenance not only deals with technology issues, it is a mix of management, operations and technology and business strategies.

2.1.5 Classifications of Maintenance

In the current era, the classification of maintenance always lies on the edges of topics discussed, as there are various classifications for maintenance. Different authors describe the topic of classification differently in their research work. For example, Lee and Cha (2016) split the classification into two, while Cavalcante and Lopes (2015) split the classifications into three parts, and De Faria, Costa and Olivas (2015) divide the classification into four or more parts. To prevent controversy, this research classifies maintenance into three classifications as stated by Dhillon (2002).

1) Preventive Maintenance – (PM).
2) Corrective Maintenance – (CM).
3) Predictive Maintenance – (PdM).

2.1.5.1 Preventive Maintenance – (PM)

The concept of Preventive Maintenance - (PM) has a multitude of significances as preventive maintenance is a maintenance in which a periodic, planned and specified schedule is carried out to do the maintenance and to keep the machinery in working condition to avoid unexpected failure during operation. To minimize the total cost of inspection, renovation and equipment downtime is the major objective of Preventive Maintenance (Xiaoning, 2016). To ensure the reliability of assets and the effective management of the costs incurred during the life cycle of assets, preventive maintenance is an absolute requirement (Mobley, 2002).

In the classifications of maintenance, preventive maintenance is feasibly the most deliberate classification and most importantly, time-based maintenance action or preventive maintenance is still a dominant maintenance policy in manufacturing plants. According to Cavalcante and Lopes (2015) PM - is considered to be the planning of a set of specific activities and tasks to keep the equipment running, with a view to preventing unexpected failures from occurring that can cause huge economic losses and significant risks for personal and environmental safety.

2.1.5.2 Corrective Maintenance – (CM)

Corrective Maintenance - (CM) is a maintenance that is an unscheduled action, which basically consists of unpredictable maintenance that needs to be done but cannot be pre-planned or programmed on the basis of it occurring at a particular time (Dhillon, 2002). It is done to bring the machinery to the operational state, from a failure. Initially, CM has a low cost but it may increase both the costs of unscheduled equipment downtime and production losses. CM is not recommended if the failure can cause a hazard for personnel or interrupts production and would harm security (Xiaoning, 2016).

Corrective Maintenance is also very useful currently despite being the oldest classification, as this maintenance worked on the failed-repaired scenario, so whenever there is a failure of the system, corrective maintenance is applied. As stated by Ben-Daya; Kumar; Murthy (2016), CM can range from minor repairs or a replacement that requires a short downtime to major repairs which require a high amount of downtime.

2.1.5.3 Predictive Maintenance – (PdM)

Predictive Maintenance - (PdM) is a maintenance strategy that can also be called right on time maintenance which is done by using modern measurement and signal processing methods to predict and diagnose the condition of machinery in use. PdM is geared to detecting the most common and delicate causes of failure (Xiaoning, 2016).

According to Nazmus and Thorsten (2018), Predictive Maintenance enhances the trade-off between maintenance and performance cost, and increases readiness. In predictive maintenance (sometimes also called condition-based maintenance (CBM)), actions are scheduled using an assessment of the condition of the equipment, which is performed by instrumentation and uses specialized expertise, conducted by appropriately trained professionals (CULLUM *et al.*, 2018). A predictive maintenance program cannot provide the means to resolve poor plant performance. The output of a predictive maintenance program is, as stated by Mobley (2002), data which if predictive maintenance is used properly, can identify most, if not all, the factors that limit the efficiency and effectiveness of the whole plant.

2.1.6 Cost

Every year, billions of dollars are expended on maintenance in the world. As stated by Dhillon (2002), the cost of maintenance materials is an important factor in the total cost of maintenance. If maintenance is used efficiently, there is scope to improve profits and company productivity. For maintenance to make this improvement, it must be reorganized as an integral part of the business strategy or competitive strength equation. Cost in this thesis is considered a central concern and is one of the criteria to be considered when defining the time to carry out inspections.

Moussault, et al. (2020) state that the operational costs can be better estimated by making provision for unpredicted maintenance costs. The amount of unpredicted maintenance costs depends on the maintenance policy generated and implemented, as well as the failure and maintenance intervals.

2.1.7 Mean Time Between Operational Failure (MTBOF)

As stated by Scarf et al. (2009), the mean time between operational failures (MTBOF), can be used in combination with some cost criterion. In this study, it is used with the Cost per time unit Q(T) in a multiple criteria approach of the policy e.g., given a reliability requirement expressed in terms of the MTBOF i.e. ($\mu \geq \mu R$) that can determine those policies for which this is true. Then, we can find the minimum cost policy in this subset. A reliability constraint could also be expressed in terms of some quantile of the distribution of the times between operational failures.

As stated by Scarf and Cavalcante (2012), the mean time between operational failure (MTBOF) provides a convenient reliability criterion. One might find that a minimum cost policy meets some reliability requirement expressed in terms of the MTBOF. A reliability constraint could also be expressed in terms of the median time between operational failures, and an expression can be noted from Scarf et al. (2005). The long-run cost and the MTBOF are used in the subsequent analysis.

The motive of the modelling is to minimize the Cost per time unit Q(T) and to maximize the Mean time between operational failures – MTBOF(T). There will be a need for a multicriteria approach to overcome the conflict in the result for which the PROMETHEE II method is applied. Using the multicriteria methodology, the interval between maintenance actions is found.

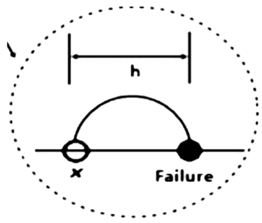
2.2 THE DELAY TIME CONCEPT

The Delay Time Model - DTM was first mentioned by Christer in 1976. The concept is used to apply to industrial maintenance problems (CHRISTER; WALLER 1984). From then until now, a series of investigations and research work in the area has appeared in relation to the theory and applications of DTM in the problems of industrial assets (Christer 1999). Delay time can be regarded as the concept that splits processing a system failure into two periods i.e., from new until the point where a defect can be identifiable and then, from this point until failure (Wang, 2012).

The Delay Time Model came into being as a maintenance modelling tool, and it considers that the failure is observed as a two-stage process as explained above. The delay time is a window of opportunity to prevent the system failing as long as an inspection is conducted during the delay time (Ferreira et al., 2009).

A defect arises in the component at some time *x*, followed by a subsequent failure after an interval *h* (Baker and Christer 1994) as shown in Figure 1 below.

Figure - 1 Delay Time between the arrival of a defect and failure



Source: Rodrigues (2020).

In Figure 1, the arrival of a defect, the failure and the Delay Time for a defect can be seen. The DTM seeks to determine maintenance schedules by setting optimum inspection intervals, considering a window of opportunity at each time T. The window of opportunity is from the beginning of defective state until a moment prior to the failure. In Figure 1, the delay time interval is shown and denoted as h.

- For this, two stages are considered:
  - Stage 1: Time until defect arrival (system operating in a good state);
  - Stage 2: Delay-time, i.e., the interval from the arrival of the defect until the system fails.

After the defect has arrived, an inspection may be performed to identify the defect. Therefore, the delay-time is a window of opportunity to avoid failure by identifying, prior to failure, a defective state and undertaking preventive maintenance.

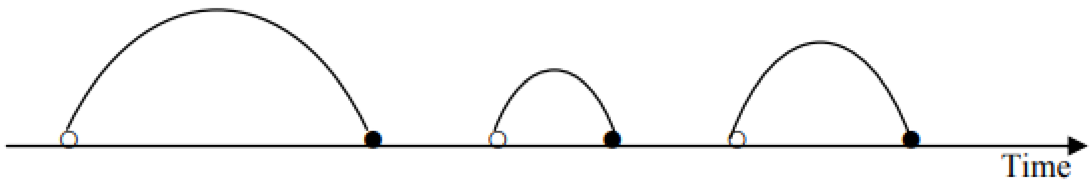
It is the presence of the defective state that DTM brings the advantage of allowing the opportunity for preventive maintenance if a defect is identified before the failure.

The repairing effort of a defect relates to time that it is observed for the very first time, the small contribution deals with the cost that is related to time in which the system remains in the defective state e.g., a pipeline leakage and the repair of the tooth as stated in the article of Santos and Cavalcante (2018). Since the Delay Time Model – DTM was formally defined 1982, it has undergone various modifications, most of which were made as a result of applying the DTM to different maintenance problems.

2.2.1 Application of DTM – Single Component systems:

In a single component system, if a defect is identified in the inspection, the component is replaced in non-repairable single component systems. Otherwise, the component will continue its operation until a failure occurs or a subsequent inspection identifies a failure, considering that in any of the situations the component is renewed and the process is resumed. The failure process of single component system is shown in Figure 2 below.

Figure – 2 Failure process of a single component system



Source: Wang (2008).

Wang (2008) states that the case of assuming a perfect inspection and the case of an imperfect inspection with the delay time model for a single component can be found in Baker and Wang (1991). The following are the additional assumptions and notations stated in Wang (2008):

1. The system is renewed at either a failure repair or at a repair done at an inspection if a defect is identified.
2. After either a failure renewal or inspection renewal the inspection process re-starts.
3. The initial time X, to the arrival of a defect has a probability density function $f(x)$.
4. The defective component identified at an inspection will be renewed either by a repair or a replacement.
5. The delay time h, has a known density function $f(h)$.
6. It is possible to model the way that defects arise since the delay-time concept can capture the relationship between the inspection interval and the number of plant failures.

Baker and Wang (1991) and Wang (2008) show in detail how to calculate the expected cost per renewal cycle of a system:

$$C(T) = \frac{E(CC)}{E(CL)}$$

Where CC is the cost of the renewal cycle, CL is the duration of the renewal cycle which is the interval between two consecutive renewals, E(CC) is the expected cost per renewal cycle and E(CL) is the expected length of the cycle. There may be two different renewal cycles, namely, renewal after failure and renewal after defect.

The delay time concept is being used to support the advancement of many mathematical models related to maintenance. Consequently, inspection intervals tend to be determined to avoid failures and their negative influences on the system. According to Alberti et al., 2018;

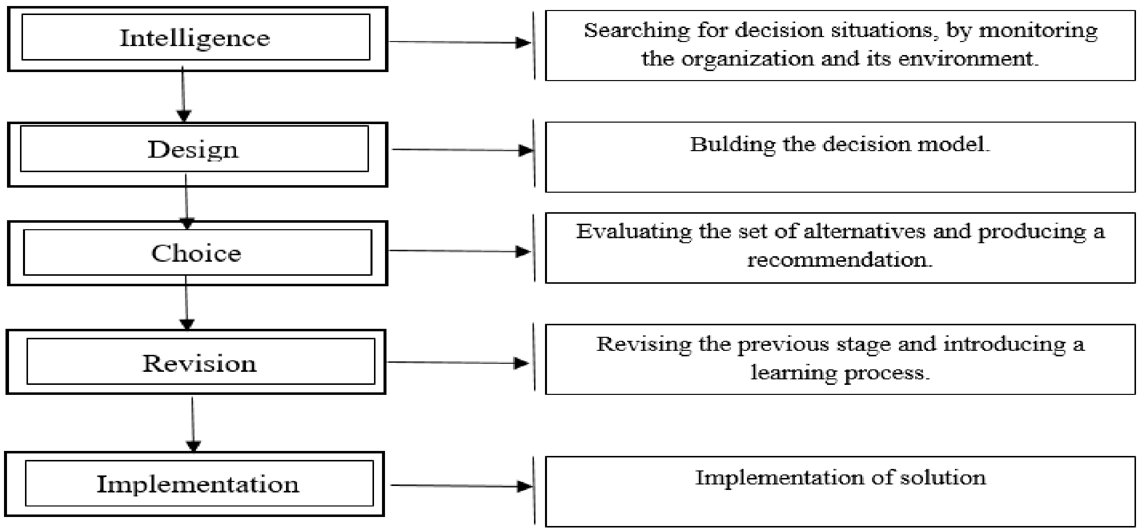
Cavalcante et al., 2019; the numbers of delay time models reported in the literature is increasing rapidly.

2.3 MULTICRITERIA DECISION-MAKING

As stated by de Almeida et al. (2015) in the multicriteria or multiobjective problem, more than one objective can be dealt with and that can lead to conflicting solutions. As Koksalan et al (2011) stated, the historical background and the relative perspective of multicriteria decision can be found in various texts. The general characterization of multicriteria decisions can be applied in building the class of multicriteria decision, that are applicable for variety of situations that are related to preference statements as described by (de Almeida et al., 2015).

Simon (1960) gives the model for the decision process that has five stages; as described in the figure below:

Figure – 3 Decision Process



Source: De Almeida et al. (2015).

In Figure 3, the stages of the Decision Process are described. Intelligence, Design and Choice are Stages 1 to 3 are the primary stages and Revision and Implementation are stages 4 and 5 and were added later.

2.3.1 Multicriteria Decision Methods

Multicriteria decision-making process in the manner of supporting, there are analytical methods available, as stated by GOMES *et al* (2002). These methods are able to structure decision problems to help the DM to recognize, equate and calculate the set of available replacements to find a desired option or a satisfactory solution, considering various criteria.

The literature on multicriteria decision methods is rich. A review of some methods can be easily found in Belton & Stewart (2002) and De Almeida (2015) etc. Thus, it quickly becomes apparent that many of the methods developed and presented for the handling of multicriteria decision problems can be classified into two large research groups that are recognized by European School of research and by the American School of research and even due to the compensatory rationality or non-compensatory measures that are being used on the criteria (de Almeida et al., 2015). The methods that are developed by the European School are the methods of the PROMETHEE family (BRANS & VINCKE, 1985; BRANS & MARESCHAL, 2002) and the ELECTRE family (ROY, 1996; TSOUKIAS and VINCKE, 1993; BELTON & STEWART, 2002). The contribution of the latter is recognized in several contexts (BEHZADIAN *et al.* 2010).

These methods are further classified by outranking methods that represent the DM's preferences in evaluating alternatives. These characteristics drive the present work to highlight the study on the multicriteria methods of overclassification, with emphasis on the PROMETHEE family.

2.3.2 The PROMETHEE Methods

The credit goes to J.P. Brans for developing PROMETHEE I (partial ranking) and PROMETHEE II (complete ranking) which was presented in 1982 for the first time. PROMETHEE II is a variation of PROMETHEE I as stated by (Belton & Stewart, 2002), as PROMETHEE II uses the conceptual basis PROMETHEE I, that are based on the recommendations of the second, offer a complete pre-order of the alternatives. In 1982, G. D'Avigon was already working on various application that use this methodology in the field related to units of health care. Dealing with these methods we discover that the key features of PROMETHEE I & II are partial pre-order and the complete pre-order respectively. The several methods of the PROMETHEE family that can be applied in different contexts in different places was explained by Behzadian, *et al.* (2010). Continuing the categorization of the PROMETHEE family, PROMETHEE III uses interval ordering to organize alternatives. PROMETHEE IV is intended for cases of continuous solutions, while PROMETHEE V is applied to solve portfolio selection problems and PROMETHEE VI uses the representation of preferences by means of value ranges for the criteria weights. As MACHARIS *et al.*, 1998; stated the explanation and addition to these methods. Other adaptations can be found in the literature.

2.3.3 The PROMETHEE II Method

The structure of PROMETHEE II is based on two operation modules. In the first occurrence, the characteristics of the criteria are assessed in order to indicate the range of differences between the performance of pairs of alternatives for each criterion. In this phase, the DM must enter information on the evaluation criteria, such as weights and preference functions. With this, it is possible that, in decision situations, the thresholds of preference and / or indifference about the performance of the alternative and the representation of the criteria become associated with a type of function to represent the DM's preferences (De Almeida, 2015).

The definition of functions for the criteria is dependent on the DM's interest in offering more information about his/her preferences. With that, it is possible to consider the thresholds of preference and indifference, and an elicitation process that leads to defining adequate values (De Almeida, 2015).

The first phase of the PROMETHEE II structure presents the interactions between parameters of the decision structure to establish the outranking relationships. Thus, the degree of outranking $\pi(a, b)$ is considered, calculated based on the comparison between two alternatives *a* and *b*, described by $P_i(a, b)$, related to a particular criterion and the interval preferably between (0,1). This index is defined by Vincke and Brans, (1985), where $w_i \geq 0$, $i = 1, 2, \ldots, n$ represents the relative importance of each criterion (which is sometimes referred to as the "weight" of the criterion).

In the second phase the outranking flows are defined that indicate the positive and negative relationships from the result of the pairwise comparison between the alternatives. The positive flow is expressed, and indicates the relationship in which the performance of *a* outperforms *b*. While the negative flow is expressed, and indicates outranking *b* in relation to alternative *a*. In these expressions, $(m-1)$ is the number of alternatives compared to a reference alternative *a*. Flows are calculated for each of the alternatives defined by the decision structure (BRANS & MARESCHAL 2002).

PROMETHEE II does not offer a specific rule for determining the weights of criteria, but assumes that the DM is able to determine appropriate values to represent the importance of the criteria, at least in situations where the number of criteria are not very great, or in situations where there are no factors that hinder the process of defining these values. When the complexity of the problem is greater and the number of criteria is extensive, the DM may present insecurity, discomfort and little knowledge or choose not to define exact values and, therefore, resorts to analytical methods that help the process of eliciting these values.

3 A MODEL TO SUPPORT THE DEFINITION OF INSPECTION INTERVALS FOR THE ELECTRICAL WIRING SYSTEM COMPONENT

In this chapter a model for the inspection of a single component to find the inspection interval is developed, considering the possibility of false positives occurring at inspections and the criteria that are to be evaluated are also discussed and modelled.

3.1 SOME MAIN SYSTEM STUDY

Before starting the modelling of this research, some information is given regarding the structure of the base theory that will help in modelling to support the definition of inspection intervals for electrical wiring systems components. This information is as follows:

In our daily life we need electrical wire to use electricity, as electricity has become essential in modern world (TOSHIFUMI et al., 2017). Electrical wire is commonly made from materials like silver, copper and aluminium. Copper and aluminium are the materials preferably used in electrical wires. As stated by Robert et al. (2013), copper and aluminium are good conductors of electricity. Therefore, they are used in wiring materials and in cables. Thus, in this thesis, we will be discussing the normal electrical wiring system that is used to supply the electrical energy from the generation power-plant to consumers.

The research is focused on a single electrical component i.e., electrical wire. Electrical components can become defective for many reasons e.g., the effects of the climate, less maintenance and because of the human error in maintenance. The major causes of failure are due to deterioration and contact failure of electrical components because of human error when maintaining the component (Won and Tae, 2018). Electrical wire is one of the components that are part of the entire system to supply energy to the population. If that wire fails, several consequences can occur. For example, the lack of supplying energy to people and industries in sufficient amounts and/or without interruptions can cause stoppages in production processes and can halt the lives of people. In short, for these and several other reasons and due to several other consequences that have already been discussed in section 1.1 of this thesis which describes the problem tackled, it is very critical to prevent the failure of the electrical wire. This why we have focused on the single component of electrical wire and its use in supplying electrical energy.

In this research, the elements of the single component version of delay time model were used to build the model and determine the functions that are treated as the decision criteria under the multicriteria approach. We use the PROMETHEE II method to appropriately deal with the conflicts between two criteria *Cost* – *Q(T)* and Mean Time Between Operational

Failure – *MTBOF(T)*. By following all the steps of PROMETHEE, the results show the order of the best met evaluation criteria.

Electrical wires are constantly exposed to the elements of Nature such as wind, rain, snowfall, thunderbolt, etc., over long periods of time and so there is always a huge demand for new inspection policies in order to keep the wire safe and in good working condition (Toshifumi *et al.*, 2017). Usually, the wire is maintained by the operator that regularly inspects wires and the wire is replaced if found to be defective and if necessary by period of time. The inspection work is performed by visual observation using video. It is a very difficult job to keep electrical wires in working condition and so developing a new policy for modelling an inspection is always in demand. Thus, in this section of the thesis, we develop a mathematical model which can be considered an inspection model for electrical wiring systems and by using this model a DM will have the opportunity to select the best time for an inspection with a view to detecting defects and making recommendations for repairs.

A false positive inspection results means that a component that does not have a defect is wrongly diagnosed as defective. A false positive occurs as the margin of error in all inspections that are not able to make accurate diagnoses. A false positive may occur because of the sensitivity to varying the weights of the criteria during the inspection e.g. the higher the sensitivity of an inspection, the greater the chance that the result will be a false positive (Hong et al., 2021).

3.2 MATHEMATICAL MODEL

The development of the model presented in this thesis was motivated by the need to review the inspection and maintenance models that are used for electrical wiring systems. Our model is based on the Delay Time Model and the PROMETHEE II method. As stated in earlier sections of this thesis, electrical wire is the most important component in the transportation of electrical energy, on which the socio-economic growth of any country, etc. depends. Therefore, there must be a constant supply of electrical energy without interruptions. Thus, a mathematical model is proposed in order to estimate the performance of a maintenance policy as a function of the time between two consecutive inspections (T), the aim of an inspection only being to identify the state of the components.

Concluding the description of the mathematical model in the research it will be noticed that the best policy will be the one in which we can identify the preferable time for the inspection in order to overcome the unreliability of the supply of electricity and to overcome the barrier that can affect economic growth and to prevent a defect leading to a system failure that can increase risks or result in a disaster. Let us keep in mind the two criteria that are aligned with the DM’s concerns, namely:

- COST PER TIME UNIT – Q(T)
- MEAN TIME BETWEEN OPERATIONAL FAILURES – MTBOF(T)

3.3 STRUCTURING THE RESEARCH MODEL

As described in previous sections, this research uses the delay time method to describe the failure process, justifying the adoption of an inspection policy based on the interval between inspections. The concept of delay time formalizes the decision process associated with the definition of maintenance policies, supported by mathematical models and, in addition, the multicriteria approach will be used to eliminate or mitigate conflicts. In this section, the proposed model is described; the different renovation scenarios are presented; and, in addition, the ratings are presented and the costs involved in the process are detailed.

3.3.1 Notations of the Model

The notations that are used in Table 1 are the main notations for the model and are used throughout this thesis.

Table – 1 Notations used in the development of the model

Decision Criteria	
T	The Interval Between Inspections
Q(T)	Cost Per Time Unit
MTBOF(T)	Mean Time Between Operational Failures
Parameters of the Model	
$\boldsymbol{\beta}$	Shape Parameter
$\boldsymbol{\eta}$	Scale Parameter
$\boldsymbol{\lambda}$	Average Delay Time
$\mathbf{C_F}$	Failure Cost (Corrective Maintenance)
$\mathbf{C_R}$	Cost of Preventive Maintenance
$\mathbf{C_I}$	Inspection Cost
$\propto$	False Positive

Source: Author (2021).

- Costs related to inspection, preventive replacement and replacement due to failure are respectively represented by C_F, C_R and C_I. It is important to note that $C_F > C_R > C_I$.
- P1(T), P2(T), P3(T), PTOTAL(T)….. are the probabilities associated with the scenarios.

3.3.2 Main Assumptions

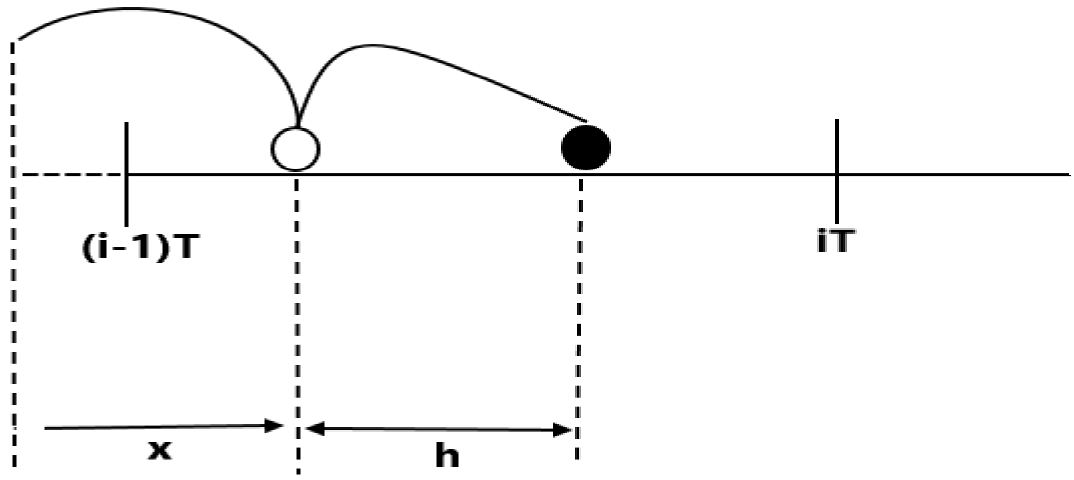
For the model developed here, some assumptions are made that are based on the concept of the delay time, which is moreover constructed on the cost function and on the other related parameters of the research. These assumptions are as follows:

- There is a failure mode in the component.
- Inspections are carried out on regular basis where T is the decision variable and represents the interval between two consecutive inspections.
- The inspection is not perfect, and thus there is a probability of it resulting in producing false positive i.e. the inspector made an error during the inspection and reported a defect even though there was no defect present. Meanwhile, the system continued operating in perfect mode.

The theoretical section of this thesis records that the pioneer of the delay time method was Christer (1982). Since then, a lot of research has been done in the field of maintenance considering the delay time method. The mathematical model present in this research is different from that in other models because it contains one additional scenario and then the two other scenarios of delay time. The scenario that is considered is false positive. The reason for introducing the false positive scenario in this thesis is because of the error that an inspector may make during the inspection. For example, if, during an inspection, the inspector makes 2 inspection errors out of 10 defects reported, that means 20% of the defects that the inspector reported were false positives. Along with all these three scenarios, for each scenario there is a probability associated with the existence of false positives. Therefore, considering these probabilities. we calculate the life of the component.

The model is based on the delay time model, so here are two classical (Traditional) Delay time scenarios and the additional scenario of this research related to False Positive inspections.

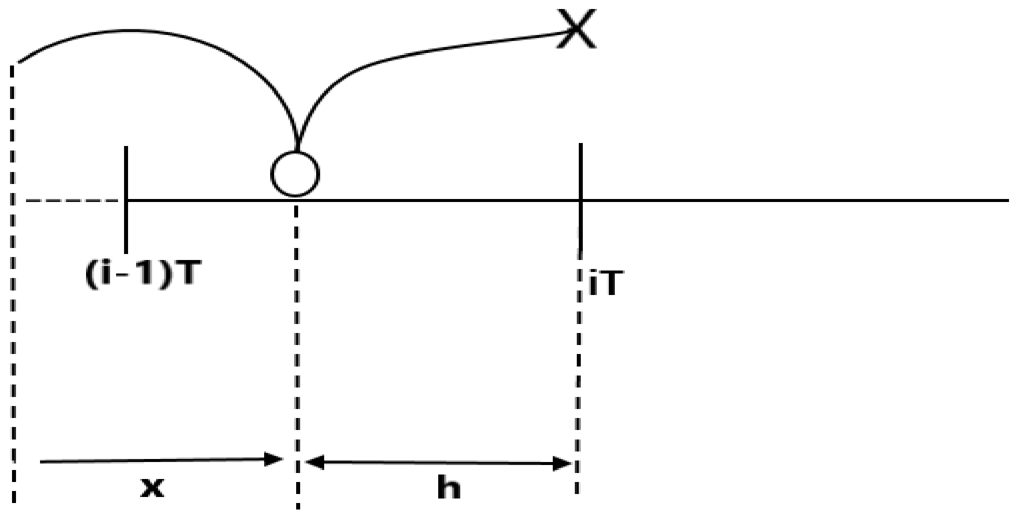
Figure – 4 Scenario # 1



Source: Author (2021).

In figure 4 it is shown that the defect arrives between inspections and becomes a failure before the next inspection (corrective replacement occurs).

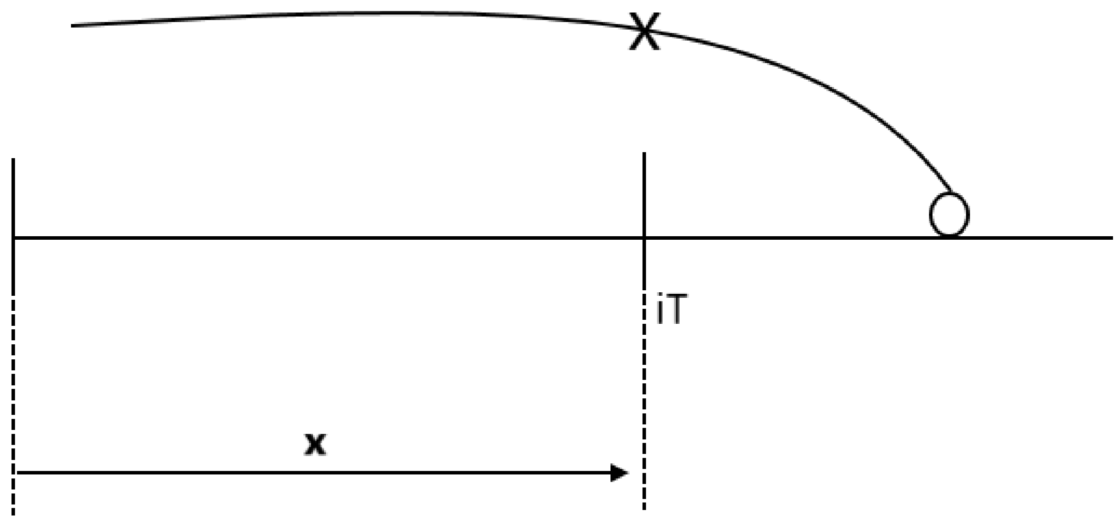
Figure – 5 Scenario # 2



Source: Author (2021).

In figure 5 it is shown that the defect arrives between inspections and the failure is avoided in the next inspection, by making a replacement (a preventive replacement occurs). The third scenario that is added in this research is:

Figure – 6 Scenario # 3



Source: Author (2021).

In figure 6, the third scenario that we consider is shown i.e., that of the false positive. A false positive is defined as being when there is no defect present, but the inspector says that there is a defect.

The system can be in any state e.g. Good, Defective or Failed. The defective state of the system can be recognized by the inspection, and the failure state is revealed immediately. A false positive occurs when the inspection says the system is defective when in fact it is good. There is always an effect on the reliability of the system and upon cost when there is an error of judgment (Berrade, *et al*., 2013). According to Ozekici and Pliska (1991), the most important scenario of their study is that the information is imperfect (the false positive). If an inspection yields a positive outcome due to an error of judgment that means a false positive has been wrongly detected in the system and this can lead to the wastage of time and money since, in fact, the defect does not exist. In this research, an inspection policy for the electrical wiring systems is modelled and the two classical (Traditional) Delay time scenarios are interlaced with an additional scenario of this research which is related to False Positive inspections. To illustrate the idea, it is considered that the DM makes an error of judgment twice in every 10 inspections which means that in every 10 inspections, there are two false positive inspections, and thus $\propto = 0.2$.

The maintenance and inspection of electrical wires is one of the most important utilities that need to be performed in order to maintain the reliability and accuracy of electrical distribution systems and this is justly required in order to protect personnel and equipment.

Starting with the scenario, along with all these three scenario for each scenario there is a probability associated with its existence, Therefore considering these probabilities we calculate the components expected life of the components.

- **Scenario 1, Probability:**

$$P1(T) := \sum_{i=1}^{\infty}[(1-\alpha)^{i-1}\int_{i-1}^{i.T} f_x(x)R_h(i.T-x)dx] \quad \textbf{(1)}$$

- **Scenario 2, Probability:**

$$P2(T) := \sum_{i=1}^{\infty}[(1-\alpha)i-1\int_{i-1}^{i.T} f_x(x)F_h(i.T-x)dx] \quad \textbf{(2)}$$

- **Scenario 3, Probability:**

$$P3(T) := \sum_{j=1}^{\infty}[\alpha.(1-\alpha)^{j-1}.Rx[T.(j)] \quad \textbf{(3)}$$

Considering the above-mentioned probabilities, the next equation constitutes the variables for calculating the total lifetime of the component.

$$\begin{aligned} V(T) = &\sum_{i=1}^{\infty}[i.T(1-\alpha)^{i-1}\int_{(i-1).T}^{i.T} f_x(x).R_h(i.T-x)dx + \sum_{j=1}^{\infty}[j.T.\alpha.(1-\alpha)^{j-1}.Rx.(jT)] \\ &+\sum_{i=1}^{\infty}[(1-\alpha)^{i-1}\int_{(i-1).T}^{i.T} f_x(x).\int_0^{i.T-x}(x+h).f_h(h)dhdx] \end{aligned} \quad \textbf{(4)}$$

After calculating the life of the component in the above equation, there is now the need to generate the equation for the Mean Time Between Operational Failure MTBOF (T).

$$MTBOF(T) = \frac{V(T)}{P2(T)} \quad \textbf{(5)}$$

From the above equation generated it is now easy to generate C(T) i.e., the expected cost of maintaining the system in a renewal cycle.

$$C(T)=\sum_{i=1}^{\infty}[(i.c_i+c_r)(1-\alpha)^{i-1}\int_{(i-1).T}^{i.T} f_x(x).R_h(i.T-x)dx]+$$
$$\sum_{j=1}^{\infty}[(j.c_i+c_r).\alpha.(1-\alpha)^{j-1}.Rx[T.(j)]]+\sum_{i=1}^{\infty}[(i-1).c_i+c_f] \quad \textbf{(6)}$$
$$.(1-\alpha)^{i-1}\int_{(i-1).T}^{i.T} f_x(x).F_h(i.T-x)dx]$$

Finally, the equation for the Cost per time unit – Q(T) is:

$$Q(T)=\frac{C(T)}{V(T)} \quad \textbf{(7)}$$

In addition, note that the probability density function (PDF) of the arrival times of a defect was adopted as a *Weibull*, which is represented in the following Equation:

$$f_x(x)=\left[\left(\frac{\beta}{\eta}\right).\left(\frac{x}{\eta}\right)^{\beta-1}.e^{-\left(\frac{x}{\eta}\right)^{\beta}}\right] \quad \textbf{(8)}$$

The distributions of delay time and cumulative density function (CDF) are given, respectively, in the following two Equations: exponential distribution.

$$f_h(h)=\lambda.e^{-\lambda.h} \quad \textbf{(9)}$$

$$F_h(h)=1-e^{-\lambda.h} \quad \textbf{(10)}$$

4 APPLYING THE MODEL TOGETHER WITH PROMETHEE II AND SENSITIVITY ANALYSIS

In this section, the first topic concerns applying and implementing the model in the real scenario using mathematical and multicriteria preference software. Since alternative rankings are considered according to the DM's choices, the DM can select the result according to his/her requirements. In the second topic, we will look at the result produced after applying mathematical and MCDM techniques in order to evaluate the sensitivity analysis.

The sensitivity analysis is conducted to know the uncertainty in the outputs from the model. The first sensitivity analysis only varied the false positive (alpha) which was varied from 0 to 0.4, and the second sensitivity analysis varied the costs (C_F, C_R, C_I). Thereafter, we will present the results and then the sensitivity analysis will be performed.

4.1 APPLICATION OF THE MODEL

Given the technological advancement of equipment in maintenance, it has become a challenge for companies that wish to remain competitive to achieve low cost and high production capacity. This is also true for this model in the context of electricity distribution. Though we have not been able to contact the electricity companies due to the current (2020) situation of the pandemic, but the utility of the model can still be observed when a real time scenario is used. Thus the contribution of this thesis is to put forward a new model to find the inspection interval for electrical wiring systems. In this section, a presentation is made of how the model is applied in order to gain the desired interval with the support of multicriteria between inspections keeping in mind the cost per time unit – Q(T) and the mean time between operational failures – MTBOF(T).

In addition, the main customers of the service which is provided by the electricity distributors via electrical wire are large industries that use electricity for productive processes because most of the machines in industrial plants depend on electricity and they have to stop working if there is a fault in electricity or if there is no electricity.

Due to the immense quantity of customers, scattered geographically over several different points, the electrical wires are spread in various areas above the surface at a certain height or in many cases underground also. Electrical wires can be found easily anywhere whether in industrial sites where their concentration is higher, beside and above normal roads for houses and shopping malls. Due to the high demand for electricity, we can find them in villages, bordering roads, within cities, close to environmental preservation areas etc.

Table 2 presents the parameters associated with the distributions used during the maintenance modelling. These are: the defect arrival function, $f\,x\,(x)$, that is considered to follow a *Weibull* distribution with a shape parameter $\beta = 3$ and a scale parameter $\eta = 1200\,days$, already for the delay time distribution function, $f\,h\,(h)$. A distribution was considered exponential with a parameter $\lambda = \frac{1}{300}$ days (i.e., the average delay time is 300 days).

Table – 2 Parameters associated with the distribution

	TYPE	PARAMETERS	
f x (x)	*Weibull*	$\beta = 3$	$\eta = 1200\,days$
f h (h)	*Exponential*	$\lambda = 1/300\,days$	

Source: Author (2021).

In Table 3, the Costs associated with maintenance actions are mentioned, where C_F is the failure cost (Corrective Maintenance), C_R is the cost of Preventive Maintenance and C_I is the inspection cost. These are the costs associated with the proposed model, in monetary values per unit of time.

Table – 3 Costs associated with maintenance actions

Costs	*C_F=250$*	*C_R=200$*	*C_I=100$*

Source: Author (2021).

After concluding table 3, the cost of failure, maintenance and inspection respectively, can be found. The probability ($\propto$), $\propto$ being determined according to the average of errors of judgments that occurred in the last inspections i.e. $\propto = 0.2$. Now in table 4, the ideal alternative intervals for inspection are shown, and are observed given the characteristics of *cost*, *mean time between operational failure.*

Table – 4 Decision alternatives

T Time alternatives									
10	*20*	*30*	*40*	*50*	*60*	*70*	*80*	*90*	*100*
110	*120*	*130*	*140*	*150*	*160*	*170*	*180*	*190*	*200*
210	*220*	*230*	*240*	*250*	*260*	*270*	*280*	*290*	*300*
310	*320*	*330*	*340*	*350*	*360*	*370*	*380*	*390*	*400*

Source: Author (2021).

So now we know all the parameters and even the ideal time of the alternatives has been defined, so they are evaluated in each of the criteria as explained above (Cost and Mean time between operational failure). The performance of each criterion of the alternatives can be easily seen in table 5.

Table – 5 Consequence Matrix

T Time Alternatives	***Cost – Q(T)***	***MTBOF - (T)***	***T Time Alternatives***	***Cost – Q(T)***	***MTBOF - (T)***
10	14.00	9022000	210	0.75	6751
20	7.00	1162000	220	0.72	6378
30	4.68	363500	230	0.70	6050
40	3.52	166100	240	0.68	5758
50	2.82	93780	250	0.65	5498
60	2.36	60560	260	0.63	5264
70	2.04	42820	270	0.61	5054
80	1.79	32290	280	0.60	4863
90	1.60	25530	290	0.58	4689
100	1.45	20920	300	0.57	4530
110	1.33	17630	310	0.55	4385
120	1.23	15180	320	0.54	4251
130	1.14	13310	330	0.53	4128
140	1.07	11850	340	0.51	4013
150	1.01	10670	350	0.50	3907
160	0.95	9707	360	0.49	3809
170	0.90	8910	370	0.48	3717
180	0.86	8239	380	0.47	3631
190	0.82	7668	390	0.47	3551
200	0.79	7177	400	0.46	3476

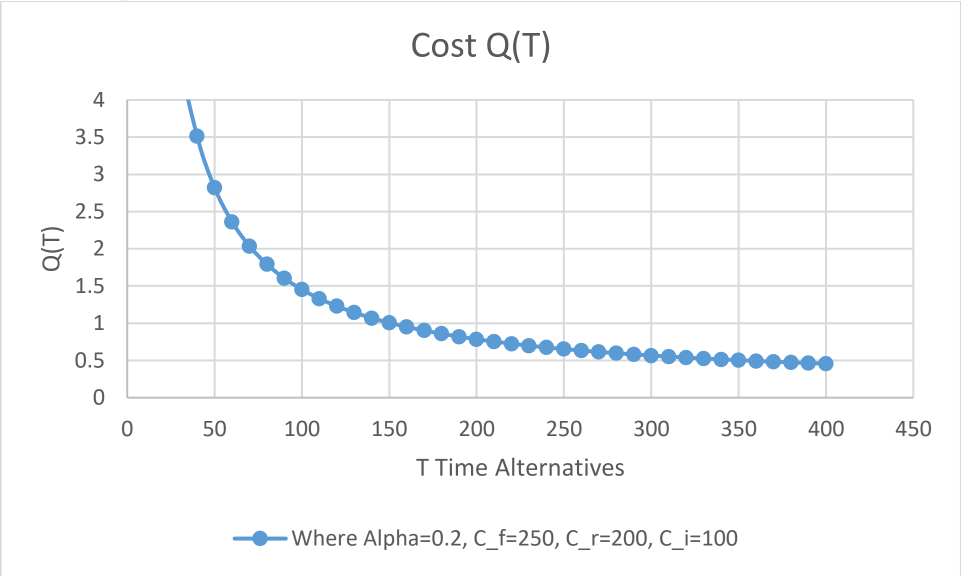
Source: Author (2021).

Now in table 5, the conflicts between MTBOF (T) and Q (T) can be seen easily, namely, the best alternative for the Q (T) is 400 according to the matrix as it gives the minimum cost, and the best alternative for the MTBOF (T) is 10 because it gives the maximum time to the operational failures, so here the importance of PROMETHEE II method will be defined, as the

PROMTHEE II method is used in this research for this purpose. Therefore, to deal with this large difference from the model, we will use the PROMETHEE II method to overcome the conflict between the alternatives.

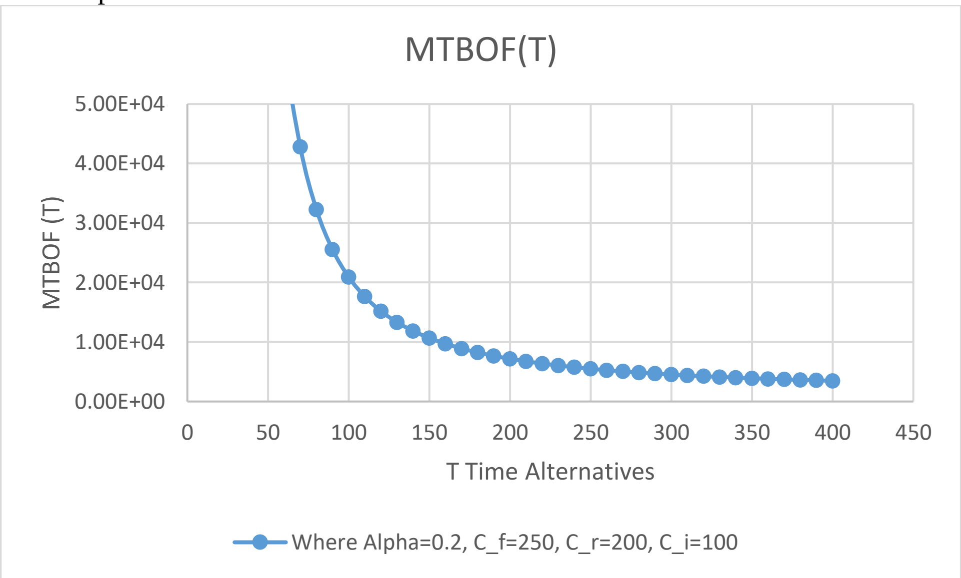
Now the outcome is entered into the Excel file to generate the results in the graphic mode so as to facilitate an understanding of what using those criteria have revealed to us when we have solved our model according to the given criteria. Remember that the third scenario, the 'False Positive', is aligned in this study i.e., $\propto$, and we have found that $\propto = 0.2$. That signifies that the error is 20% in this case.

Graph - 1 Behaviour of the 'Cost' function for the set of alternatives



Source: Author (2021).

Graph – 2 Behaviour of the 'MTBOF' function for the set of alternatives



Source: Author (2021).

So now after looking at the performance of the alternatives on each criterion in table 6 and in graphs 1 and 2, it is observed that there are conflicts. In other words, with regard to Alternatives with best performances in the cost criterion, the alternatives do not correspond with the best performance at the mean time between operational failure criteria.

In practice, this means that both the criteria that are considered in this research are opposite to each other and this shows that at a very high cost we get the maximum time for the inspection MTBOF and at a low cost we get the lowest time between operational failures. In order to overcome these conflicts, the PROMETHEE II method is considered. Thus, the fundamental issue is to observe alternatives performing well in two criteria and that the alternatives are better aligned with the preferences of the DM concerned.

Table 6 and graphs 1 and 2, which represents the behaviour of functions for the set of alternatives. It is observed that, when it comes to the cost per unit of time, T the inspection time should be as great as possible because this is the main interest of the DM, as the cost tends to decrease, in another view, *MTBOF* decreases. So table 6 shows clearly that the alternative that is better for the Cost Q (T) criteria is not the same as the alternatives that perform better for the MTBOF (T) criteria. Therefore, the PROMETHEE II method is used to overcome the conflicts between criteria and as a result, the DM can also observe what is the second most favourable alternative, the third one and so on.

Now with the PROMETHEE II following the steps, the DM establishes the weights for each criterion. This is initially considered as 0.5 for the Cost Q (T) and 0.5 for the MTBOF (T), where it simulates applying the process to a real DM, who considers the requirement to choose the best time interval for the inspection. The DM puts the data in the visual PROMETHEE software and runs the software and the software gives the best day as the result, and then the second best day, the third best one and so on. The result that is generated after applying PROMETHEE II method can be seen easily in Table 6 below.

Table – 6 Ordering of alternatives to do the inspection

Ordering	***Alternatives***	***Ordering***	***Alternatives***
1^{st}	90 days	21^{st}	10 days
2^{nd}	100 days	22^{nd}	230 days
3^{rd}	80 days	23^{rd}	20 days
4^{th}	110 days	24^{th}	240 days
5^{th}	120 days	25^{th}	250 days
6^{th}	70 days	26^{th}	260 days

7th	130 days	27th	270 days
8th	140 days	28th	280 days
9th	150 days	29th	290 days
10th	160 days	30th	300 days
11th	60 days	31st	310 days
12th	170 days	32nd	320 days
13th	180 days	33rd	330 days
14th	190 days	34th	340 days
15th	200 days	35th	350 days
16th	50 days	36th	360 days
17th	210 days	37th	370 days
18th	220 days	38th	380 days
19th	30 days	39th	390 days
20th	40 days	40th	400 days

Source: Author (2021).

So now we can easily see in Table 6, that after executing the PROMETHEE method, the alternative that came first was T = 90 (days) with the Cost – $Q(T) = 1.60$ and Mean time between operational failure – $MTBOF(T) = 25530.00$ and the representation of table 6 shows that the inspections should be carried out every 90 days.

After examining Table 6, we can see that we have already achieved our desired objective which was to find the inspection interval and now we know that we have to do the inspection of electrical wire every 90 days according to the data given and applied in this research.

Now as assurance, in the next topic, we will conduct a sensitivity analysis of the alpha, which in our case is False Positive. Thus, all we need to do is to vary the value of alpha in the application of the model and find the sensitivity analysis for alpha and with that we will also do the sensitivity analysis of costs which in our case are the Failure Cost (C_F), the Cost of Preventive Maintenance (C_R), and the Inspection Cost (C_I) respectively.

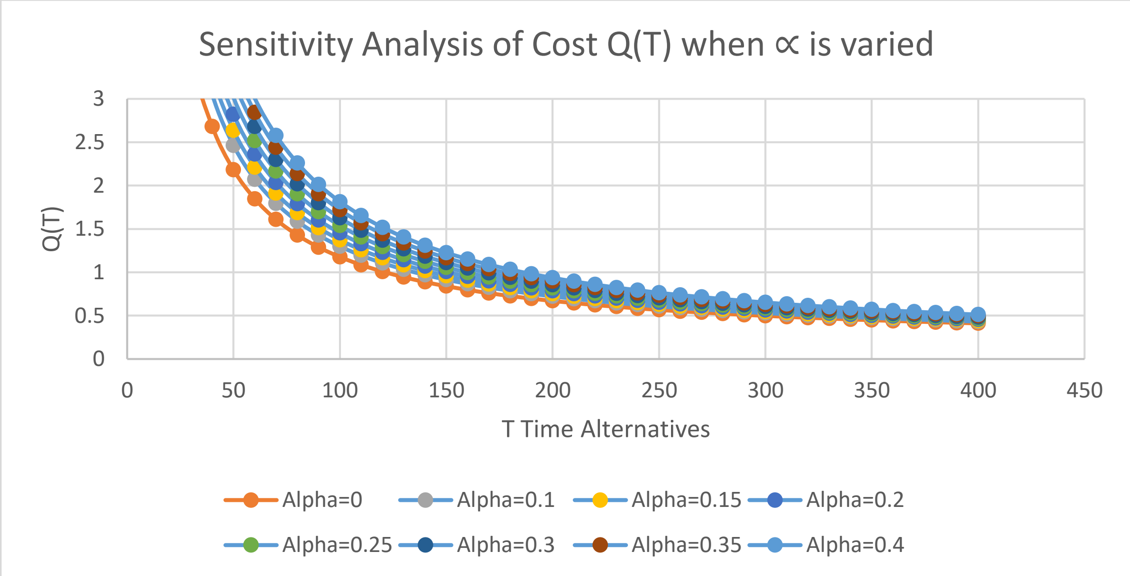
4.2 SENSITIVITY ANALYSIS

We will continue by varying our third scenario which in this case is false positive $\propto$ and will do the sensitivity analysis from all the data we obtain. The $\propto$ that is False Positive will be varied with the following values e.g.: $\propto = 0$, $\propto = 0.1$, $\propto = 0.15$, $\propto = 0.2$, $\propto = 0.25$, $\propto = 0.3$, $\propto =$

0.35 and $\propto = 0.4$. So after entering $\propto = 0.2$, $C_F=250$, $C_R=200$, $C_I=100$, the result according to the graphical view is as shown in Graphs 3 and 4.

By means of the sensitivity analysis applied to the model, expressed in Table 7 below, one can observe the influence of the parameters on the final results. It was decided to vary these parameters several more times. The other parameters were analysed with a variation of 5% in relation to the base case values. Graphs 3 and 4 show the impact of the variation of the parameter $\propto$ criteria. The recommendations made by each criterion are analysed and subsequently, the recommendation is presented using multiple criteria.

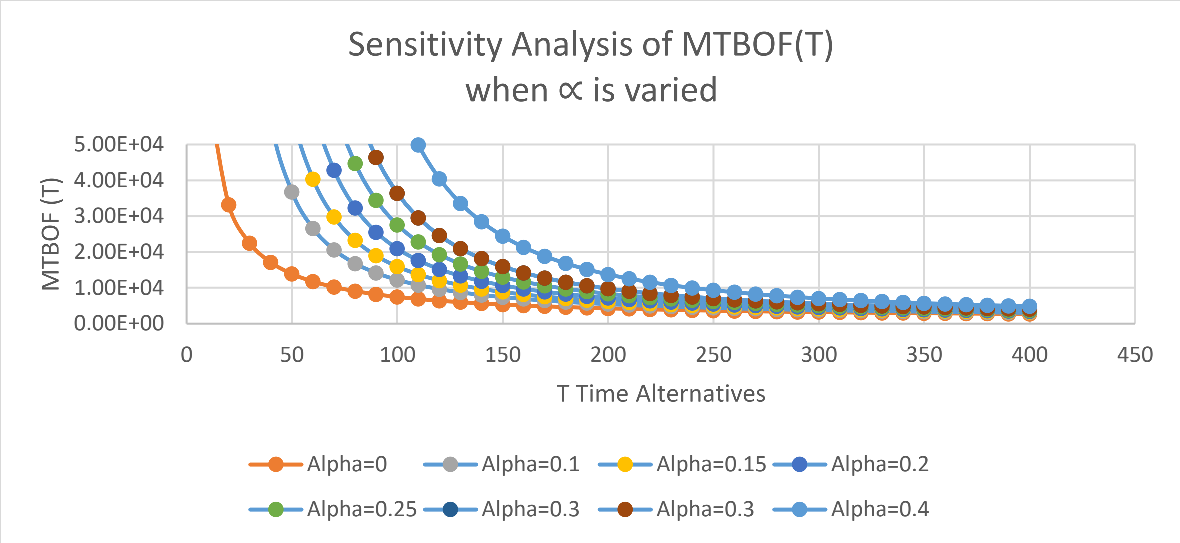
Graph – 3 Behaviour of the model for the Q(T) function



Source: Author (2021).

After doing the sensitivity analysis as shown in Graph 3 which explains that as the probability of a false positive ($\propto$) increases, the Q(T) of a renewal cycle also increases. The increase is due to the fact that more errors of judgment are made by the inspector. Accordingly, if the DM were to take only the costs involved into consideration, this criterion would recommend - as growth occurs - that inspections were more routine. It is possible to see in the graph that, for longer-term alternatives, the effect of the false positive variation is not very big. As for alternatives with a smaller interval, they are mostly affected by variations in the probability of there being a false positive.

Graph – 4 Behaviour of the model for the MTBOF(T) function



Source: Author (2021).

As shown in Graph 4, the MTBOF(T) of a renewal cycle also increases since the ∝ parameter grows. This second criterion recommends carrying out inspections every 10 units of time as per the DM's requirement as it is the time with a greater availability. It can also be seen, that in addition to the behaviour of the graphs, the two criteria continue to show the same trend with the variation of ∝. It is now possible to identify that if the same MTBOF value is to be maintained, if there are variations in quality (greater probability of false positive), the intervals between inspections must be increased to contain the tendency to interrupt the life of a device even earlier, Not defective. Another observation that can be made is that when setting a time value T = 100, variations in quality 0-0.30, this corresponds to an amplitude of variation in MTBOF of almost 30,000 time units. This implies that for each 10% variation in the false positive probability, this corresponds to a variation of 10,000 in MTBOF. This is a very critical factor in changing the reliability of the device.

Now, facing a multicriteria approach and expressing more, Table 7, highlights the main results obtained with the variation of all other parameters such as $\propto, Cf, Cr, Ci$.

Table – 7 SA report when ∝ & C_f, C_r, C_i are varied

Model Parameters							**Best Values**				
Case	**∝**	C_f	C_r	C_i	**η**	**λ**	**Q(T) Min**	**T**	**MTBOF(T) Max**	**T**	**Interval (T)**
1(case base)	0	250	200	100	1200	1/300	0.411	400	65310	10	90 Days

2	0.1	250	200	100	1200	$1/300$	0.432	400	2023000	10	90 Days
3	0.15	250	200	100	1200	$1/300$	0.444	400	4766000	10	90 Days
4	0.2	250	200	100	1200	$1/300$	0.456	400	9022000	10	90 Days
5	0.25	250	200	100	1200	$1/300$	0.469	400	15100000	10	90 Days
6	0.30	250	200	100	1200	$1/300$	0.483	400	23390000	10	90 Days
7	0.35	250	200	100	1200	$1/300$	0.497	400	34390000	10	90 Days
8	0.4	250	200	100	1200	$1/300$	0.512	400	48750000	10	90 Days
9	0.2	250	200	65	1200	$1/300$	0.375	400	9022000	10	70 Days
10	0.2	250	150	100	1200	$1/300$	0,418	400	9022000	10	90 Days
11	0.2	180	115	45	1200	$1/300$	0.244	400	9022000	10	50 Days
12	0.2	200	100	50	1200	$1/300$	0.25	400	9022000	10	60 Days

Source: Author (2021).

While analysing Table 7, we can easily measure what the condition of $\propto$ is from the table, which in our case is false positive and also the situation of C_f, C_r, C_i, these being C_f = Failure Cost (Corrective Maintenance), C_r = Cost of Preventive Maintenance, C_i = Inspection Cost, Respectively. Considering $\propto$ we can see in table 8, that we have varied $\propto$ 8 times with the values of: $\propto= 0$, $\propto= 0.1$, $\propto= 0.15$, $\propto= 0.2$, $\propto= 0.25$, $\propto= 0.3$, $\propto= 0.35$ and $\propto= 4$ and $C_f, C_r, C_i$with $C_f = 250, 200, 180$ $C_r = 200, 150, 115, 100$ $C_i = 100, 65, 50, 45$.

Regarding the costs involved, when the inspection cost C_i increases, inspections with longer intervals are recommended. The Q(T)- also increases for the costs of preventive replacement (C_r) and correction (C_f). However the inspection recommended by this criterion when the $\propto$ is varied, does not vary as it sticks on 90 days. These parameters have very little influence on the Q(T) and on the MTBOF(T).

Last but not the least in the cases of 9, 10, 11, 12 with the same possibility of the error that the inspector can make while doing the inspection i.e., $\propto= 0.2$, we increase and decrease the value of C_f = Failure Cost (Corrective Maintenance), C_r = Cost of Preventive Maintenance, C_i = Inspection Cost. The result produced was as expected. This shows the right decision, namely, it increases the inspection and the time of the inspection will be up to 50, 60 and 70 days less. This can be seen in Table 7.

The sensitivity analysis endorsed the results of the MCDM by revealing that this tool had the highest consistency, despite the changes in the scenarios. As stated by Evripidis et al. (2020), MCDM has grown from the part of (OR) operations research that was concerned with designing computational and mathematical tools. Moreover, MCDA is considered to be a new

OR approach to simple and complex problems. In this research we believe that our study will extend to a new route for a more current and workable model leading to greater utilization of electrical wires with less, unnecessary maintenance. Additionally, our analysis can also be useful for other electrical components. The Multi-Criteria approach brings all these benefits arising from this research that can lead to a more sustainable maintenance model with greater adeptness and one that minimizes unexploited sweats, hazards, and that reduces errors and adverse effects on times and costs.

5 CONCLUSION AND FUTURE WORK

As it managed to develop the model, this thesis will add to collaboration from the academic point of view as it is organised, conducted and introduced according to the bibliographic review on the essential concepts of maintenance, Delay Time and PROMETHEE II methods.

The model that is developed in this research will have a positive impact on Society and Industry as it will save costs and defines the mean time between operational failures by defining the inspection time. Applying the model proposed in this thesis will tend to lessen risks, hazards and disasters as electrical wires will be well maintained according to the time that will be defined after applying this research.

The important advantage that the electrical industries will have by adopting this maintenance model is that it offers an opportunity for the DM to choose the best interval for the inspection as this study, besides the first most preferable option, gives an order with the preferable options and that is the reason why this research is important as the DM has an opportunity to select the best inspection alternative according to his/her requirements and preferences.

This research introduces one additional scenario, namely the false positive one, to the normal two scenarios of delay-time. The reason for considering the third scenario is to include consideration of the possibility of errors of judgment. Furthermore, as far as future suggestions are concerned, it is recommended that more criteria be added as this will emphasize the need for more appropriate results in the service context as the area is a little outmoded in the industrial revolution. The electrical wiring systems were used to know the applicability of the model and its efficiency and it is found that the result was satisfactory. The model is able to find an interval (T) between inspections for the electrical wiring system and focuses on obtaining better results for the system.

The two major contributions that arise from using the model are the cost effectiveness of maintenance will be improved and that better control can be exerted to seek to prevent the unreliable supply of electrical energy.

Finally, an extension of the model is suggested for future research considering other parameters, such as defect induction, analysis of the effect of the opportunity and even the aggregation of false negatives (since we consider only false positives).

REFERENCES

ALBERTI, A. R.; CAVALCANTE, C. A.V.; SCARF, P.; SILVA, A. L. O. **Modelling inspection and replacement quality for a protection system**, 2018.

ALMEIDA, A. T.; SOUZA, F. M. C. **Gestão da Manutenção na Direção da Competitividade**. Recife: Ed. Universitária da UFPE, 2001.

ALMEIDA, A. T. **Process of decision organizations**: constructing models of multicriteria decision. São Paulo: Editora Atlas, 2013.

AMARAL, T.; COSTA, A. Improving decision-making and management of hospital resources: An application of the PROMETHEE II method in an Emergency Department. **Operations Research for Health Care.** 3. 1–6. 10.1016/j.orhc.2013.10.002, 2014.

ANDREA, S. Sensitivity Analysis for Importance Assessment. **Risk analysis:** an official publication of the Society for Risk Analysis. 22. 579-90. 10.1111/0272-4332.00040, 2002.

BAKER, R. D.; CHRISTER, A. H. Reviewing delay-time OR modelling of engineering aspects of maintenance**. European Journal of Operational Research**, v. 73, p. 407-422, 1994.

Baker, R.; Wang, W. Estimating the delay-time distribution of faults in repairable machinery from failure data. **IMA Journal of Management Mathematics** - Ima J Manag Math. 3. 259-281. 10.1093/imaman/3.4.259, 1991.

BEHZADIAN, M.; KAZEMZADEH, R.; ALBADVI, A.; AGHDASSI, M. PROMETHEE: A comprehensive literature review on methodologies and applications. **European Journal of Operational Research**. 200. 198-215. 10.1016/j.ejor.2009.01.021, 2010.

BELTON, V.; STEWART, T. **Multiple Criteria Decision Analysis**: An Integrated Approach. 10.1007/978-1-4615-1495-4, 2002.

BEN-DAYA, M.; KUMAR, U.; MURTHY, D.N.P. **Introduction to maintenance engineering**: modelling, optimization, and management. Chichester: Wiley, 2016.

BEN-DAYA, M.; DUFFUAA, S. O.; RAOUF, A.; KNEZEVIC, J.; AIT-KADI, D. (orgs.). **Handbook of maintenance management and engineering**. London: Springer, p. 44-74, 2009.

BERRADE, M. D.; SCARF, P.; CAVALCANTE, C.; DWIGHT, R. Imperfect inspection and replacement of a system with a defective state: a cost and reliability analysis. **Reliability Engineering** [?] System Safety. 120. 80-87. 10.1016/j.ress.2013.02.024. 2016.

BRANS, J. P.; MARESCHAL, B. **Prométhée-Gaia**: a decision support methodology in the presence of multiple criteria, 2002.

CAPPUCCIO, D. Ensure cost balances out with risk in high-availability data centres. **Gartner,** 2013.

CAVALCANTE, C. A. V.; LOPES, R.S. Multi-criteria model to support the definition of opportunistic maintenance policy: A study in a cogeneration system. **Energy**, v. 80, p. 32-40, 2015.

CAVALCANTE, C.A.V., SCARF, P.A., BERRADE, M.D. Imperfect inspection of a system with unrevealed failure and an unrevealed defective state, **IEEE Trans. Reliability**, 2019.

CHRISTER, A. H. Innovatory decision making. *In*: **NATO conference on role and effectiveness of decision theory in practice**, 1976.

CHRISTER, A. H.; WALLER, W. M. Delay time models of industrial inspection maintenance problems. **Journal of the Operational Research Society**, v. 35, n. 5, p. 401-406, 1984.

CHRISTER, A. H. Developments in delay time analysis for modelling plant maintenance. **Journal of the Operational Research Society**, v. 50, 1999.

CULLUM, J.; BINNS, J.; LONSDALE, M.; ABBASSI, R.; GARANIYA, V. Risk-Based Maintenance Scheduling with application to naval vessels and ships. **Ocean Engineering**, v. 148, p. 476-485, 2018.

DE ALMEIDA, A. T.; CAVALCANTE, C. A. V.; ALENCAR, M. H.; FERREIRA, R. J. P.; ALMEIDA-FILHO, A. T.; GARCEZ, T.V. Multicriteria and Multiobjective Models for Risk. **Reliability and Maintenance Decision Analysis**, Springer, v. 231, 2015.

DE FARIA JR, H.; COSTA, J. G. S.; OLIVAS, J. L. M. A review of monitoring methods for predictive maintenance of electric power transformers based on dissolved gas analysis. **Renewable and sustainable energy reviews**, v. 46, p. 201-209, 2015.

DER MAUER, M. A.; BEHRENS, T.; DERAKHSHANMANESH, M.; HANSEN, C.; MUDERACK, S. Applying Sound-Based Analysis at Porsche Production: Towards Predictive Maintenance of Production Machines Using Deep Learning and Internet-of-Things Technology. *In:* **Digitalization Cases. Springer, Cham**, p. 79-97, 2019.

Dhillon, B.S. **Engineering Maintenance**: a modern approach. Boca Raton, FL: CRC, 2002.

DUNN, S. The fourth generation of maintenance. *In:* INTERNATIONAL CONFERENCE OF MAINTENANCE SOCIETIES (ICOMS 2003), Perth, Australia. **Proceedings** […]. Perth: ICOMS, 2003.

Evripidis, K.; Sotiris, G.; Grigorios D., K; Georgios, P. An Application of a Multi-Criteria Approach for the Development of a Process Reference Model for Supply Chain Operations. **Sustainability.** 12. 5791. 10.3390/su12145791, 2020.

FERREIRA, R. J. P.; DE ALMEIDA, A. T.; CAVALCANTE, C. A. V. A multi-criteria decision model to determine inspection intervals of condition monitoring based on delay time analysis. **Reliability Engineering & System Safety**, v. 94, 2009.

FRANKLIN, B. **The Canon of Benjamin Franklin, 1722-1776**: new attributions and reconsiderations. **(**American Literature, 1722).

FISHER-VANDEN, K.; MANSUR, E.; WANG, Q. Electricity Shortages and Firm Productivity: Evidence from China’s Industrial Firms. **Journal of Development Economics,** 2015.

G, D'Avignon. Projects ordering with multicriteria analysis. **European Journal of Operational Research**. 10. 56-69. 10.1016/0377-2217(82)90132-1, 1982.

GILL, P. Electrical power equipment maintenance and testing / Paul Gill. **SERBIULA,** 2020.

GOMES, L. F. A. M.; GOMES, C. F. S.; ALMEIDA, A. T. **Tomada de decisão gerencial**: enfoque multicritério. São Paulo: Editora Atlas: 2002.

GRAINGER, C.; ZHANG, F. Electricity shortages and manufacturing productivity in Pakistan. **Energy Policy**, 2019.

HAMMOND, J.; KEENEY, R.; RAIFFA, H. The Hidden Traps in Decision Making. Clinical laboratory management review: official publication of the **Clinical Laboratory Management Association** / CLMA. 13. 39-47, 1998.

HICKS, T. G. Piping. **Maintenance engineering handbook**. 7ed, New York: McGraw-Hill, 2008.

Hong, C.; Hyuk, L.; Jin-Young, C.; Is a False Positive really False Positive?. 145-149. 10.23919/ICACT51234.2021.9370442, 2021.

HORENBEEK, A.; PINTELON, L.; MUCHIRI, P. Maintenance optimization models and criteria. **International Journal of System Assurance Engineering and Management**, 2011.

KEENEY, H. RAIFFA. Decisions with multiple objectives–preferences and value tradeoffs. Behavioral Science. 39. 10.1002/bs.3830390206, 1976.

KHAN, M.; QAYYUM, A. The demand for electricity in Pakistan. **OPEC Review,** 2009.

KOKSALAN, M.; WALLENIUS, J.; ZIONTS, S. Multiple criteria decision making: From early history to the 21st century, **World Scientific,** 2011.

LEE, H.; CHA, J. H. New stochastic models for preventive maintenance and maintenance optimization. **European Journal of Operational Research**, v. 255, n. 1, p. 80-90, 2016.

LEE, J.; KWON, D.; Kim, N.; LEEA, C. PHM-based Wiring System Damage Estimation for Near Zero Downtime in Manufacturing Facilities. **Reliability Engineering & System Safety**. 184. 10.1016/j.ress.2018.02.006, 2018.

MACHARIS, C.; BRANS, J.P.; MARESCHAL, B. The GDSS PROMETHEE procedure – A PROMETHEE-GAIA based procedure for group decision support. **Journal of Decision Systems, 7, 283,** 1998.

MCKONE, K.; ELLIOT, W. TPM: planned and autonomous maintenance: bridging the gap between practice and research**. Production and Operations Management** 1998.

MILLET, G.; BRUILLOT, S.; DEJARDIN, D.; IMBERT, N.; AUZANNEAU, F.; INCARBONE, L.; OLIVAS-CARRION, M.; VINCENT, L.; CREMIZI, A.; POIGNANT, S. Aircraft Electrical Wiring Monitoring System, 2014.

MOBLEY, R. K. Introduction to the theory and practice of maintenance. **Maintenance Engineering Handbook**. New York: McGraw-Hill, p. 1.3-1.10, 2002.

MOUBRAY, J. Reliability-centered maintenance, 2nd ed., **Butterworth-Heinemann,** Oxford, UK, 1997.

MOUSSAULT, S.; PRUYN, J.; VOORT, E.; IJSERLOO, G. Modelling Maintenance - Cost Optimised Maintenance in Shipping, 2020. In V. Bertram (Ed.), Proceedings of the 12th Symposium on High Performance Marine Vehicles, HIPER '20 (pp. 196-213). Technische Universität Hamburg-Harburg.

NAQVI, Z.; RAHBAR, A. A survey on citizenship accidents in the Electricity Distribution Company in a 5-year period, **Safety message,** 2009.

NAZMUS, S.; THORSTEN, W. Challenges and Opportunities of Condition-based Predictive Maintenance: A Review. **Procedia CIRP**. 2018.

OSMANI, K.; HADDAD, A.; LEMENANAD, T.; CASTANIER, B.; RAMADAN, M. A review on maintenance strategies for PV systems. **Science of "The Total Environment",** 2020.

Ozekici, S. & Pliska, Stanley. Optimal Scheduling of Inspections: A Delayed Markov Model with False Positives and Negatives. **Operations Research**. 39. 261-273. 10.1287/opre.39.2.261. 1991.

PARIDA, A.; KUMAR, U.; GALAR, D. Decision Making Based on Maintenance Data Fusion of Different Nature. **Sixth Annual World Congress on Engineering Asset Management (WCEAM).** Cincinnati, Ohio. USA, October 2 - 5, 2011.

PINTELON, L.; PARODI-HERZ, A. Maintenance: an evolutionary perspective. In: KOBBACY, K. A. H.; MURTHY, D. N. P. (Orgs.) **Complex System Maintenance Handbook**. New York: Springer, p. 21-48, 2008.

RAIZ, H. Energy saving and conservation measures. **Pakistan Textile Journal, 41–42, April**, 2008.

REASON, J. Cognitive Engineering in Aviation Domain, **Lawrence Erlbaum Associates, Mahwah**, NJ, 2000.

Robert, S. Fred, M. and Garris, III. Electrical wire and method of fabricating the electrical wire. 2013.

RODRIGUES, A. J. da S. Multicriteria model based on the FITradeoff method for defining inspection times in a system subject to imperfect inspections. 2020. **Dissertation (Master's in Production Engineering) - Federal University of Pernambuco**, Recife, 2020.

ROY, B.; VANDERPOOTEN, D. The European school of MCDA: Emergence, basic features and current works**. Journal of Multi-criteria Decision Analysis,** 1996.

Santos, Augusto & Cavalcante, Cristiano. Insight into cost of defective state using delay-time concept. 10.19124/ima.2018.001.24. 2018.

SANTOS, A. **Proposta de metodologia para modelagem da manutenção e inserção do custo em estado defeituoso em modelos DELAY TIME para componente simples e para sistema multicomponente** [Master's thesis]. Recife, Brazil: Federal University of Pernambuco, 2019.

Scarf, P. Cavalcante, C. Richard, A, D. and Peter Gordan. An Age-Based Inspection and Replacement Policy for Heterogeneous Components. **IEEE Transactions on Reliability,** v.58, 2009.

Scarf, Phil & Cavalcante, Cristiano. Modelling quality in replacement and inspection maintenance**. International Journal of Production Economics**. 135.10.1016/j.ijpe.2011.08. 011. 2012.

Scarf, Phil & Dwight, Richard & Al-Musrati, A. On reliability criteria and the implied cost of failure for a maintained component. **Reliability Engineering & System Safety**. 89. 10.1016/j.ress.2004.08.019. 2005.

SCURATI, G. W.; GATTULLO, M.; FIORENTINO, M.; FERRISE, F.; BORDEGONI, M.; UVA, A. E. Converting maintenance actions into standard symbols for Augmented Reality applications in Industry 4.0. **Computers in Industry**, v. 98, p. 68-79, 2018.

SIMEU-ABAZI, Z.; SASSINE, C. Maintenance integration in manufacturing systems by using stochastic Petri nets. **International Journal of Production Research**. 37. 2010.

Simon, H. **The New Science of Management Decision**, 1960.

SINGH, G.; KUMAR, T. C. A.; NAIKAN, V. N. A. Efficiency monitoring as a strategy for cost effective maintenance of induction motors for minimizing carbon emission and energy consumption. **Reliability Engineering & System Safety**, v. 184, 2019.

TANG, D.; MAKIS, V.; JAFARI, L.; YU, J. Optimal maintenance policy and residual life estimation for a slowly degrading system subject to condition monitoring. **Reliability Engineering & System Safety**, 2015.

Toshifumi, K.; Mizuki, H.; Tadahito, E.; Kazuhiko, T.; Yutaka, H. **Electric wire inspection by discriminant analysis method.** 251-254. 10.1109/ICMLC.2017.8107773, 2017.

VINCKE, J.P.; BRANS, P. A preference ranking organization method the PROMETHEE method for MCDM. **Management Science.** 31. 647-656, 1985.

TSOUKIAS, A.; VINCKE, P. Multicriteria Decision-Aid. **The Journal of the Operational Research Society.** 44. 317. 10.2307/2584205, 1993.

WAEYENBERGH, G.; PINTELON, L. A framework for maintenance concept development. **International Journal of Production Economics** – 2002.

Wang W. A delay-time based approach for risk analysis of maintenance activities. **Journal of the Safety and Reliability Society**, 23(1): 81. 103-113, 2003.

WANG, C.; HWANG, S. A stochastic maintenance management model with recovery factor. **Journal of Quality in Maintenance Engineering**, Vol. 10, 154-165, 2004.

WANG, W. Delay time modelling. In: KOBBACY, A. H.; MURTHY, D. N. P. **Complex System Maintenance Handbook. London:** Springer, 2008.

WANG. W. An overview of the recent advances in delay-time based maintenance modelling. **Reliability Engineering and System Safety**, v. 106, 2012.

WANG, J.; ZIONTS, S. The aspiration level interactive method (AIM) reconsidered: Robustness of solutions. **European Journal of Operational Research**. 175. 948-958. 10.1016/j.ejor.2005.06.039, 2006.

Won, C.; Tae, A. A Classification of Electrical Component Failures and Their Human Error Types in South Korean NPPs during Last 10 Years. **Nuclear Engineering and Technology**. 51. 10.1016/j.net.2018.12.011, 2018.

WU, S.; COOLEN, F.; LIU, B. Optimization of maintenance policy under parameter uncertainty using portfolio theory. **IISE Transactions**, v. 49, n. 7, p. 711-721, 2017.

XIAONING, J.; SIEGEL, D.; WEISS, B. G.; ELLEN & WANG, W.; LEE, J.; NI, J. The present status and future growth of maintenance in US manufacturing: **Results from a pilot survey. Manufacturing Review**, 2016.