Master Thesis

Master's degree in Smart Electrical Networks and Systems (SENSE)

A static approach to investigate the impact of predictive maintenance in the reliability level and the failure cost of industrial installations

Thesis

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Abstract

Digital IoT (Internet of Things) solutions for equipment condition monitoring and new advanced algorithms to process big data, enable the application of predictive maintenance. Consequently, actual implementations of such a system in industrial installations triggers the verification of its potential benefits. Thus, this project attempts to quantify the impact of a predictive maintenance system in the failure rate and the maintenance cost of industrial installations.

The lack of time depended data lead to a static approach that utilizes average failure rate and mean time to repair values coming from IEEE standards and other sources. Next, a methodology that links the equipment causes of failure with a predictive maintenance system functions, is proposed. Consequently, new reduced failure rates for the assets under monitoring are defined.

To perform the reliability calculations the spreadsheet methodology is presented and utilized. Additionally, the revenue requirement methodology is described and is used for the cost benefit analysis.

Finally, the approach is applied in two theoretical and two actual industrial installations. Sensitivity analyses regarding different parameters of a predictive maintenance system are conducted in the first two cases, to evaluate the impact on different reliability indices. Moreover, cost benefit analysis is performed in the actual industrial networks and according to the results predictive maintenance should be preferred. Lastly, regarding the failure rate, a small or high reduction is observed depending on the type of failures, the utility sources, the system configuration, the number of monitored equipment and other parameters.

Keywords:

Asset management, predictive maintenance, reliability, failure rate, maintenance cost, revenue requirement method, spreadsheet methodology, industrial installations maintenance.

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Abbreviations

A	Availability
Ai	Inherent availability
CAPEX	Capital Expenditures
CB	Circuit Breaker
CBM	Condition Based Maintenance
CCF	Common Cause of Failure
ED	Electrical Distribution
FiS	Failure in Service
FMECA	Failure Mode, Effect and Criticality Analysis
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
LF	Lambda Factor
LV	Low Voltage
Mdt	Mean downtime
MRR	Minimum Revenue Requirement
MTBF	Mean Time Between Failure
MTTR	Mean Time to Repair
MV	Medium Voltage
O&M	Operations and Maintenance
OPEX	Operating Expenditure
PdM	Predictive Maintenance
PM	Preventive Maintenance
RBD	Reliability Block Diagrams
RCM	Reliability Centered Maintenance
Rdt	Repair downtime
RR	Revenue Requirement
TCO	Total Cost of Ownership
Tf	Total failures
Tp	Total period

1. Introduction

In this small chapter the background, the motivation, the objectives and the outline of the project are summarized.

1.1. Background

Nowadays, due to different business drivers and global economic factors, the capital investment and the maintenance cost of the assets should be optimized and financially be justified. At the same time, the demand for asset reliability and availability continuous to increase, changing in that way the concept of asset management and requiring efficient maintenance strategies.

Maintenance of electrical infrastructure in an industrial environment is crucial to ensure safety, service continuation, energy efficiency of the equipment and total cost of ownership optimization. A forced outage can have detrimental financial impact on the business and can generate a series of unpredictable events. Nevertheless, there are different maintenance approaches that can be followed to prevent that from happening. Except from reactive, when actions are taken after a failure occurs, preventive, predictive and reliability centered maintenance attempt to reduce the number of failures.

The industry today applies, in the best case, an on-site condition-based approach under a preventive maintenance concept. Although, advances in digital IoT solutions for equipment condition monitoring, along with new advanced algorithms to process big data, enable a new potential of maintenance strategies. Thus, predictive maintenance becomes possible providing condition-based maintenance and fault prediction based on real time and historical data. That is an important step towards reliability centered maintenance, a strategy that combines all the maintenance approaches in a cost-effective way considering higher safety and reliability.

The motivation of this project comes from the actual implementations of a predictive maintenance system in industrial installations and attempts to quantify its impact on the failure rate and the maintenance cost. No such attempt has been found in the bibliography while the topic can be considered a quite complex process. Although, based on a static approach, a simple tool and a proposed methodology a preliminary assessment of predictive maintenance impact is presented. That analysis could potentially assist different stakeholders to take investment decisions in their installations.

1.2. Objectives of the project

The objectives of the project are the following:

- Based on the available data and resources, identify and understand the tool that enables a reliability analysis with sufficient result accuracy.
- Identify a methodology that enables cost benefit analysis considering reliability indices.
- Identify the causes of failure of equipment under monitoring.
- Link the causes of failure with the functions of a predictive maintenance system.
- Define an approach to measure the impact of predictive maintenance on the failure rate of assets under monitoring.
- Apply the proposed methodologies in theoretical and real case systems and quantify the impact of predictive maintenance on the failure rate and the maintenance cost of industrial installations.

1.3. Thesis outline

The report consists of six chapters followed by conclusions and some proposals for future work. In summary the outline of the thesis report is the following:

- *Chapter 1*, which is the current chapter, presents briefly the background, the motivation and the objectives of the project.
- *Chapter 2* provides briefly the different maintenance practices with their advantages and disadvantages along with the basic reliability concept required for the understanding of the project. At the end, the different methodologies to perform reliability analysis are summarized.
- *Chapter 3* explains the motivation for choosing the spreadsheet methodology to perform the reliability analysis. Additionally, the background of the method is presented along with the description of the utilized tool.
- *Chapter 4* presents the revenue requirement method which is the identified methodology to perform cost benefit analysis based on reliability indices.
- *Chapter 5* describes the applied approach to evaluate the impact of predictive maintenance on the failure rate. Furthermore, the causes of failure are presented along with their link with the predictive maintenance system functions.
- *Chapter 6* presents the results of the application of the proposed approach in two theoretical systems and in two real cases. Cost benefit and different sensitivity analyses are also described.

2. Maintenance Types and Reliability Basics

Maintenance is defined as the series of actions that need to be taken to maintain equipment in a proper condition. Additionally, maintenance includes all the steps that are necessary to prevent a component from failing or to control equipment degradation due to its operation. The purpose of it is to keep systems and equipment in operation at an efficient level for at least design life. At an electrical distribution (ED) level, maintenance can have the following benefits [2]:

- Ensures equipment protection and safety
- Minimizes service interruptions
- Ensures the energy efficiency of the equipment
- Enables efficient management of spare parts
- Optimizes the total cost of ownership (TCO) which includes the capital expenditures (CAPEX) and the operating expenses (OPEX)

Maintenance and equipment failure are interconnected since maintenance practices or the absence of them (reactive approach), have an impact on the failure rate of a component or a system.

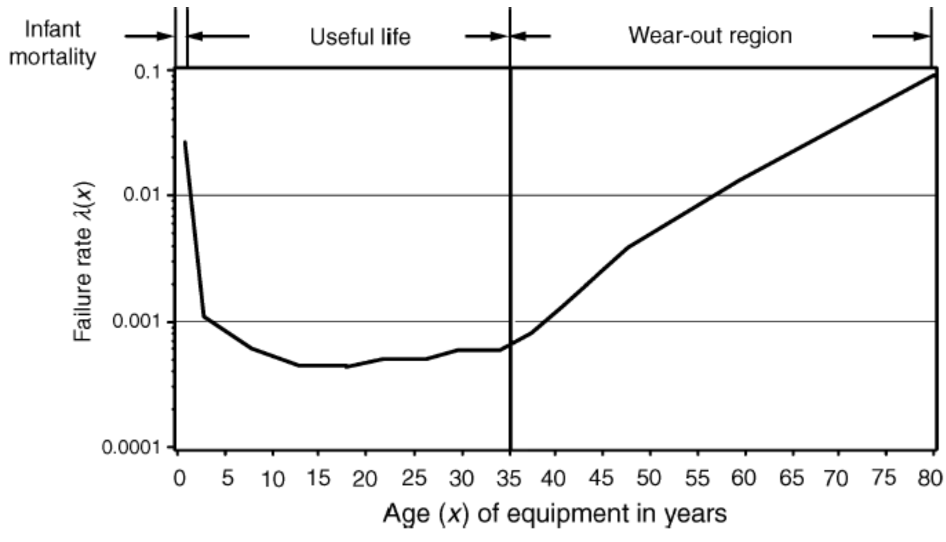


Figure 1 Equipment failure rate over time [3]

The failure rate of equipment, as a function of time can be represented with the so-called bathtub curve shown in figure 1 [3] [4]. The curve is divided in three regions based on the characteristics of the failure rate. The first one, called infant mortality, is presenting a high component failure that can be attributed to poor installation or misapplication and poor design. Next, the useful life period follows, characterized by an almost constant failure rate for a long period of time. Failures during that region are caused due to poor O&M practices and it is generally agreed that preventive and predictive maintenance strategies can have a beneficial impact and extend that period [5]. Finally, a rapid increase of failure rate is taking place during the ware out period due to the impact of deterioration.

Based on the bathtub curve, the useful life period can be modeled using the exponential distribution, whereas the wear out period can be represented by the Weibull distribution [3]. More details regarding the exponential distribution and its use, will be presented in the following sections.

Maintenance can be performed in different ways in an industrial environment, thus a brief description of each one of them is presented in the following sections, along with their advantages and disadvantages. The focus should be on the predictive maintenance approach which is under the scope of this project.

2.1. Reactive Maintenance

This type of maintenance is referred to the repair actions after a failure and is based on the concept of taking no actions till a failure appears. Based on studies, this is the predominant maintenance strategy applied in the industry [5]. The results of reactive maintenance can be temporary or curative [2]. The first allow a faulty item to perform its function till repair actions take place, while the latter resumes the component to its initial healthy state. The advantages and the disadvantages of a reactive maintenance strategy are the following [5] [6]:

- Advantages
    - Low cost during the time between failures since no maintenance actions are taking place.
    - Less staff requirements since no maintenance personnel is needed during periods without a failure.
    - It is the right approach for equipment that is not repairable (like small electronics) and doesn't interrupt the business processes.

- Disadvantages
    - During unplanned downtimes the cost increases rapidly
    - The labor cost also increases
    - Inefficient use of staff resources is taking place
    - Additional cost is involved with repair or replacement of components
    - There is a possible secondary equipment or process damage from equipment failure

2.2. Preventive Maintenance

This type of maintenance strategy is based on time or machine run time schedule to perform actions that can mitigate deterioration and failure of a component or a system [4] [7]. It consists of regular inspections, part replacement and work on mechanisms and can be categorized in three levels based on the complexity of the inspections [2]. Preventive maintenance (PM) is conducted during scheduled downtimes in order to have a low impact on business operations.

An alternative concept of preventive maintenance is based on onsite condition instead of time/use base [2]. This type of maintenance is applied on critical assets of the installation where a failure can have significant impact on safety, uptime and business aspects and it involves onsite diagnosis interventions. This approach is the latest applied on industrial installations. Finally, onsite condition-based maintenance can be considered the entry level of condition-based maintenance (CBM) and predictive maintenance (PdM).

The advantages and the disadvantages of preventive maintenance are the following [5] [7]:

- Advantages
    - Reduced process or equipment failure
    - Possible energy savings
    - Component life cycle increase
    - Periodicity of maintenance can be adjusted
    - Cost effective in many capital-intensive processes
    - Compare to reactive maintenance an estimate between 12% to 18% in cost savings is achieved

- Disadvantages
    - Labor intensive strategy
    - May include unneeded maintenance
    - Crucial failures are still likely to occur
    - Unneeded maintenance can cause incidental damage to components

2.3. Predictive Maintenance

Predictive maintenance approach utilizes digital IoT solutions with big data and advanced IT platforms that allow condition monitoring of the equipment [2] [4] [8]. The purpose of this maintenance strategy is to control deterioration of components by measuring its different parameters and by triggering alarms when thresholds are reached. Additionally, fault prediction is performed. That way, maintenance actions are conducted according to equipment's actual condition and not in a predefined time schedule or times of equipment use

[5]. Based on the number of utilized sensors and the analysis of parameters different levels of predictive maintenance can be applied. The advantages and the disadvantages of this maintenance approach are the following [2] [5]:

- Advantages:
    - Safety is improved
    - Product quality is ensured
    - Energy savings are achieved
    - The cost for parts and labor is decreased
    - Downtime of process or equipment is reduced
    - Allows for proactive corrective actions
    - Equipment operational life and availability is increased
    - Compare to preventive maintenance an estimate between 12% to 18% in cost savings is achieved

- Disadvantages
    - Investment cost is increased due to the installation of monitoring infrastructure
    - Investment required for staff training
    - The cost avoidance by mitigation of risk of failure is not readily seen by management

A summary of the different maintenance approaches, that have been described so far, is presented in figure 2 [2].

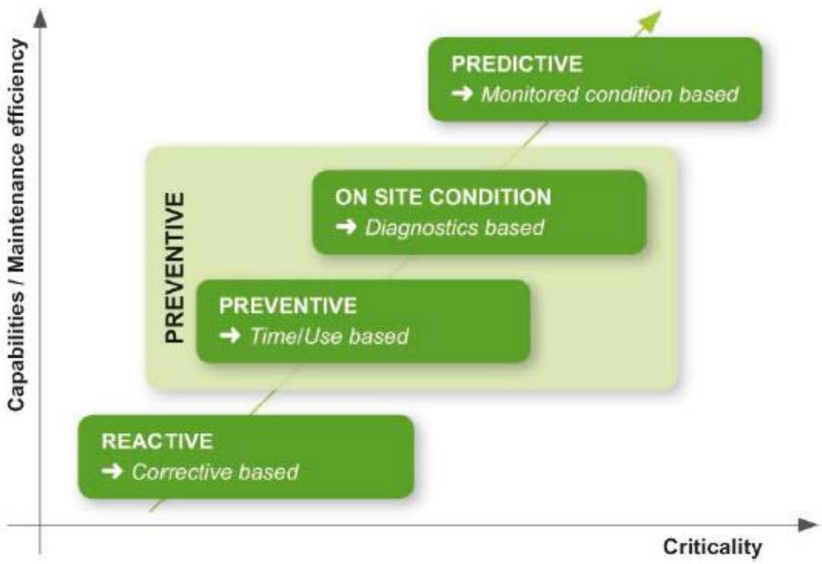


Figure 2 Maintenance Maturity Curve [2]

The maintenance maturity curve presents the capabilities of each approach against the criticality of the equipment that should be applied. Every maintenance strategy is related to its application cost, with the lower being the cost of reactive and the higher of predictive maintenance. Thus, each strategy should be applied considering the criticality of the equipment and the maintenance application cost. In other words, equipment that its failure can have an important impact on safety and business aspects, is classified as critical thus, predictive and preventive maintenance should be applied. On the other hand, equipment with low criticality can go through preventive or reactive maintenance. That idea, of combining the different maintenance approaches, is the introduction of the reliability centered maintenance concept, more details of which are described in the following subsection.

Based on [9], some metrics against industry benchmarks are presented in table 1, as a guide.

Table 1 O&M Industry Metrics and Benchmarks [9]

Metric	Equation	Benchmark
Emergency Maintenance	$\frac{Total\ hours\ worked\ on\ emergency\ jobs}{Total\ hours\ worked}$	< 10%
Maintenance Overtime Period	$\frac{Total\ maintenance\ overtime\ during\ period}{Total\ regular\ maintenance\ hour\ during\ period}$	< 5%
Preventive Maintenance Completion	$\frac{Preventive\ maintenance\ actions\ completed}{Preventive\ maintenance\ actions\ scheduled}$	> 90%
Preventive Maintenance Budget/Cost	$\frac{Preventive\ maintenance\ cost}{Total\ maintenance\ cost}$	15% - 18%
Predictive Maintenance Budget/Cost	$\frac{Predictive\ maintenance\ cost}{Total\ maintenance\ cost}$	10% - 12%

2.4. Reliability Centered Maintenance

Reliability centered maintenance (RCM) utilizes all the previous maintenance approaches with the goal to increase the reliability of the installation and perform maintenance in a cost-effective way [7]. This methodology distinguishes the equipment of the facility based on its importance to the production process and the safety of the installation. Consequently, different maintenance strategies are utilized to each component in a concept focused on cost-effectiveness and reliability. Examples of maintenance strategies applied on the equipment of the installation under an RCM program are presented in table 2.

Table 2 RCM component applications [5]

Hierarchy of Reliability Centered Maintenance		
Components under reactive maintenance	*Components under preventive maintenance*	*Components under predictive maintenance*
Small parts and equipment	Equipment subject to wear	Equipment with random failure patterns
Non-critical equipment	Consumable equipment	Critical equipment
Equipment unlikely to fail	Equipment with known failure patterns	Equipment non subject to wear
Redundant system	Manufacturer recommendations	Systems which failure may be included by incorrect preventive maintenance

The predominant maintenance approach during RCM is predictive thus the following advantages and disadvantages are closely related to the ones previously mentioned [5] [7]:

- Advantages:
    - Is considered the most efficient maintenance program
    - Reduces frequency of detailed inspections
    - Reduces the overall maintenance cost by mitigating unnecessary maintenance actions
    - Minimizes the probability of unexpected failures
    - Maintenance is focused on critical equipment
    - Component reliability increased
    - Root cause analysis is incorporated
- Disadvantages
    - The initial cost for the installation and training is high
    - The potential savings in a long term are not readily seen by management

2.5. Maintenance Past, Present and Future

In this section and after the description of the different maintenance approaches, a short overview of the previous, current and future maintenance practices is presented [10] [11].

During the past decades, maintenance was conducted based on guidelines of equipment manufacturers or industry standards. A small portion of the maintenance frequency was dictated by the number of equipment operations, but in most cases a time-based schedule had to be adhered. For instance, transformers and circuit breakers were tested annually, then every three years and then every five or in the case of a failure occurrence. Although, this type of maintenance practice was not followed by the end-users for various reasons, like cost or limited skilled resources and instead reactive maintenance was applied.

Nowadays, maintenance practice has been transformed from a non-followed time-based maintenance to an approach focused on the equipment operating conditions. Of course, some features of the time-based maintenance are still included. Based on that approach, the equipment is classified and rated by reviewing past maintenance records. According to the data, the components that present high deterioration indications will go through a full maintenance process. On the other hand, components that present a better condition will go through an operational maintenance that is less detailed and requires fewer man-hours. Consequently, this type of maintenance approach can lead to cost savings, since between 30% to 50% of the equipment is not going though detail maintenance procedures [12].

In the upcoming future, it is expected for maintenance to be more focused on the components operating conditions and in a way abolish any time-based scheduled actions. End users would like to perform maintenance based on indications of a monitoring system that, at the same time, could deliver recommendations on what kind of actions should be taken. Additionally, real time warnings about symptoms of failure of the installation and suggestions on how to handle them is another feature of this expected maintenance approach.

2.6. Reliability Basics

At this section, basic information related to the reliability principles are provided. The definitions of different terms are presented along with their equations. The following information is required to understand the methodologies that are utilized in this project.

2.6.1. Definitions

The definitions described above are used during this report and they are provided at [3] [13] and [14].

Availability: (A) (general) The ability of an item—under combined aspects of its reliability, maintainability, and maintenance support—to perform its required function at a stated instant of time or over a stated period of time. (B) (as a performance metric for individual components or a system) The long-term average fraction of time that a component or system is in service and satisfactorily performing its intended function. (C) (as a future prediction) The instantaneous probability that a component or system will be in operation at time t.

Common Cause Failure: Common cause failures are dependent events in which a single failure or condition affects the operation of two or more devices that would otherwise be considered independent.

Failure: The termination of the ability of a component or system to perform a required function.

Failure Mode: The manner of failure. Failure mode is a description of how we can observe a fault.

Failure Rate (λ): The mean (arithmetic average) number of failures of a component and/or system per unit exposure time. The most common unit in reliability analyses is hours (h) or years (y). Therefore, the failure rate is expressed in failures per hour (f/h) or failures per year (f/y). The term is synonymous with the forced outage rate. Failure rate is calculated by the following formula:

$$\lambda = \frac{Tf}{Tp}\left[\frac{f}{h}\right] \; or \; \lambda = \frac{Tf}{\left({}^{Tp}/_{8760}\right)}\left[\frac{f}{y}\right] \tag{2.1}$$

Inherent Availability (Ai): Long-term average fraction of time that a component or system is in service and satisfactorily performing its intended function. Ai considers only downtime for repair of failures. No logistics time, preventive maintenance, etc., is included. Inherent availability is described by the following formula:

$$Ai = \frac{MTBF}{MTBF + MTTR} \tag{2.2}$$

Maintenance Downtime (Mdt): The total downtime for scheduled maintenance (including logistics time, spare parts availability, crew availability, etc.) for a given time period (Tp) (hours).

Mean Time Between Failures (MTBF): MTBF is the arithmetic mean of the times (observed or calculated) between random failures of a component or system. The formula describing MTBF is:

$$MTBF = \frac{Tp}{Tf}\;[h] \tag{2.3}$$

Repair Downtime (Rdt): The total downtime for unscheduled maintenance (excluding logistics time) for a given total period (hours).

Mean Time To Repair (MTTR): The mean time to replace or repair a failed component. Logistics time associated with the repair, such as parts acquisitions, crew mobilization, are not included. It can be estimated by dividing the summation of repair times by the number of repairs and, therefore, is practically the average repair time. The most common unit in reliability analyses is hours (h/f). MTTR is described by the following formula.

$$MTTR = \frac{Rdt}{Tf}\left[\frac{h}{f}\right] \tag{2.4}$$

Reliability: The probability that a component or system will perform required functions under stated conditions for a stated period of time t, or (for discreet missions) a stated number of demands. Considering the exponential distribution, reliability is given by the following formula:

$$R(t) = e^{-\lambda t} \tag{2.5}$$

Total Failures (Tf): The total number failures during the total period.

Total Period (Tp): The calendar time over which data for the item was collected (hours).

2.6.2. Exponential Distribution

Given the data available for power components the most suitable distribution function is the exponential [13]. That implies a constant failure rate for the equipment whereas the failures are random in nature [3]. The probability density function of the exponential distribution is given by:

$$f(t) = \lambda e^{-\lambda t} \tag{2.6}$$

And the reliability function, as it was previously mentioned, is described as:

$$R(t) = e^{-\lambda t} \tag{2.7}$$

The hazard function is defined as the instantaneous failure rate for the remaining population of time t and it can be calculated using the following equation:

$$H(t) = \frac{f(t)}{R(t)} \tag{2.8}$$

In the case of the exponential distribution the hazard function is equal to the constant failure rate:

$$H(t) = \frac{f(t)}{R(t)} = \lambda \tag{2.9}$$

The characteristic of a constant failure rate indicates that a component has equal probabilities of failure during the first years as the last ones of its useful life. Most of the component do not exhibit such characteristic although, it is widely used due to the available data, since it requires only the MTBF to be defined [13].

2.6.3. Weibull Distribution

Weibull is a widely used distribution function due to its versatile nature and is given by the following formula [3]:

$$f(t,\beta,\eta) = \frac{\beta}{\eta}(\frac{t}{\eta})^{\beta-1}e^{-(\frac{t}{\eta})^{\beta}} \tag{2.10}$$

Where β is the shape parameter and η is the location parameter. Beta is giving information on how a component is going to fail whereas eta is providing information about the time of that will happen [14]. The cumulative distribution function $F(t)$, the reliability $R(t)$, the failure rate $\lambda(t)$ and the mean time to fail (MTTF can be assumed equal to MTBF) are given by the following equations [15]:

$$F(t) = 1 - e^{-(\frac{t}{\eta})^{\beta}} \tag{2.11}$$

$$R(t) = 1 - F(t) = e^{-(\frac{t}{\eta})^{\beta}} \tag{2.12}$$

$$\lambda(t) = \frac{f(t,\beta,\eta)}{R(t)} = \frac{\beta}{\eta}(\frac{t}{\eta})^{\beta-1} \tag{2.13}$$

$$MTBF = \eta \cdot \Gamma\left[1 + \frac{1}{\beta}\right] \tag{2.14}$$

Where $\Gamma\left[1 + \frac{1}{\beta}\right]$ is the gamma function evaluated at the value of $(1 + \frac{1}{\beta})$.

If the shape parameter beta is assumed equal to one, then the Weibull distribution is equal to the exponential.

A plot of the reliability over time for the different parameters of beta of the Weibull distribution, is presented in figure 3 [16].

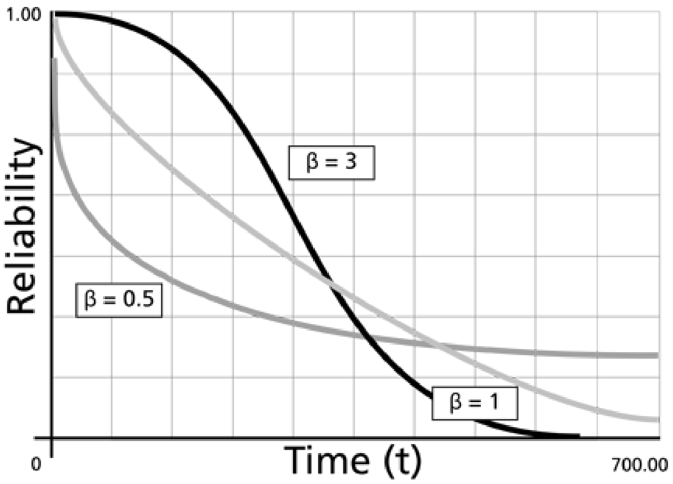


Figure 3 Reliability function of Weibull distribution [16]

The hazard function of the Weibull distribution is given by:

$$H(t,\beta,\eta) = \beta t^{\beta-1} \tag{2.15}$$

Based on the value of β, Weibull can have the characteristics of other distributions. For instance, if β>1 the wear out mode is present and Weibull distribution, as it was previously mentioned can be utilized to model the wear out period of a component. In the case of β<1, Weibull distribution can be used to model the infant mortality region of the bathtub curve. Finally, as it was mentioned previously, when β=1 the Weibull distribution is equal to the exponential. A plot of the different failure rate functions based on the parameter beta is presented in figure 5 [16].

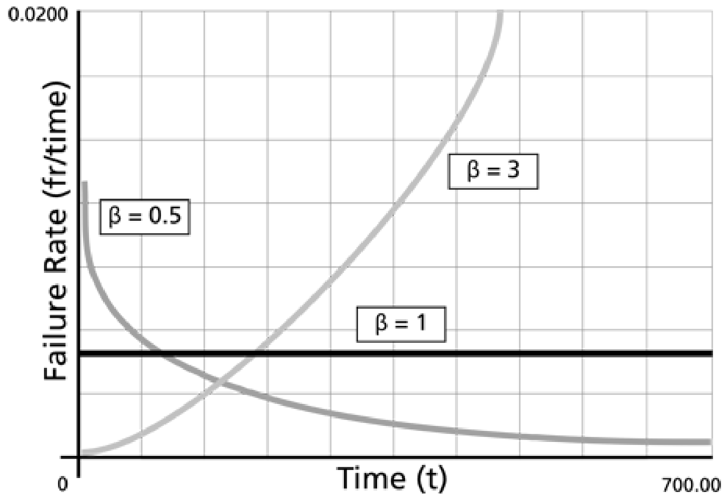


Figure 4 Failure rate function of Weibull distribution [16]

2.7. Methods of reliability and availability analysis

In this last part of the chapter, some of the possible methods to perform reliability and availability analysis, are presented shortly. These methods can be classified in two categories the analytical and the numerical [14] [16] [17] [18].

2.7.1. Analytical Methodologies

In the case of analytical methods, algebraic formulas are used to arrive at a closed-form, exact solution to a model of a system. Some of the methodologies are the following:

Event Tree Analysis

Starting from an initial event, event tree analysis identifies all the possible outcomes when such event occurs. Starting from left to right a tree is structured consisting of different nodes and different paths based on the occurrence or not of the next possible event. In the case of available data, probabilities can be assigned to every event and a quantitative analysis can be performed.

Failure Mode, Effect and Criticality Analysis (FMECA)

FMECA is used to identify all the potential failure modes of different parts of a system. That information can be utilized to identify the effects of those failures in the system and how to avoid them or mitigate their impact.

Cause and Effect Diagrams

Cause and effect diagrams are a qualitative and graphical method used mostly from quality engineers to identify, sort and display possible causes of a problem or quality characteristic.

GO Algorithm

GO is a system analysis technique in a success-oriented structure, that exhibits characteristics such as model modifications and model capabilities that fault trees don't possess. The methodology utilizes a inductive logic and enables the GO models to be constructed directly from engineering drawings in an easy way. GO procedure is using 17 standard logical operators to represent the logical operation, combination and interaction of human actions and physical equipment.

Bayesian Belief Networks

This a graphical modeling methodology that utilizes graphical structures that represent knowledge about the system combined with a set of probabilities tables.

Fault Tree Analysis

This method is a top down deductive failure analysis approach. The first step is to define the so-called TOP event which it can be considered as a potential accident. Then, possible causes that can contribute to the TOP event should be identified. After the qualitative part of the approach a quantitative can follow by assigning the probabilities and calculating the chances of the TOP event to occur. The construction of the fault tree starts from the TOP event and goes down to the basic events by utilizing different symbols that are showing the connection among the events.

As a part of the methodology is the identification of the cut sets, which defined as “a set of components whose failure alone will cause system failure”.

Reliability Block Diagrams (RBD)

This is another graphical tool that enables modelling of simple and complex systems. By utilizing blocks in series or in parallel connection and by providing the relevant data, different indexes of the systems such as the failure rate, the reliability, the MTBF and the availability can be calculated.

The difference between RBDs and fault trees is that the first ones are success oriented while the latter are focused on the failure paths. A fault tree might be generated from a RBD although, the opposite is not always possible. Finally, one last point between these two methodologies, is that RBDs utilize time varying distributions whereas fault trees typically use fixed probabilities.

Network Reduction

The network reduction methodology is suitable for systems that utilize series and parallel connections since it is reduces the size of the system by equivalent components. That technique can be combined with RBDs.

2.7.2. Numerical Methodologies

Probability density functions can be used in their greatest potential by utilizing numerical methodologies such as state space or Monte Carlo simulation. A short description of both is presented below.

State Space

State space has its foundation in the mathematical concept of Markov chains, which is a modeling technique that describes the system's possible states. In the case of reliability and availability analysis there are two possible conditions, the up or down. The probabilities between the transition between the stages should be known whereas, the solution to the model derives from the time spent in the down vs, up states.

Monte Carlo Simulation

This methodology is considered the most versatile and it can be used from simple to complex models. The simulation is based on iterative process and each iteration is a description of what the system could experience through a set mission life. Different possible future scenarios are considered along with their probabilities during the simulation process. In each repetition the repair attributes and the failures are defined for every component of the system. Then, the availability of each iteration is calculated. Finally, for all the iteration the average uptime vs. downtime is defined including the average durations of downtime.

3. Spreadsheet Methodology

Knowledge of reliability performance for different components that are included in a system and the utilization of quantitative methodologies, enable the calculation of various reliability indexes. Consequently, alternative system designs can be compared and the impact on the reliability and cost can be evaluated. Those systems can be different in terms of their configuration, component reliability, operating policy including maintenance practices and protection schemes.

The purpose of this chapter is to provide the theoretical background of the utilized methodology and describe the tool that was used in this project in order to define the impact of predictive maintenance in the reliability.

3.1. Choosing the methodology

Among the different methodologies that were described in the previous chapter, the spreadsheet methodology, which is similar to the zone branch methodology [3] [19], was chosen to conduct the analysis. The reasons for this choice are that the spreadsheet methodology is available in an Excel environment, it doesn't not require any paid license it is relatively simple to use while its generated results are similar to the other methodologies [13] [20] [21] [22].

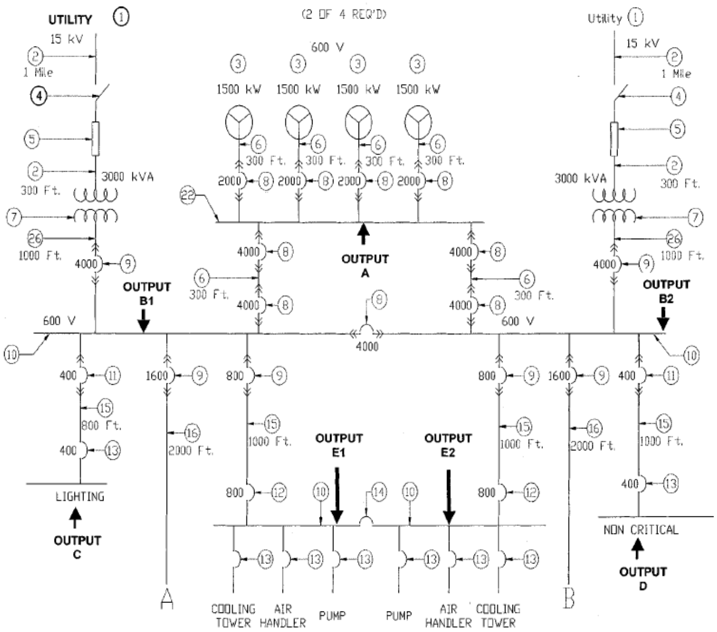


Figure 5 The Gold Book Standard Network [13]

The tool was built by the people involved in the development of the IEEE 493-2007 Std and it was compared with the GO and the cut-set reliability methodologies applied on the IEEE Gold Book Standard Network [13], which is introduced in figure 5. The results of the comparison on the availability between the methodologies, are presented in table 3.

Table 3 Availability at the output locations of the network by utilizing different methodologies [20]

Output Location	Spreadsheet Methodology	GO Algorithm	Minimal Cut-Set Method
Main switchgear bus B1	0.999991241	0.999991230	0.999990613
Main switchgear bus B2	0.999991241	0.999991230	0.999990613
Generation Bus A	0.999996377	0.999996300	0.999996377
Mechanical switchgear bus E1	0.999974337	0.999988600	0.999974186
Mechanical switchgear bus E2	0.999974337	0.999988600	0.999974186
Lighting bus C	0.999987699	0.999987690	0.999988792
Noncritical bus D	0.999986036	0.999987680	0.999989614

As it can be observed, the results are in close agreement and any differences can be attributed in the characteristics of each model such as the handling of redundant paths and other internal model assumptions [20]. An important advantage of the spreadsheet methodology is the fact that can evaluate the impact of protection schemes on load point reliability indexes. Finally, it should be mentioned that, the method can be applied to very large industrial systems with several branches without any restrictions.

3.2. Background of the method

The first step is to identify the parameters that are important to perform a reliability evaluation. Consequently, based on the IEEE 493-2007 Std [13], the most useful indexes to assess the reliability of a system are the frequency and the expected duration of the load point interruptions events. Those indexes are also known as failure rate (λ) and average downtime per failure (r), respectively. Failure rate can be considered as a measure of unreliability whereas, average downtime can be called as restorability. The product of the failure rate and the average downtime (λ·r) indicates the forced hours downtime per year and is a measure of unavailability. Those are the indexes that were utilized during the cost benefit analysis of this project.

The fundamental components of the approach are the protective zones. Industrial power systems consist of different protective equipment such as, breakers, relays, fuses, sectionalizes, reclosers and automatic or manual switches. The operation or the nonoperation of those devices has a direct impact on the reliability of the installation thus, the first step of the spreadsheet methodology is to define the protective zones of the system based on that protective equipment. A protective zone is defined as a part of the power system, in which a fault within the segment will cause the first upstream protective device to isolate the system.

The utilized spreadsheet methodology is providing a snapshot in time of the system. It is based on a constant failure rate of the components and the exponential distribution is assumed with the related equations described in section 2.6.2. It is a static approach and to be valuable for an installation the information of the equipment should be kept updated frequently based on site real data.

The difference between the zone branch and the spreadsheet method is the fact that the failure mode of the switching equipment is not considered. For instance, a failed to trip or failed to interrupt failure mode on the low voltage circuit breakers could cause the upper breakers to trip. That recognition of fault factor that is utilized in the zone branch method is not applied in the spreadsheet although, the results of both methods on the Gold Book Standard Network are in close agreement [23] [24]. Despite that, in one of the next chapters, where the applied methodology is described, a parameter linked with the fault recognition of the system in total (system efficiency) is included in the calculations.

The following assumptions are considered in the methodology and the utilization of the tool:

- A fault is defined as complete loss of power for more than 5 seconds
- All faults are permanent
- The protective equipment perfectly isolates all permanent faults instantaneously
- The protective equipment is perfectly coordinated i.e. the device closest to the fault operates first

In the last part of this section, the equations in which the method and the analysis is based are presented, depending on the connection of the components.

<u>Series Connected Components</u>

Assuming that two components are connected in series, as shown in figure 6, with their related failure rate and time to repair indicated with λ and r, respectively the calculations of the methodology are based on the following equations [25].

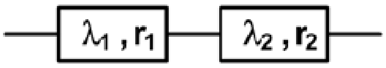


Figure 6 Repairable components in series

In accordance with section 2.6, the MTBF the availability A_i (inherited) and the reliability R_i of each component i are described by the formulas:

$$MTBF_i = \frac{1}{\lambda_i} \tag{3.1}$$

$$A_i = \frac{1}{\lambda_i \cdot MTTR_i + 1} \tag{3.2}$$

$$R_i = e^{-\lambda_i t} \; or \; R_i = e^{-\lambda_i 8760} \; for \; one \; year \tag{3.3}$$

The Mean Time To Repair of two components in series is given by:

$$MTTR = \frac{\lambda_1 r_1 + \lambda_2 r_2}{\lambda_1 + \lambda_2} \tag{3.4}$$

And the combined failure rate will be:

$$\lambda_s = \sum_{i=1}^{N} \lambda_i \; or \; \lambda_s = \prod_{i=1}^{N} R_i \tag{3.5}$$

Where N is total number of components in series. The reliability for one year is given by:

$$R_s = e^{-\lambda_s 8760} \tag{3.6}$$

The availability of the series connection is:

$$A_s = \prod_{i=1}^{N} A_i \tag{3.7}$$

Finally, the probability of failure during a year P_s and the forced downtime FDT are based on the following formulas:

$$P_s = (1 - R_s) \cdot 100 \tag{3.8}$$

$$FDT = (1 - A_s) \tag{3.9}$$

Parallel Connected Equipment

In case of parallel repairable equipment, as it is presented in figure 7, the following equations are utilized [26]:

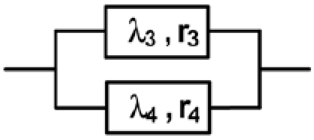


Figure 7 Repairable parallel components

The failure rate for two redundant components is calculated based on the following formula:

$$\lambda_p = \frac{\lambda_3 \lambda_4 r_3 r_4 + \lambda_c r_{eq}}{(1 + \lambda_3 r_3 + \lambda_4 r_4) \cdot r_p} \tag{3.10}$$

Where λ_3, λ_4 and r_3, r_4 are the failure rates and the repair times of each component, respectively. The total repair time (MTTR) of the parallel configuration is given by:

$$r_p = \frac{r_{eq}(1 + X)}{1 + \dfrac{r_{eq} \cdot X}{max(r_3, r_4)}} \tag{3.11}$$

Where,

$$r_{eq} = \frac{r_3 \cdot r_4}{r_3 + r_4} \tag{3.12}$$

And

$$X = \frac{\lambda_c}{\lambda_3 \lambda_4 r_4} \tag{3.13}$$

Where λ_c is the common cause failure rate, which is defined as follows:

$$\lambda_c = CCF \cdot max(\lambda_3, \lambda_4) \tag{3.14}$$

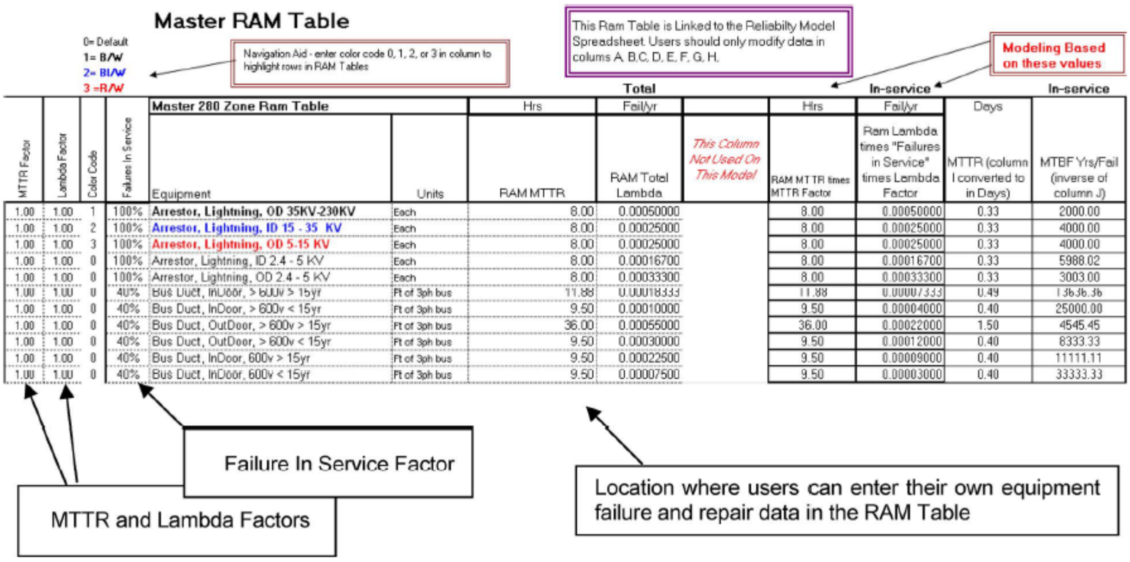
The CCF is called common cause factor and is referred to the likelihood of both parallel components failing in common cause mode. The range of CCF is between one and zero, where one indicates a high probability of common failure and zero the opposite. In the case of zero CCF r_p is equal to r_{eq}. The remaining reliability indexes can be calculated based on the total repair time (r_p) and the failure rate (λ_p) of the parallel configuration.

3.3. Tool Description

The original model was presented in 1994 in the IEEE Petroleum and Chemical Industry Committee (PCIC) Conference [27] and since its final version in 2007 many modifications and addition of new features took place. The purpose of this section is to present briefly the basics of the tool in which the analysis was conducted.

The tool, as its name suggest, was developed in a spreadsheet environment and consists of five worksheets [21]. The first one, called “History and Restrictions” describes the background and the copyrights of the tool. The second worksheet with the title “MODEL280pd3” represents the third version of the model and is the place where all the calculations take place. “RAM Table” is the name of the third worksheet, in which the user can find a database containing information regarding the MTTR and the lambda of 140 different components. The fourth sheet with the title “Utility” is linked with the “RAM Table” and introduces manually the MTTR and the lambda for the incoming utility supply. It is a simple utility simulator, where the user can define the effects of disturbances and the configuration of the supply. Finally, a complementary to the RAM table sheet, with the title “Chem Ram” includes failure rate and repair data that are commonly found in the chemical manufacturing industry.

The calculations of the Utility worksheet are linked with the RAM Table and represent the failure rate and the repair time of the supply of the industrial installation. Next, the RAM Table is linked, and its values are pasted in the MODEL280pd3 sheet where the reliability and availability calculations are performed based on the zones. The RAM Table of the model is presented in figure 8 [21].



				Master 280 Zone Ram Table		Hrs	Fail/yr (Total)		Hrs	Fail/yr (In-service)	Days	(In-service)
MTTR Factor	Lambda Factor	Color Code	Failures In Service	Equipment	Units	RAM MTTR	RAM Total Lambda	This Column Not Used On This Model	RAM MTTR times MTTR Factor	Ram Lambda times "Failures in Service" times Lambda Factor	MTTR (column I converted to in Days)	MTBF Yrs/Fail (inverse of column J)
1.00	1.00	1	100%	**Arrestor, Lightning, OD 35KV-230KV**	Each	8.00	0.00050000		8.00	0.00050000	0.33	2000.00
1.00	1.00	2	100%	**Arrestor, Lightning, ID 15 - 35 KV**	Each	8.00	0.00025000		8.00	0.00025000	0.33	4000.00
1.00	1.00	3	100%	**Arrestor, Lightning, OD 5-15 KV**	Each	8.00	0.00025000		8.00	0.00025000	0.33	4000.00
1.00	1.00	0	100%	Arrestor, Lightning, ID 2.4 - 5 KV	Each	8.00	0.00016700		8.00	0.00016700	0.33	5988.02
1.00	1.00	0	100%	Arrestor, Lightning, OD 2.4 - 5 KV	Each	8.00	0.00033300		8.00	0.00033300	0.33	3003.00
1.00	1.00	0	40%	Bus Duct, InDoor, > 600v > 15yr	Ft of 3ph bus	11.88	0.00018333		11.88	0.00007333	0.49	13636.36
1.00	1.00	0	40%	Bus Duct, InDoor, > 600v < 15yr	Ft of 3ph bus	9.50	0.00010000		9.50	0.00004000	0.40	25000.00
1.00	1.00	0	40%	Bus Duct, OutDoor, > 600v > 15yr	Ft of 3ph bus	36.00	0.00055000		36.00	0.00022000	1.50	4545.45
1.00	1.00	0	40%	Bus Duct, OutDoor, > 600v < 15yr	Ft of 3ph bus	9.50	0.00030000		9.50	0.00012000	0.40	8333.33
1.00	1.00	0	40%	Bus Duct, InDoor, 600v > 15yr	Ft of 3ph bus	9.50	0.00022500		9.50	0.00009000	0.40	11111.11
1.00	1.00	0	40%	Bus Duct, InDoor, 600v < 15yr	Ft of 3ph bus	9.50	0.00007500		9.50	0.00003000	0.40	33333.33

Figure 8 RAM Table of Spreadsheet tool [21]

Based on the operating manual of the tool *[25]* and the related publications *[21] [28] [26]*, to perform the calculations, four steps are followed. Firstly, from the single line diagram of the installation the zones related to the protective devices are identified. That process can start from the top of the installation till the point of interest, which is normally a load point. Each zone includes the portion of the system that a failure will affect all its components. The latest version of the tool can deal with up to 280 zones thus, large complex installations can be simulated.

The second step is the review of the RAM table of the equipment. The component that are included in the system should be identified while the MTTR and the failure rate should be verified. The most accurate results will be provided by utilizing data coming from the analysed installation. In case that is not possible, the default values, different sources such as the Gold Book, other equipment reliability studies or a combination of all with experience, can be used.

One additional feature of the RAM Table is the MTTR and failure rate factors that provide the capability to perform what if scenarios and sensitivity analyses by modifying their values. That capability was used by the approach, that is described in one of the following chapters, to evaluate the impact of predictive maintenance.

The "Failure in Service" parameter of the RAM Table enables the filtering of failures. For instance, the user can adjust that parameter if he/she intends to focus on the failures of the circuit breakers that caused failure in service and not all the failures of the circuit breaker. Based on that, the failure rate that will be considered in the calculations is reduced by the inserted percentage. Finally, different failure rate and MTTR can be considered for the analysis depending on the ageing of the equipment, since the RAM table includes data with different ranges based on years of usage.

The third step is taking place in the MODEL280pd3 sheet, where the user inserts the zones in the tool according to the single line diagram. As it was previously mentioned, up to 280 zones can be considered and with the combination of the 140-equipment data a wide range of industrial installations can be evaluated by utilizing the tool.

The final step of the process is to insert the configuration of the installation in the tool. To do so, the Zone Table included in the MODEL280pd3 sheet is utilized. In the table the connection of the zones in series or in parallel is defined based on the single line diagram. Additionally, the common cause factor (CCF) is inserted in the case of parallel connections. The CCF, as it was previously mentioned, range from zero to one and represents the likelihood of a fault affecting the parallel circuits. If CCF is close to zero, the parallel branches can be considered independent whereas, if is close to one, the probabilities of both branches failing due to the common cause mode are higher.

The results of the tool are summarized in the Point table of the MODEL280pd3 sheet. Considering sections 2.6 and 3.2 and adjusting the values in a per year basis, for every point of the system the following information is available:

- Failure rate (λ) per year. Calculated based on section 3.2.
- Mean time to repair (MTTR) in hours per event. Calculated based on section 3.2.
- Reliability at each point of the system as a percentage

$$R = e^{-\lambda} \tag{3.15}$$

- Availability per year

$$A = \frac{8760}{\lambda \cdot MTTR + 8760} \tag{3.16}$$

- Probability of failure per year as a percentage

$$P = 1 - e^{-\lambda} \tag{3.17}$$

- Mean time between failures (MTBF) in years

$$MTBF = \frac{1}{\lambda} \tag{3.18}$$

- Forced downtime (FDT) in hours per year

$$FDT = 8760 - 8760 \cdot A \tag{3.19}$$

A point in the Point Table is any point within a zone. The results related to it represent the reliability of the system and the other indexes from the top down to that point. Typically, a point will be shown as the lowest point within a zone.

The overview of the model, where all the previous information can be related, is presented in figure 9 [25]. The calculation steps from 1 to 10 and the table associated to them are shown while it should be mentioned that tables 8,9 and 10 (Unit Impact, Consequences and Component Summary) were not considered since another cost benefit analysis method was assumed and will be described in the following chapter.

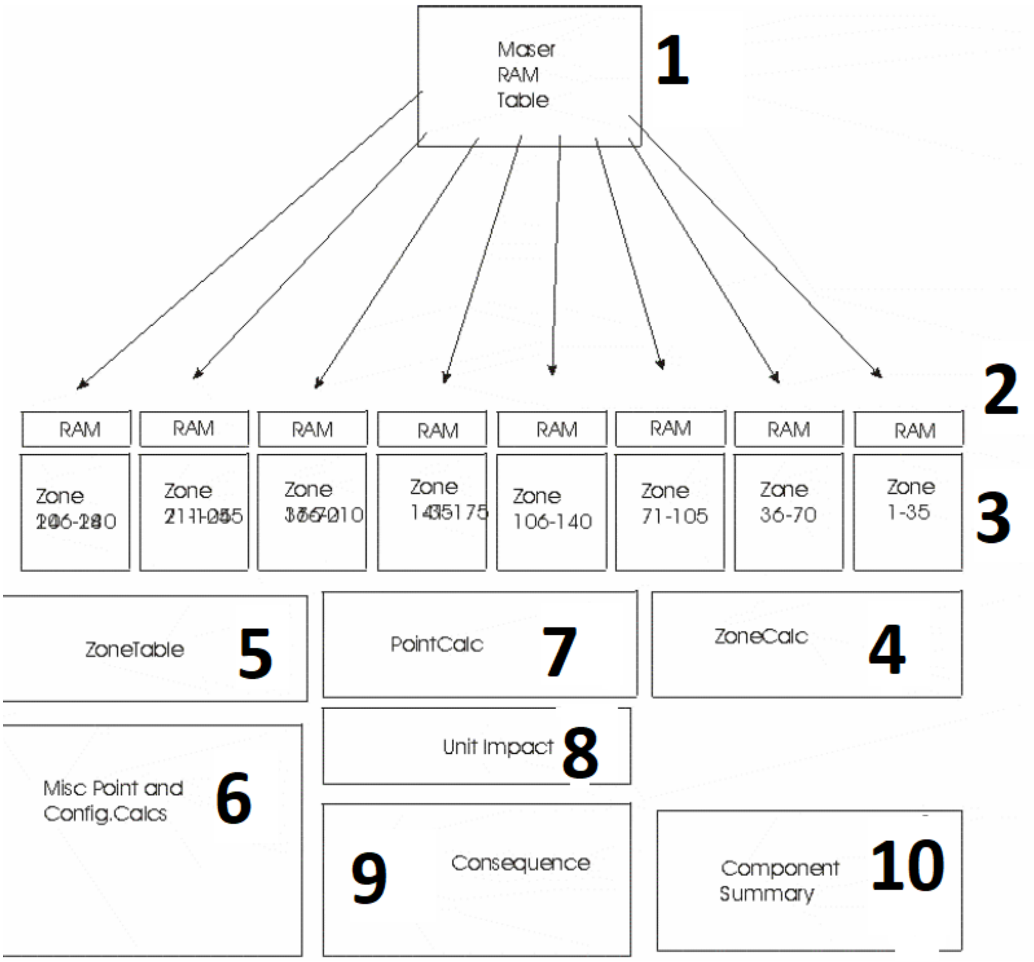


Figure 9 Spreadsheet model layout [25]

4. Cost Benefit Analysis - Revenue Requirement Methodology

In this chapter the cost benefit analysis that was implemented in different industrial installations is described. The revenue requirement (RR) method mentioned in the IEEE 493-2007 standard [13] is utilized to evaluate different system designs. In Particular, a cost evaluation of a system before and after the implementation of a predictive maintenance system is attempted. This comparison is useful during cost-reliability trade-off decisions in the design of power distribution systems for industrial installations.

4.1. Cost evaluation of reliability

The process of the RR methodology defines the minimum revenue requirements (MRR) which describe the amount of necessary revenues to achieve the minimum acceptable earnings related to the investment plus all expenses associated with the investment. Among the different alternatives the one that demonstrates the lowest MRR is the economic choice since it leaves, out of any available revenues, the maximum amount of plant earnings [29].

The calculation of MRR is divided in two parts, one proportional and the other not proportional to the investment of the analysed system option. The formula to calculate the MRR is given by [29]:

$$G = X + C \cdot F \tag{4.1}$$

where G describes the MRR per year, X the variable operating expenses, C the capital investment and F the fixed investment charge factor. The product of C and F includes the minimum acceptable earnings, depreciation, income taxes and fixed operating expenses.

The application of the RR method requires present worth analysis and levelizing. Present worth analysis determines the equivalent value of present and future sums, discounting or compounding at some specified rate. Levelizing uses a specified discount rate to uniform annual amounts which are equivalent to a series of nonuniform amounts. That way all investments in a plan are expressed in a uniform annual basis over the life of the investment.

Considering the above, figure 10 is presenting graphically the revenue requirements for an investment made initially, where c is the years prior to start up that the investment is made and L is the lifetime of the project in years [29].

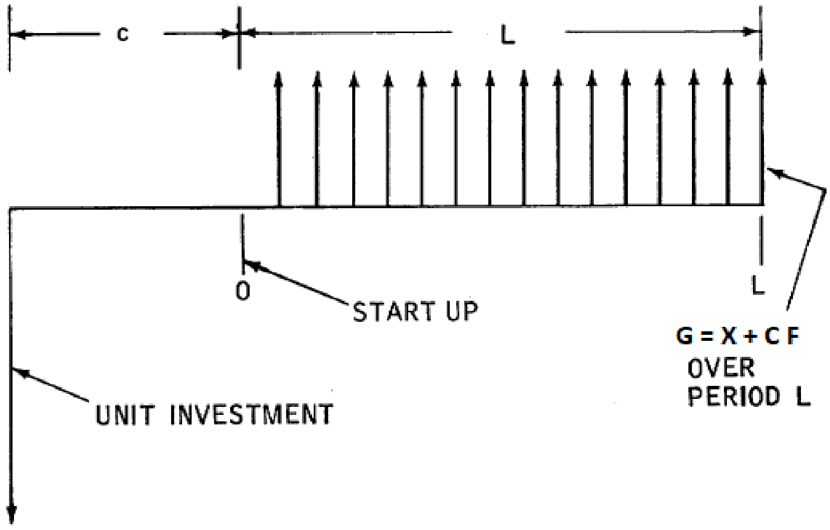


Figure 10 Revenue requirement for investment made initially [29]

4.1.1. Variable expenses (X)

The focus of the variable expenses when cost-reliability studies are conducted is on the effects of a failure. That amount depends on the configuration of the installation and the criticality of the failed component. Furthermore, except from the failure cost itself the total variable expenses depend on the duration of downtime.

In terms of failure, the cost is affected by the damaged plant equipment, the extra maintenance costs, the production process losses and the cost to repair a failed component. Considering the duration of total downtime due to a failure, it is influenced by the repair time, the plant restart time, and the time required to change the source of the affected circuits, if that is applicable [13] [30].

During downtime due to a failure, losses and savings are taking place at the same time. Firstly, production is reduced and consequently sales are affected, and revenues are lost. On the other hand, savings are achieved due to the production related expenses that during downtime are on hold. Depending on the duration of the interruption, labour, power, fuel and material costs are reduced. Although those expenses might vary in time, it is assumed that they present a fixed value per hour during downtime.

Consequently, the total amount of variable expenses can be described with following formula [13]:

$$X = \lambda\left[x_i + \left(g_p - x_p\right)(r + s)\right] \tag{4.2}$$

where X are the variable expenses expressed in $ per year, λ is the failure rate expressed in failures per year, x_i represents the extra expenses incurred per failure in $ per failure, g_p are the revenues lost per hour of plant downtime in $ per hour and x_p is related to the variable expenses saved per hour of plant downtime in $ per hour. Finally, regarding time, r expresses the replacement or repair time in hours after a failure or the time required to switch sources and s is the start-up time of plant after a failure, in hours.

4.1.2. Capital investment (C)

The methodology defines the capital investment as the expenditure related to the installation of the power distribution system of the plant or a part of that system. It is associated to the equipment, its installation cost and the system configuration.

During cost-reliability analysis the option with the least required capital investment is not in most cases the preferable choice. For instance, redundancies or monitoring systems, might increase the required cost of the installation but on the other hand improve the reliability of the system and reduce the variable expenses due to a failure. This is exactly the point of the use of the RR method.

4.1.3. Investment charge factor (F)

As it was previously mentioned the investment charge factor includes the fixed expenses, depreciation, income taxes and the minimum acceptable rate of return on investment, allowing for risk [29].

The formula to calculate the investment charge factor is the following:

$$F = \frac{\left(S_c \, {}^{a_L}/_{f_r}\right) - td_t}{1 - t} + e \qquad (4.3)$$

where S_c is the growth factor or the future value factor and it is given by:

$$S_c = (1 + R)^c \qquad (4.4)$$

where c is the number of years prior to start-up that an investment is made, and R is the minimum acceptable return on investment.

R can be defined by the average rate of return on investment which is based either on past history or anticipated results. A typical value of minimum acceptable rate of return in many industrial plants is considered to be around 15%, thus it can be assumed that R=0.15.

a_L is the amortization factor or leveling factor and can be calculated based on the following equation:

$$a_L = R + d_L \tag{4.5}$$

where L is the lifetime of investment in years and d_L is the sinking fund factor given by:

$$d_L = \frac{R}{S_L - 1} \tag{4.6}$$

and

$$S_L = (1 + R)^L \tag{4.7}$$

f_r is the risk adjustment factor or probability of success and its determination is a matter of judgement. A typical value can be around 1 while for plants that present a risk higher than the average this value is lower.

t are the income taxes per $ of investment (C) and d_t is the income tax depreciation, levelized per $ of investment (C) and it is equal to:

$$d_t = \frac{1}{L} \tag{4.8}$$

Finally, parameter e represents the fixed expenses such as insurance, property taxes and fixed maintenance cost.

Equation 4.3 can also be expressed as:

$$F = r + d + t + e \tag{4.9}$$

where r is the levelized return on investment per $ of investment and it is given by:

$$r = \frac{S_c R}{f_r} \tag{4.10}$$

d is the levelized depreciation on investment per $ of investment:

$$d = \frac{S_c d_L}{f_r} \tag{4.11}$$

and t is the levelized income taxes on investment per $ of investment:

$$t = \left(\frac{S_c a_L}{f_r} - d_t\right)\left(\frac{t}{1 - t}\right) \tag{4.12}$$

The steps to perform economic comparisons based on RR methodology are summarized in figure 11.

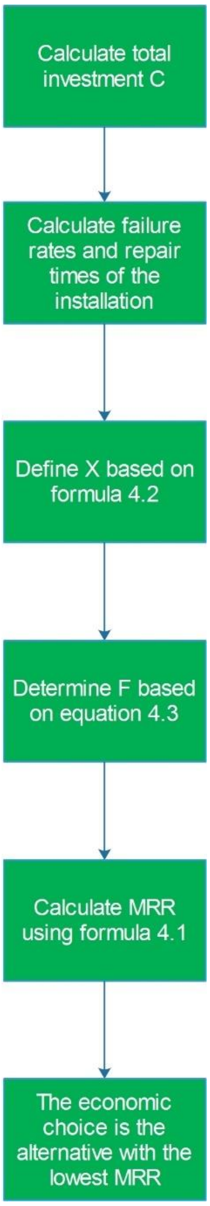


Figure 11 Revenue Requirement method flow chart

5. Approach to Investigate the Impact of Predictive Maintenance

In this chapter the approach to quantify the impact of the implementation of a predictive maintenance system is described. A literature research was conducted, and a number of publications were reviewed and considered to draw conclusions and take the decision on the best possible methodology according to the resources and data available.

At [31] and [32] a failure rate analysis of high voltage circuit breakers along with the impact of preventive actions are presented. Twenty years of recorded failure rate data are considered to analyze the causes of failure of the circuit breakers components. Next, the components are classified in three categories and by utilizing the Weibull distribution their probability of failure and the failure rate as functions of time are approximated. Based on that information, replacement preventing actions of the circuit breaker components are suggested in specific years and the impact of those actions are quantified. Similar approach, based on the authors, can be followed for different components.

A similar method as in the previous publication is followed in [33]. Based on an extensive study of SF6 circuit breakers the reliability of their parts is modeled and consequently modelling of maintenance actions is also achieved. The Weibull distribution and the condition failure intensity are utilized to quantify the effect of preventive maintenance.

Paoletti et al. in [10] and [30] is focusing on condition based maintenance and the monitoring of electrical equipment. The approach quantifies the failure avoidance that can be achieved due to on-line predictive diagnostic technologies. A link between the most probable causes of failure and the available solutions is presented.

Finally, Bertling et al. in [34], [35] and [36] proposes two approaches to quantify the preventive maintenance measures on reliability at electrical distribution systems. Both methods are based on RCM thus the critical components of the system are initially identified. The first approach considers that preventive maintenance actions lead to the reduction of causes of failure of the affected components and thus to a reduction of their failure rate. The exponential distribution is assumed, and the analyzed parameters are not considered time dependent. On the other hand, the second approach is based on functional relationship between failure rate and maintenance actions. Detailed knowledge of the mechanisms and the characteristics of failure rate are utilized in this case and consequently input data are required. Both methodologies were applied on a 11-kV cable at a distribution power system in Sweden.

5.1. Approach

To be able to consider both the failure and the maintenance characteristics, time-dependent functions should be used. The probability density functions of the equipment should be known, thus failure data in a time period should be accessible. Although, historical failure data for industrial installations are not available due to the relatively new application of the advanced monitor systems. The data acquisition of equipment in industrial installations is a new process without many years applied in the field. Additionally, even though some data might exist, access to them is not possible due to restrictions and property rights. Consequently, an approach utilizing average equipment failure data that are accessible (Gold Book Standard, RAM Table of Spreadsheet, IEEE 3006.8 Standard) is followed.

The exponential distribution for the equipment is assumed implying a constant failure rate in time. The utilization of a Weibull or another distribution is not possible due to the aforementioned lack of data and instead a static approach is considered.

The followed methodology considers references [30] and [34] to evaluate a new failure rate when a predictive maintenance system is implemented in an industrial installation. Approach 1 in [34] is used as a base but with a different argument. Predictive maintenance with the frequent monitoring of the equipment enables the mitigation of the causes related to the monitored parameters whereas preventive maintenance based on a predefined schedule, is not. Additionally, is assumed that a predictive maintenance system provides warnings on the actual and predicted health condition of the equipment and triggers maintenance actions.

The approach consists of the following basic five steps related to the spreadsheet methodology described in the previous chapter and then continuous with the definition of the failure rate depending on if a predictive maintenance system is implemented. The initial steps of the approach are presented in a flow chart format in figure 12.

1. The first step of the approach is to define the components of the system in terms of voltage, type, length (for cables) and age. For instance, for a circuit breaker it is required to know the voltage level, if it is an indoor or outdoor, its type and if it is older than 15 years. The same information is required for transformers, cables, fuses, generators, motors and the rest of the equipment of the analyzed industrial installation.

2. The next step is to define the Failure Rate and the MTTR of the equipment. The default values provided by the RAM table of the Spreadsheet tool can be used or be updated. Ideally, the source of the values should be the records of the analyzed installation otherwise, the default values could be utilized or be updated based on the IEEE

Standards [13] [37] or other databases.

3. Next, the failure in service parameter, as it was described in the spreadsheet tool, should be defined for each component. The focus of the calculations is on the failures that lead to system downtime and not to every single failure, thus that factor should be adjusted on the RAM table of the tool.

4. Based on the single line diagram of the installation, the protective zones are defined and are inserted in the tool.

5. Lastly, the system configuration is applied according to the parallel or series connection of the protective zones of the system. Details for the aforementioned actions can be found in the previous chapter.

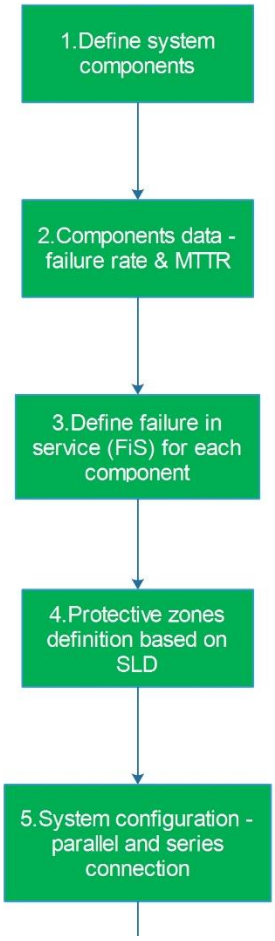


Figure 12 Approach Flow Chart – Initial Steps

The next steps of the approach are affected by the application or not of a predictive maintenance system. The flow chart diagram of the second part of the approach is presented in figure 13. Both flow charts combined create the steps of the followed methodology.

<u>Predictive Maintenance Applied</u>

If a predictive maintenance system is applied the following series of steps should be performed to define the new reduced lambda factor:

1. Firstly, only the monitored assets of the installation should be defined and be analyzed.

2. Consequently, for each category (transformers, low and medium voltage circuit breakers), the causes of failure should be identified. This process will be furtherly analyzed in the following section.

3. Next, the fault prediction efficiency should be set. This parameter is affected by the system's implemented technology.

4. Finally, for each cause of failure the impact of predictive maintenance should be calculated. The details of this process will be described in the following sections.

5. The new reduced lambda factor (LF) for each category is calculated based on the following formula:

$$LF_{new} = 1 - \eta \cdot \sum_{i=1}^{k} x_i \tag{5.1}$$

   Where η is the causes identification efficiency (predictive maintenance system efficiency), k is the total number of causes of failure for the equipment type and x_i is the percentage of the cause of failure that can be addressed by the monitoring system.

6. The calculated factors for each category can then be inserted in the RAM table of the tool. The new reduced failure rate is given by:

$$\lambda_{new} = FiS \cdot LF_{new} \cdot \lambda \tag{5.2}$$

   Where FiS is the failure in service factor and λ is the failure rate provided by the databases or the user. In the base case scenario without the application of a predictive maintenance system the LF_{new} factor is equal to one.

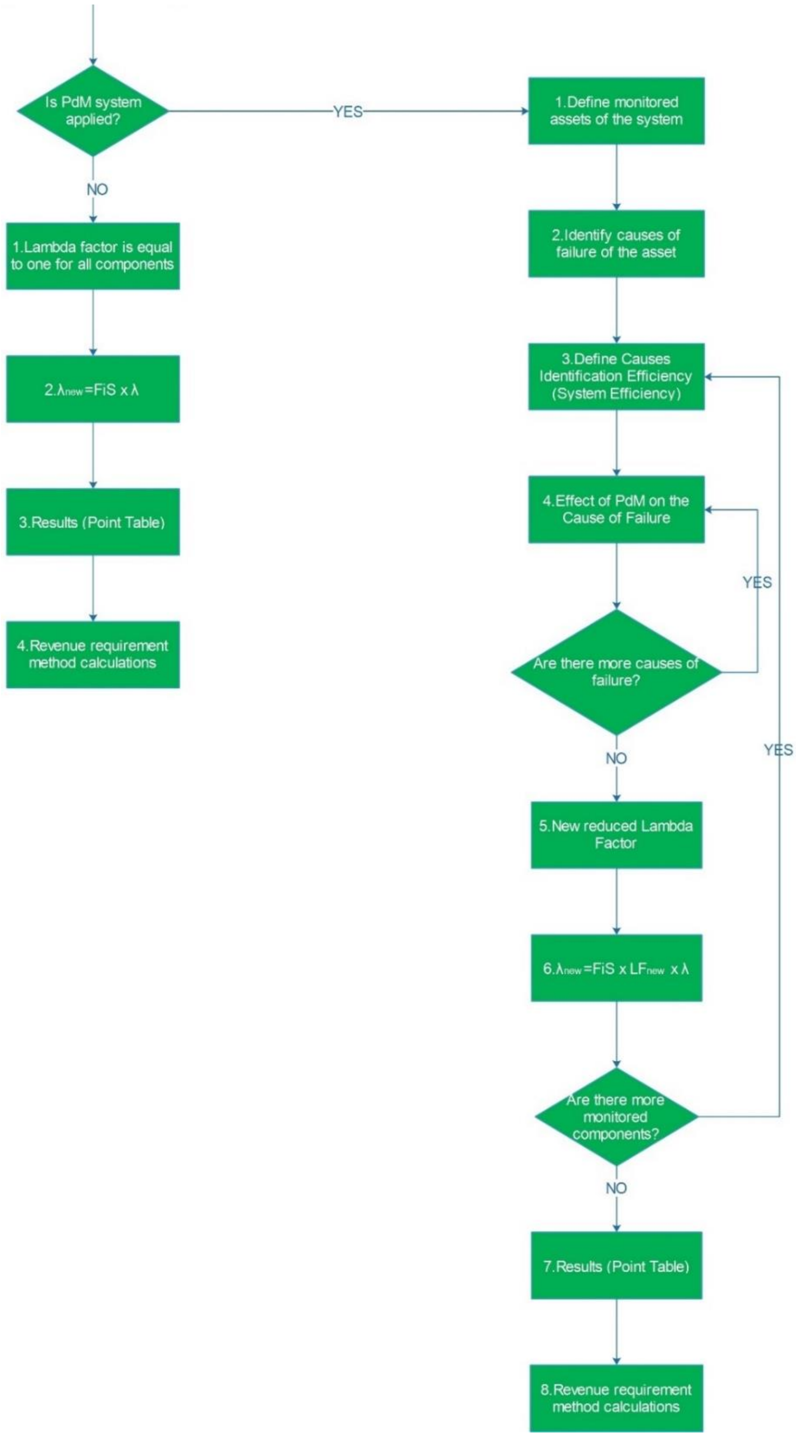


Figure 13 Approach Flow Chart - Next Steps

7. The results of the application of a predictive maintenance system based on the new reduced failure rate can be found in the Point Table of the tool.

8. Based on the reliability calculations, cost benefit analysis by utilizing the Revenue Requirement Method can be performed.

<u>Base Case</u>

1. If we consider the base case, then the lambda factor in the RAM table is equal to one for all the components.

2. There is no change on the failure rate and its final value is only affected by the failure in service parameter (FiS):

$$\lambda_{new} = FiS \cdot \lambda \tag{5.3}$$

3. The results of the calculations can be found in the Point Table of the tool.

4. Finally, according to the reliability analysis of the base and the predictive maintenance case, comparisons can be performed along with cost benefit analyses of both cases.

5.2. Causes of Failure

The execution of the methodology requires the identification of the causes of failure for the assets under monitoring. Additionally, as it will be described in the following paragraph, a predictive maintenance system utilizes sensors and measures parameters for transformers and low and medium voltage circuit breakers. Consequently, in this paragraph the causes of failure for the aforementioned types of equipment are presented.

The data are based on reports [38] and [39] where initiating and contributing causes are presented along with the suspected failure responsibility. Although, during the analysis only the initiating causes will be considered since they can effectively be related to the monitored parameters described in the next paragraph. Finally, it is assumed that the following data present the same values in a yearly basis. This is important since the calculations are based on failures per year.

The initiating causes of failure in the case of low voltage electromechanical circuit breakers are summarized in table 4. It should be noted that in the results molded case circuit breakers are not included. As it can be observed, malfunction of protective relay or tripping device is dominating the failures by 93%. The remaining percentage is reported in other causes whereas all the rest of the categories indicate no failure.

Table 4 Low and Medium Voltage Circuit Breaker Initiating Causes [38]

	LV CB	MV CB
Initiating Cause	Percentage (%)	Percentage (%)
Transient overvoltage such as lighting, switching surges, or system faults	-	25
Insulation Breakdown	-	-
Mechanical burnout, friction or sizing of moving parts	-	-
Mechanical breakdown such as cracking, loosening abrading or deforming of static structural parts	-	25
Physical damage or shorting from outside source such as vehicular accident	-	-
Electrical fault or malfunction	-	25
Malfunction of protective relay or tripping device	93	-
Other auxiliary device malfunction	-	-
Low, or no, auxiliary voltage for circuits such as air compressors and SF6 heaters	-	-
Other	7	25

Additionally, in table 4 information regarding the medium voltage circuit breakers can be found. It should be noted that those percentages are derived from a small sample according to [38]. The results indicate an equal distribution of failure among four causes. Specifically, transient overvoltage, mechanical breakdowns, electrical fault or malfunctions and the other category demonstrate failures of 25% each.

Finally, the information regarding the power transformers is summarized in table 5. All the categories in this case exhibit a failure occurrence with the dominating causes being the one related to winding insulation breakdowns, transient overvoltage disturbances and insulating bushing breakdown.

Table 5 Transformer Initiating Causes [38]

Initiating Cause	Percentage (%)
Transient overvoltage disturbance (switching surges, arcing ground fault etc.)	16.4
Overheating	2.7
Winding insulation breakdown	29.1
Insulating bushing breakdown	13.6
Other insulation breakdown	5.5
Mechanical breaking, cracking, loosening, abrading or deforming of static or structural parts	7.3
Mechanical burnout, friction or seizing of moving parts	2.7
Mechanically caused damage from foreign source (digging, vehicular accident etc.)	2.7
Shorting by tools or other metal objects	0.9
Shorting by birds, snakes, rodents etc.	2.7
Malfunction of protective relay control device or auxiliary device	4.6
Improper operating procedure	3.6
Loose connection or termination	7.3
Other	0.9

5.3. Monitored Parameters and Causes of Failure

A predictive maintenance system based on specialized sensors and controllers is assessing the aging, the wear and the stress level of the equipment, while based on specified rules fault detection is performed [40]. Additionally, model-based diagnosis, machine learning algorithms and advanced statistical treatment enable the prediction of faults. Based on those features, optimization of maintenance plans and advices on optimum usage of assets are achieved.

The system enables the monitoring of low and medium voltage circuit breakers, dry and oil transformers and variable speed drivers. Its background is based on equipment manufacturer reports that indicate the mechanical endurance, the nominal lifetime and include test results [40]. Additionally, the system is taking into account international standards such as the IEC and IEEE, thermal and aging models of the equipment, field experience and laboratory bench testing. Finally, advanced statistics and machine learning enable the detection of any deviation from normal conditions.

In table 6 to 8 the functions of the system for low voltage circuit breakers, medium voltage circuit breakers and transformers are presented along with their descriptions and the required parameters [41].

Table 6 System functions for low voltage circuit breakers

Function	Parameters Required	Description
Electrical Wear	Contact wear	Measure degradation of circuit breaker contact based on cumulative breaking current by protection relay or computed cumulative breaking current history
Mechanical Wear	Number of operations	Measure degradation of Circuit Breaker mechanism based on number of operations vs maximum operations (Failure of mechanical part (not opening or not closing))
Temperature Ageing Trip Unit	Current Ambient temperature	Provide Ageing of trip unit related to temperature
Corrosion Ageing of Circuit Breaker	Ambient temperature Air pollution level Salty environment	Provide impact of corrosion due to environmental conditions (incl. Temperature) on asset Ageing
Corrosion Ageing Trip Unit	Air pollution level Salty environment	Provide impact of corrosion (no temperature) on asset Ageing
Identify settings modifications (several settings in amps and seconds)	Settings	Detect and identify settings change

Table 7 System functions for medium voltage circuit breakers

Function	Parameters Required	Description
Electrical Wear	Total cumulative breaking current (kA^2)	Measure degradation of circuit breaker contact based on cumulative breaking current by protection relay or computed cumulative breaking current history
Mechanical Wear	Number of operations	Measure degradation of Circuit Breaker mechanism based on number of operations vs maximum operations (Failure of mechanical part (not opening or not closing))
Auxiliary Voltage Status	Auxiliary voltage	Check voltage level compliance with specifications to ensure proper operation of the CB/protection relay
Stress Level	N/A	Provides a synthetized vision of overall Ageing / wear / usage impact to define stress level
PD sensors	N/A	Detect partial discharges

Table 8 System functions for transformers

Function	Parameters Required	Description
Top Oil Temperature	Ambient temperature 3 phase currents	Compute the oil temperature based on the current
Hot spot temperature	Top oil temperature	Compute the hot spot temperature based on top oil temperature
PD sensors	N/A	Detect partial discharges
Connections monitoring	N/A	Thermal monitoring of connections
Protection relay status	N/A	Alarm from protection relay fault status
Health index	All KPIs	Indicators aggregation to define the health index

In tables 9 to 11 the predictive maintenance (PdM) system functions are related with the causes of equipment failure. To be able to perform that connection, deep understanding of the failure mode mechanisms and the utilized technology is required. The methodology at this step considered the approach described in [30]. Although an investigation took place, the following results are based mostly on use cases of actual predictive maintenance system implementation [42] and interviews with experts [43].

Table 9 LV Circuit Breaker addressable causes of failure by PdM

Initiating Cause	Percentage (%)	PdM System function
Transient overvoltage such as lighting, switching surges, or system faults	-	NO
Insulation Breakdown	-	NO
Mechanical burnout, friction or sizing of moving parts	-	Electrical Wear Mechanical Wear
Mechanical breakdown such as cracking, loosening abrading or deforming of static structural parts	-	NO
Physical damage or shorting from outside source such as vehicular accident	-	NO
Electrical fault or malfunction	-	NO
Malfunction of protective relay or tripping device	93	Temperature Aging Trip Unit Corrosion Ageing of CB Corrosion Ageing of Trip Unit Identify settings modification
Other auxiliary device malfunction	-	NO
Low, or no, auxiliary voltage for circuits such as air compressors and SF6 heaters	-	NO
Other	7	NO
TOTAL % OF CAUSES ADDRESSED	93	

Table 10 MV Circuit Breaker addressable causes of failure by PdM

Initiating Cause	Percentage (%)	PdM System function
Transient overvoltage such as lighting, switching surges, or system faults	25	NO
Insulation Breakdown	-	PD Sensors
Mechanical burnout, friction or sizing of moving parts	-	Electrical Wear Mechanical Wear
Mechanical breakdown such as cracking, loosening abrading or deforming of static structural parts	25	NO
Physical damage or shorting from outside source such as vehicular accident	-	NO
Electrical fault or malfunction	25	Stress Level
Malfunction of protective relay or tripping device	-	NO
Other auxiliary device malfunction	-	NO
Low, or no, auxiliary voltage for circuits such as air compressors and SF6 heaters	-	Auxiliary Voltage Status
Other	25	NO
TOTAL % OF CAUSES ADDRESSED	25	

Table 11 Oil Transformer addressable causes of failure by PdM

Initiating Cause	Percentage (%)	PdM System function
Transient overvoltage disturbance (switching surges, arcing ground fault etc.)	16.4	NO
Overheating	2.7	Top Oil Temperature Hotspot Temperature
Winding insulation breakdown	29.1	NO
Insulating bushing breakdown	13.6	PD Sensors
Other insulation breakdown	5.5	Hotspot Temperature
Mechanical breaking, cracking, loosening, abrading or deforming of static or structural parts	7.3	NO
Mechanical burnout, friction or seizing of moving parts	2.7	Connections monitoring
Mechanically caused damage from foreign	2.7	NO

Initiating Cause	Percentage (%)	PdM System function
source (digging, vehicular accident etc.)		
Shorting by tools or other metal objects	0.9	NO
Shorting by birds, snakes, rodents etc.	2.7	NO
Malfunction of protective relay control device or auxiliary device	4.6	Protection relay status
Improper operating procedure	3.6	Health Index
Loose connection or termination	7.3	Connections monitoring
Other	0.9	NO
TOTAL % OF CAUSES ADDRESSED	40	

The results of the analysis indicate that 93, 25 and 40 percent of causes of failure can be mitigated for the low and medium voltage circuit breakers and oil transformers, respectively. It was assumed that the detection is leading to a complete elimination of the cause. Based on the results steps 2 and 4 of the approach when a predictive maintenance system is implemented, are defined.

5.4. Defining the impact of Predictive Maintenance in the failure rate

The lack of time-based data dictates an approach that is built on average failure rate and mean time to repair values. Those data are utilized and along with the proposed methodology the impact of predictive maintenance on the failure rate due to the monitored parameters linked with some causes of failure, can be quantified. Although, the impact of additional maintenance actions that take place is not addressed in this approach.

Predictive maintenance differs from preventive on the fact that the maintenance actions are performed according to the actual condition of the equipment and not on a predefined schedule. Consequently, it can be said, that predictive maintenance optimizes the time that preventive maintenance is performed. Additionally, predictive maintenance by monitoring the equipment enables the mitigation of the causes of failures that can be detected. Thus, a permanent reduction of the failure rate is achieved.

In other words, with predictive maintenance a component is not replaced due to its high possibility to fail in the upcoming period, as in the case of preventive, but actions are taken by monitoring the conditions and the health status of the component. Additionally, by frequently monitoring different parameters the new reduced failure rate is kept constant in its decreased value.

In summary, the impact of predictive maintenance can be considered in two aspects:

- Firstly, it mitigates the addressable by the system causes of failure, thus reduces the overall failure rate of the equipment. In other words, it provides warnings and triggers maintenance actions that are not allowing the failures related to those causes to happen.
- Secondly, optimizes the time that preventive maintenance should be performed based on the actual conditions of the component and not on a schedule.

The current approach considers and quantifies the impact of the first point. By applying predictive maintenance, the failure rate is reduced. The impact of other optimized preventive maintenance actions cannot be represented when a constant failure rate is assumed. When the component is replaced or fixed, it returns to its initial fixed failure rate, thus no impact is visible. That can only be observed when the failure rate increases in time. Although, as it was previously explained that would require time depended data.

Figure 14 shows the impact of predictive maintenance (PdM) due to causes of failure mitigation from the initial red to the new green failure rate. The failure rate is assumed to be constant. This is the impact shown by the approach of this project.

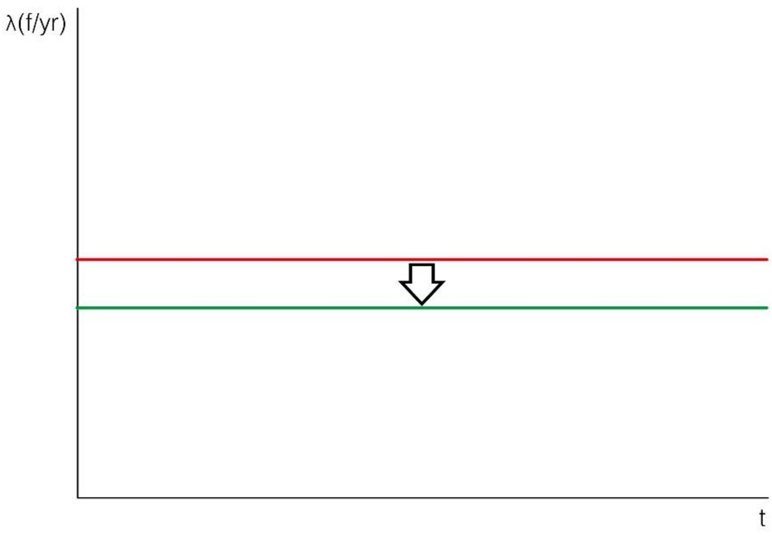


Figure 14 Impact of PdM - Constant failure rate

Figure 15 shows the impact of predictive maintenance in total. The red line represents the initial failure rate of the system that is reduced to the green line due to the mitigation of causes of failure by predictive maintenance. In that case, based on the graph, the lifetime of the system is extended. Next, preventive maintenance actions are taking place according to the conditions of the equipment, and the failure rate is furtherly reduced by following the black line. Consequently, it is understandable that in reality predictive and preventive maintenance coexist.

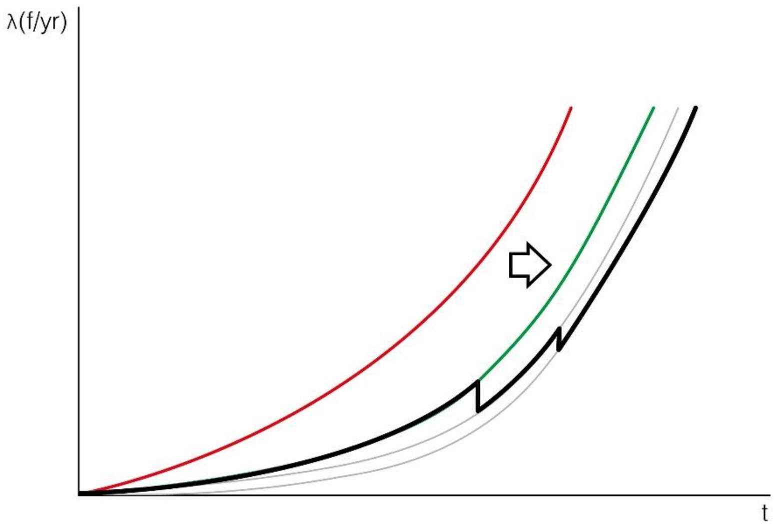


Figure 15 Impact of PdM - Increasing failure rate

By implementing the approach and the analysis described in this chapter, figure 16 summarizes the addressable causes of failure on the monitored equipment when a predictive maintenance (PdM) system is applied in an industrial installation. Additionally, the chart includes a reduced percentage of the addressable causes as a result of the system efficiency. The application of a PdM system is not considered ideal thus, a realistic 67% of causes identification efficiency is assumed.

Causes identification efficiency refers to the effectiveness of predicting a potential failure by the online monitoring devices [44]. That parameter can be affected by the technical capability, the failure mode and the system sensitivity and availability.

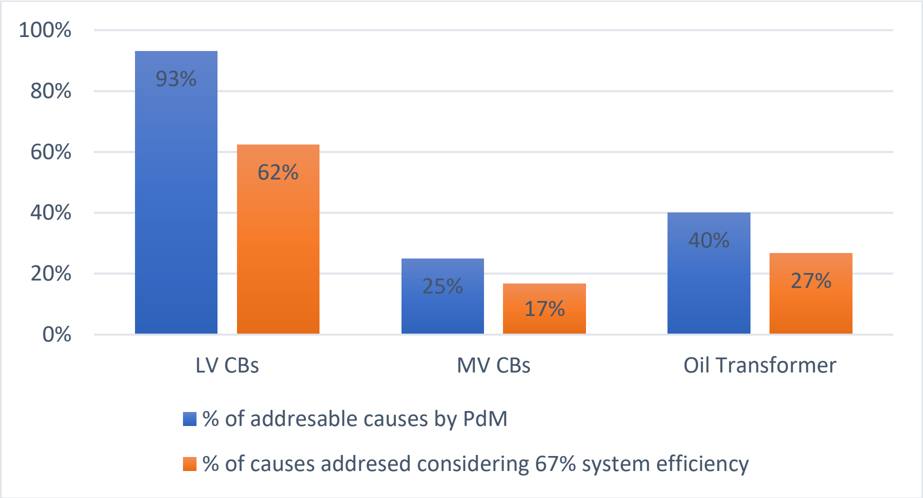


Figure 16 Percentage of addressable causes of failure for the equipment under monitoring

6. Results

In this chapter the methodologies and the approach are combined and are applied in industrial installation in an attempt to investigate the impact of predictive maintenance. The spreadsheet methodology described in chapter 3 is utilized considering the approach of chapter 5. At the end a cost-benefit analysis is conducted according to the revenue requirement methodology presented in chapter 4.

The focus will be on indexes such as the failure rate, the forced downtime and the meat time to repair (MTTR). Those indexes can be calculated based on the failure rate assuming an exponential distribution. Additionally, force downtime is used to derive the average downtime per failure at a specific point and then that parameter is utilized in the cost benefit analysis with the revenue requirement method. Alternatively, the MTTR can be used.

The steps for the reliability analysis are the ones summarized in figure 12 and 13 whereas for the cost benefit evaluation the actions of figure 11 were followed. Those steps are applied in four different industrial installations. The first two are theoretical, are coming from the literature and are utilized for sensitivity analysis of reliability parameters. The last two configurations are real cases where the impact of predictive maintenance is under evaluation.

6.1. Gold Book Standard Network

The gold book standard network was firstly introduced in paragraph 3.1. The reason for its use is the fact that represents a system configuration found in industrial and commercial facilities, while at the same time it enables different reliability methodologies to be compared [13].

The Gold Book Standard Network is a dual utility source system with standby generation. The service transformers supply a double-ended 4000 A, 600 V bus, referred as main switchgear. Mechanical equipment is served from the 800 A, 600 V double-ended bus, supplied from the main switchgear. The network is supplied by two independent 15 kV primary distribution feeders. There are four diesel engine generators at the facility where two out of four generators are required to meet the network load demands at all times. The single line diagram of the network with the protective zones is presented in figure 17.

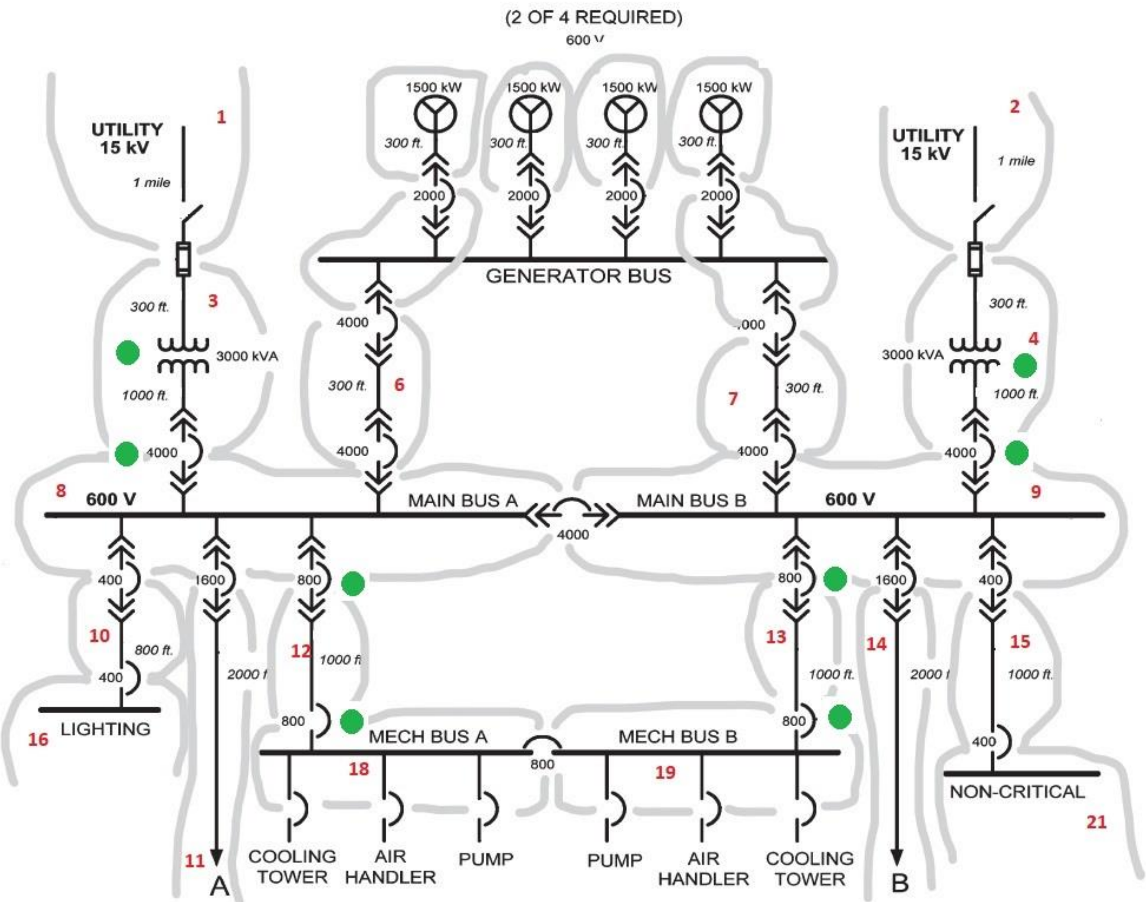


Figure 17 Gold Book Standard Network with protective zones added [13]

Regarding the assumptions of the network, it is considered that manual switching operation require 15 min, and generators start automatically. Furthermore, as it was mentioned previously two out of four generators are necessary to carry the load, while the utility supply and the switchgear are design to carry the load from one single source.

The equipment of the network is listed in table 12 with their related failure rate, MTTR and failure in service data (percentage of failures that cause downtime). The utilized values in this chapter are related to an average level of maintenance which means that in the facilities the manufacturer's recommended maintenance policies was followed.

Table 12 Equipment of gold book standard network [13]

Equipment	Failure rate (f/yr)	MTTR (h)	Failure in Service (%)
Single-circuit utility supply	1.956	1.32	100
Cable Arial, <=15kV, per mile	0.04717000	1.82	98
Diesel Eng Gen, Packaged, Standby, 1500kW	0.12350000	18.28	20
Manual Disconnect Switch	0.00174000	1.00	100
Fuse, 15 kV	0.10154000	4.00	100
Cable below Ground in conduit, <=600V	0.00201000	11.22	98
Transformer, Liquid, Non-Forced Air, 3000kVA	0.00111000	5.00	90
Ckt. Breaker, 600V, Draw out, NO, >600A	0.00553000	2.00	5
Ckt. Breaker, 600V, Draw out, NC, >600A	0.00185000	0.50	5
Switchgear, Bare bus, 600V	0.00949000	7.3	100
Ckt. Breaker, 600V Draw out, NC, <600A	0.00021000	6.00	5
Ckt. Breaker, NC, >600A	0.00960000	9.60	5
Ckt. Breaker, 3Ph Fixed, NC, <=600A	0.00520000	5.80	5
Ckt. Breaker, 3Ph Fixed, NO, >600A	0.00343000	37.50	5
Cable, Above Ground, No conduit, <=600V	0.00012000	2.50	98
Cable, Above Ground, Trays, <=600V	0.00141000	10.50	98
Switchgear, Insulated bus, <=600V	0.00170000	2.40	100
Bus Duct	0.00012500	12.90	100

In the following subsection several sensitivity analyses are conducted to evaluate the impact of different parameters on the reliability indices when predictive maintenance is applied.

6.1.1. Number of monitored assets

The analyzed configuration is theoretical and there are no assets under monitoring, thus an investigation of the impact on the reliability of the number of monitored equipment is conducted. Three different scenarios are considered. The first is the base case with no assets under monitor. The second assumes that all transformers, LV and MV circuit breakers are monitored. Finally, in a more realistic approach, during the last scenario, the critical equipment as indicated with a green dot in figure 17 is under condition monitoring.

For the calculations the system efficiency was considered to be 67%. That parameter will be investigated further in paragraph 6.1.3.

In table 13 the results between the different cases are summarized. The failure rate of each case along with the percentage difference from the base case are provided. The failure rate percentage reduction is equal to the MTBF percentage since the two parameters are linked with equation 3.18.

As expected, the higher the number of monitored assets the bigger the impact of PdM. For instance, at point 16 with all equipment under monitoring (transformers, LV and MV circuit breakers) the failure rate is reduced by 3.7% whereas in the case of critical equipment monitoring the reduced percentage is just 0.5. Although, the cost between the implementation of these two cases will vary and probably will not justify the first choice when a cost benefit analysis is conducted.

Regarding the second scenario, a 28.24% percent reduction in the failure rate per year of points 6 and 7 is observed. These points are the link between the diesel generators and the utilities supplies and thus they exhibit a low value of failure rate. Consequently, the impact on the reduction of the failure rate is more visible since it affects the low decimal points of the failure rate of the equipment. This point will be furtherly discussed in section 6.2.2.

Table 13 Number of monitored assets results comparison

Point number	Base Case Failure rate (f/yr)	All transformers, LV and MV CBs under monitoring Failure rate (f/yr)	Difference (%)	Critical equipment under monitoring Failure rate (f/yr)	Difference (%)
Point 1	2.0039666	2.0039666	0.0000%	2.0039666	0.0000%
Point 2	2.0039666	2.0039666	0.0000%	2.0039666	0.0000%
Point 3	2.234132111	2.233862381	-0.0121%	2.233862381	-0.0121%
Point 4	2.234132111	2.233862381	-0.0121%	2.233862381	-0.0121%
Point 6	0.001829771	0.001312909	-28.2473%	0.001829771	0.0000%
Point 7	0.001829771	0.001312909	-28.2473%	0.001829771	0.0000%
Point 8	0.00992615	0.009677233	-2.5077%	0.009868513	-0.5807%
Point 9	0.00992615	0.009677233	-2.5077%	0.009868513	-0.5807%
Point 10	0.01104209	0.01078663	-2.3135%	0.010984453	-0.5220%
Point 11	0.01278225	0.012475696	-2.3983%	0.012724613	-0.4509%
Point 12	0.01013625	0.009829696	-3.0243%	0.010020976	-1.1372%
Point 13	0.01013625	0.009829696	-3.0243%	0.010020976	-1.1372%
Point 14	0.01278225	0.012475696	-2.3983%	0.012724613	-0.4509%
Point 15	0.01131845	0.01106299	-2.2570%	0.011260813	-0.5092%
Point 16	0.01130209	0.010884624	-3.6937%	0.011244453	-0.5100%
Point 18	0.01061625	0.010010608	-5.7049%	0.010201888	-3.9031%
Point 19	0.01061625	0.010010608	-5.7049%	0.010201888	-3.9031%
Point 21	0.01157845	0.011160984	-3.6055%	0.011520813	-0.4978%

6.1.2. Failures causing downtime and standard failures

So far only the failures of the equipment that lead to system failure were analyzed. To be able to assess the impact of PdM to the standard failures the failure in service parameter in the spreadsheet tool has to be adjusted for all the equipment to 100%.

Based on that, and assuming a system efficiency of 67% with monitoring applied only on the critical components, the results of a predictive maintenance system on the standard failures are presented in table 14. Moreover, for comparison, the results (difference) from the analysis of failures that cause downtime from the previous section are included.

Table 14 Standard failures and failures causing downtime

	Failures causing downtime	Standard failures		
Point number	Difference (%)	Base case Failure rate (f/yr)	PdM applied Failure rate (f/yr)	Difference (%)
Point 1	0.0000%	2.00491	2.00491	0.0000%
Point 2	0.0000%	2.00491	2.00491	0.0000%
Point 3	-0.0121%	2.235240114	2.234942634	-0.0133%
Point 4	-0.0121%	2.235240114	2.234942634	-0.0133%
Point 6	0.0000%	0.021180966	0.021180966	0.0000%
Point 7	0.0000%	0.021180966	0.021180966	0.0000%
Point 8	-0.5807%	0.017648902	0.016496164	-6.5315%
Point 9	-0.5807%	0.017648902	0.016496164	-6.5315%
Point 10	-0.5220%	0.018986902	0.017834164	-6.0712%
Point 11	-0.4509%	0.022318902	0.021166164	-5.1649%
Point 12	-1.1372%	0.019618902	0.017313429	-11.7513%
Point 13	-1.1372%	0.019618902	0.017313429	-11.7513%
Point 14	-0.4509%	0.022318902	0.021166164	-5.1649%
Point 15	-0.5092%	0.019268902	0.018116164	-5.9824%
Point 16	-0.5100%	0.024186902	0.023034164	-4.7660%
Point 18	-3.9031%	0.029218902	0.020931669	-28.3626%
Point 19	-3.9031%	0.029218902	0.020931669	-28.3626%
Point 21	-0.4978%	0.024468902	0.023316164	-4.7110%

For the low voltage circuit breakers, the failure in service parameter is only 5% when the downtime failures are analyzed, whereas for standard failures that parameter is set to 100%. Additionally, one of the main characteristics of the gold book standard network is that it consists entirely from low voltage circuit breakers where the impact of PdM is the highest according to paragraph 5.3. Consequently, due to those two reasons the failure rate per year of standard failures can be reduced by up to 28.36%.

6.1.3. Prediction efficiency

In this subparagraph, the impact of prediction efficiency on the failure rate is investigated. It is assumed, as in the previous case, that only critical equipment is under monitoring. The focus of the calculations will be on points 18 and 19 in which important loads are supplied. These points exhibit the same characteristics thus the results for one of them applies for both.

Table 15 can be considered as an extension of figure 16 with more information regarding causes of failures addressed and system efficiency.

Table 15 Causes of failure addressed by PdM against system efficiency

System Efficiency	Addressable causes of failure for LV CBs	Addressable causes of failure for MV CBs	Addressable causes of failure for Transformers
20%	19%	5%	8%
30%	28%	8%	12%
40%	37%	10%	16%
50%	47%	13%	20%
60%	56%	15%	24%
67%	62%	17%	27%
70%	65%	18%	28%
80%	74%	20%	32%
90%	84%	23%	36%
100%	93%	25%	40%

By applying the different percentage for each system efficiency case on the lambda factor of the spreadsheet tool, the following graph is obtained.

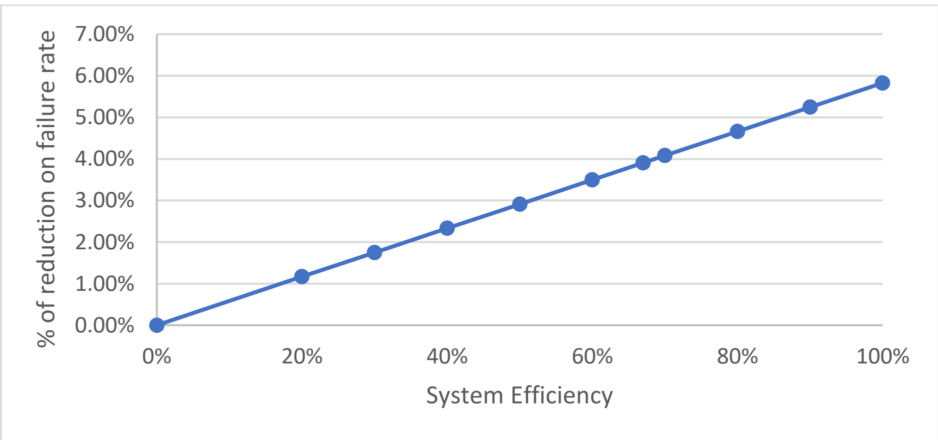


Figure 18 Failure rate reduction at point 18 vs system efficiency

The graph indicates a linear relationship of the system efficiency with the percentage of failure rate reduction on point 18. The best case enables the mitigation of causes of failure for the LV, MV circuit breakers and transformers by 93, 25 and 40 percent, respectively, leading to a total failure rate reduction of 5.83 at point 18 of the installation. Although, along this project, as it was previously mentioned, a system efficiency of 67% was considered as a realistic value according to [43].

6.2. Alternative to the G.B. Std. Net.

In [21] an alternative network to the gold book standard is proposed to deal with larger and more complex systems found in the industry. Some concepts that are commonly found and are included in the model are the use of double-ended systems with automatic switches, normally open and normally close circuit breakers. The idea of using the model is to perform comparisons and challenge different analytical methodologies. Although, in this section the model is used to evaluate the impact of a predictive maintenance to the failure rate at different points of the installation.

In figure 19 the single line diagram of the alternative network with its protective zones is presented and in table 16 the equipment of the model is listed with the failure rate, the MTTR and the failure in service data.

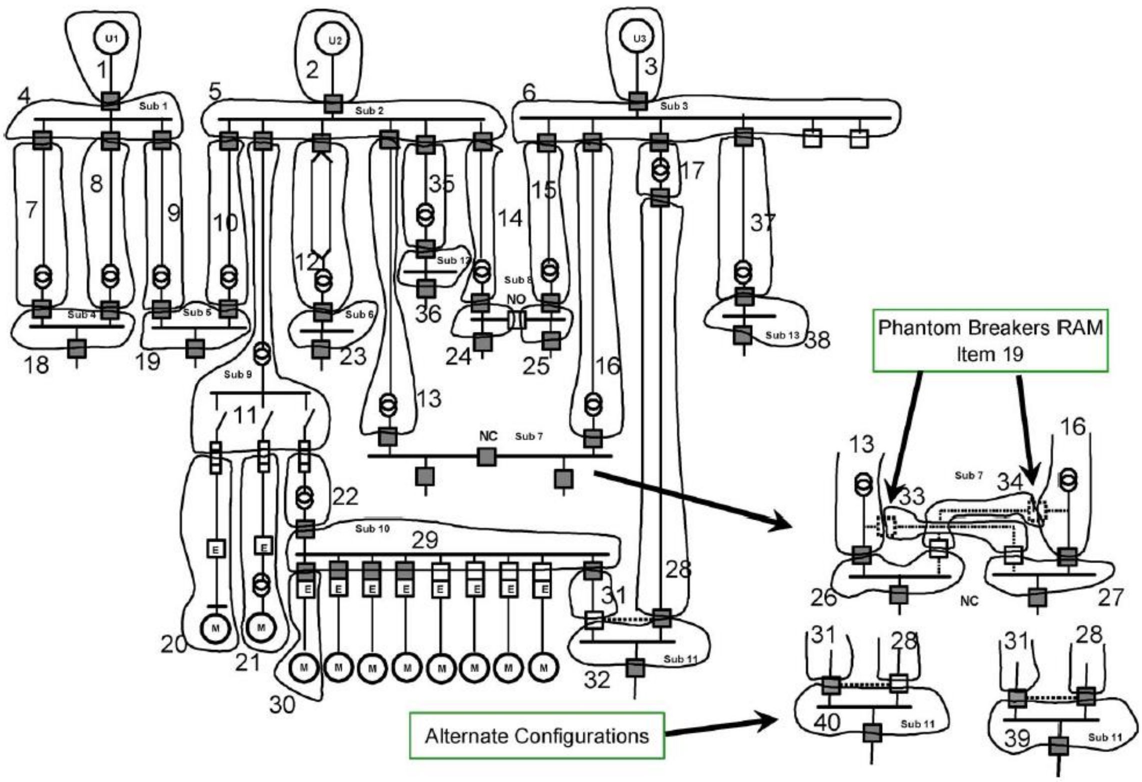


Figure 19 Alternative Network with protective zones added [21]

Table 16 Equipment of alternative network [21]

Equipment	Failure rate (f/yr)	MTTR (h)	Failure in Service (%)
Bus Duct, Outdoor, > 600v	0.00030000	9.50	40
Bus Duct, Outdoor, 600v	0.00033300	9.50	40
Cable, 15 KV Tray	0.00360000	48.00	98
Cable, 5 KV Tray	0.00523000	48.00	98
Cable, 600 V Tray	0.00400000	5.00	98
Circuit Breaker, 15 KV Indoor	0.00360000	8.00	5
Circuit Breaker, 5 KV Indoor	0.00400000	8.00	5
Circuit Breaker, 600 V ID Metaclad	0.00500000	16.00	5
Circuit Breaker, 600 V Molded	0.00520000	4.00	50
Fused switch, 5 KV Enclosed, indoor	0.00250000	8.00	100
MCC, 600 V Vert Section	0.00100000	72.00	80
Starter MCC, motor 600V	0.01390000	24.00	80
Starter, motor E-2 and E-1	0.00500000	24.00	75
Switch, Auto Transfer mechanism	0.07800325	6.31	95
Switchgear, Cubicle Indoor > 600v	0.00191700	36.00	8
Switchgear, Cubicle Indoor 600v	0.00720000	36.00	8
Transformer 300 - 10000 KVA	0.00100000	300.00	90
5 kv Motor	0.05000000	250.00	94
Utility U1 and U2	0.22222222	0.63	100
480 v Motor	0.08000000	8.00	100
Utility U3	4.75000000	2.16	100

6.2.1. Results

In table 17 the results of the reliability analysis on the alternative network are presented. In this case it was assumed that all the transformers, LV and MV circuit breakers are under monitoring and the predictive maintenance system efficiency is 67%. Both standard failures and failures related to downtime are presented in the table with their percentage difference from each base case.

Table 17 Standard failures and failures causing downtime

	Failures causing downtime			Standard failures		
Point number	Base case Failure rate (f/yr)	PdM applied Failure rate (f/yr)	Difference (%)	Base case Failure rate (f/yr)	PdM applied Failure rate (f/yr)	Difference (%)
Point 1	0.222375582	0.222376	0.0000%	0.224139222	0.224139	0.0000%
Point 2	0.222375582	0.222376	0.0000%	0.224139222	0.224139	0.0000%
Point 3	4.75015336	4.750153	0.0000%	4.751917	4.751917	0.0000%
Point 4	0.223015662	0.222986	-0.0135%	0.233490222	0.232887	-0.2583%
Point 5	0.223475742	0.223446	-0.0135%	0.239241222	0.238638	-0.2520%
Point 6	4.75140688	4.751377	-0.0006%	4.768936	4.768333	-0.0126%
Point 7	0.234659022	0.234358	-0.1285%	0.259507222	0.258033	-0.5680%
Point 8	0.234659022	0.234358	-0.1285%	0.259507222	0.258033	-0.5680%
Point 9	0.234659022	0.234358	-0.1285%	0.259507222	0.258033	-0.5680%
Point 10	0.235119102	0.234818	-0.1282%	0.265258222	0.263784	-0.5557%
Point 11	0.230201742	0.2299	-0.1310%	0.254041222	0.252567	-0.5802%
Point 12	0.239529102	0.239228	-0.1259%	0.269758222	0.268284	-0.5464%
Point 13	0.235272462	0.234971	-0.1281%	0.267175222	0.265701	-0.5517%
Point 14	0.235119102	0.234818	-0.1282%	0.265258222	0.263784	-0.5557%
Point 15	4.76305024	4.762749	-0.0063%	4.794953	4.793479	-0.0307%
Point 16	4.7632036	4.762902	-0.0063%	4.79687	4.795396	-0.0307%
Point 17	4.75330288	4.753001	-0.0063%	4.781336	4.779862	-0.0308%
Point 18	0.235250416	0.234878	-0.1583%	0.269495434	0.266676	-1.0463%
Point 19	0.024058192	0.023957	-0.4202%	0.035951976	0.034459	-4.1530%
Point 20	0.304978422	0.304677	-0.0989%	0.333507222	0.332033	-0.4420%
Point 21	0.338757882	0.338215	-0.1602%	0.364384222	0.362642	-0.4781%
Point 22	0.251653242	0.251111	-0.2157%	0.289471222	0.287729	-0.6018%
Point 23	0.239882462	0.239547	-0.1397%	0.275675222	0.273531	-0.7777%
Point 24	0.235625822	0.235291	-0.1422%	0.273092222	0.270948	-0.7851%
Point 25	4.7634036	4.763069	-0.0070%	4.80087	4.798726	-0.0447%
Point 26	0.024724196	0.024619	-0.4272%	0.035719614	0.034848	-2.4403%
Point 27	0.024742565	0.024637	-0.4268%	0.035949435	0.035078	-2.4247%
Point 28	4.828749976	4.828293	-0.0095%	4.865639259	4.86105	-0.0943%
Point 29	0.261503242	0.260805	-0.2671%	0.306471222	0.301614	-1.5850%
Point 30	0.353799242	0.353101	-0.1974%	0.401571222	0.396714	-1.2096%

	Failures causing downtime			Standard failures		
Point 31	0.339084738	0.338386	-0.2060%	0.390754481	0.385897	-1.2431%
Point 32	4.832149976	4.831693	-0.0095%	4.871839259	4.86725	-0.0942%
Point 33	0.235425842	0.235124	-0.1281%	0.269094222	0.26762	-0.5478%
Point 34	4.76335698	4.763055	-0.0063%	4.798789	4.797315	-0.0307%
Point 35	0.235119102	0.234818	-0.1282%	0.265258222	0.263784	-0.5557%
Point 36	0.235472462	0.235137	-0.1423%	0.271175222	0.269031	-0.7906%
Point 37	4.76305024	4.762749	-0.0063%	4.794953	4.793479	-0.0307%
Point 38	4.7634036	4.763069	-0.0070%	4.80087	4.798726	-0.0447%

According to the results, a reduction up to 4.15% can be achieved regarding the standard failures, whereas in the case of failures per year that cause downtime the reduction is much lower due to the impact of the failure in service factor on the calculations. Specifically, for the circuit breakers, when the analysis of system failures is conducted, the failure in service factor is only 5%, since only a small amount of circuit breakers failure lead to system failure. Thus, considering that for every circuit breaker of the system, it is understandable that any impact of a predictive maintenance system is low. Equation (5.2) analyzed in chapter 5 is used to describe that relationship between the different parameters.

6.2.2. Impact of the utility source

The previous results trigger a question about the impact of the source failure rate on the calculations.

Based on the listed equipment of table 16 and the single line diagram of the system there are three utility supplies. The first two have failure rate and MTTR data coming from conventional textbooks such as the gold book standard. On the other hand, the third utility supply has a more real-life performance values based on [21].

The points linked to the third source, which present a much higher failure rate compare to the other two sources, show a small impact when a predictive maintenance system is applied based on the results of table 17. To investigate that further, the results of an unrealistic scenario with the source omitted are presented in table 18.

As in the previous case all transformers, LV and MV circuit breakers are assumed under monitor with a system efficiency of 67%.

Table 18 Standard failures with and without system sources omitted

	Standard failures with utility sources			Standard failures without utility sources		
Point number	Base case Failure rate (f/yr)	PdM applied Failure rate (f/yr)	Difference (%)	Base case Failure rate (f/yr)	PdM applied Failure rate (f/yr)	Difference (%)
Point 1	0.224139222	0.224139	0.0000%	0.001917	0.001917	0.0000%
Point 2	0.224139222	0.224139	0.0000%	0.001917	0.001917	0.0000%
Point 3	4.751917	4.751917	0.0000%	0.001917	0.001917	0.0000%
Point 4	0.233490222	0.232887	-0.2583%	0.011268	0.010665	-5.3514%
Point 5	0.239241222	0.238638	-0.2520%	0.017019	0.016416	-3.5431%
Point 6	4.768936	4.768333	-0.0126%	0.018936	0.018333	-3.1844%
Point 7	0.259507222	0.258033	-0.5680%	0.037285	0.035811	-3.9533%
Point 8	0.259507222	0.258033	-0.5680%	0.037285	0.035811	-3.9533%
Point 9	0.259507222	0.258033	-0.5680%	0.037285	0.035811	-3.9533%
Point 10	0.265258222	0.263784	-0.5557%	0.043036	0.041562	-3.4250%
Point 11	0.254041222	0.252567	-0.5802%	0.031819	0.030345	-4.6325%
Point 12	0.269758222	0.268284	-0.5464%	0.047536	0.046062	-3.1008%
Point 13	0.267175222	0.265701	-0.5517%	0.044953	0.043479	-3.2790%
Point 14	0.265258222	0.263784	-0.5557%	0.043036	0.041562	-3.4250%
Point 15	4.794953	4.793479	-0.0307%	0.044953	0.043479	-3.2790%
Point 16	4.79687	4.795396	-0.0307%	0.04687	0.045396	-3.1449%
Point 17	4.781336	4.779862	-0.0308%	0.031336	0.029862	-4.7039%
Point 18	0.269495434	0.266676	-1.0463%	0.047211033	0.044396	-5.9628%
Point 19	0.035951976	0.034459	-4.1530%	0.013656302	0.012168	-10.9002%
Point 20	0.333507222	0.332033	-0.4420%	0.111285	0.109811	-1.3245%
Point 21	0.364384222	0.362642	-0.4781%	0.142162	0.14042	-1.2254%
Point 22	0.289471222	0.287729	-0.6018%	0.067249	0.065507	-2.5904%
Point 23	0.275675222	0.273531	-0.7777%	0.053453	0.051309	-4.0110%
Point 24	0.273092222	0.270948	-0.7851%	0.05087	0.048726	-4.2147%
Point 25	4.80087	4.798726	-0.0447%	0.05087	0.048726	-4.2147%
Point 26	0.035719614	0.034848	-2.4403%	0.012344443	0.011526	-6.6329%
Point 27	0.035949435	0.035078	-2.4247%	0.012536049	0.011717	-6.5316%
Point 28	4.865639259	4.86105	-0.0943%	0.115639259	0.11105	-3.9688%
Point 29	0.306471222	0.301614	-1.5850%	0.084249	0.079392	-5.7656%

	Standard failures with utility sources			Standard failures without utility sources		
Point 30	0.401571222	0.396714	-1.2096%	0.179349	0.174492	-2.7084%
Point 31	0.390754481	0.385897	-1.2431%	0.168532259	0.163675	-2.8822%
Point 32	4.871839259	4.86725	-0.0942%	0.121839259	0.11725	-3.7668%
Point 33	0.269094222	0.26762	-0.5478%	0.046872	0.045398	-3.1447%
Point 34	4.798789	4.797315	-0.0307%	0.048789	0.047315	-3.0212%
Point 35	0.265258222	0.263784	-0.5557%	0.043036	0.041562	-3.4250%
Point 36	0.271175222	0.269031	-0.7906%	0.048953	0.046809	-4.3797%
Point 37	4.794953	4.793479	-0.0307%	0.044953	0.043479	-3.2790%
Point 38	4.80087	4.798726	-0.0447%	0.05087	0.048726	-4.2147%

The results reveal the impact of the sources on the failure rate calculations. The higher the source failure rate the less visible is the impact of a predictive maintenance system. The main reason for that, is that the equipment under monitoring present low failure rate values compare to the sources. Thus, the source failure rate dictates the cumulated failure rate at the different points of the system. The improvement is only taking place on the equipment under monitoring while the sources cannot be affected. Consequently, the general impact of a predictive maintenance system is low.

6.3. Case 1: Chemical industry in US circuit 1

After the implementation and the sensitivity analysis of the approach in two theoretical networks, real case investigations are presented in the following sections.

In this first case, a part of a chemical manufacturing industrial system is analyzed. The single line diagram of the installation is presented in figure 20 along with its zones and the monitored equipment, indicated with greed dots. It should be noted though, that the impact on the motors is not included in the calculations.

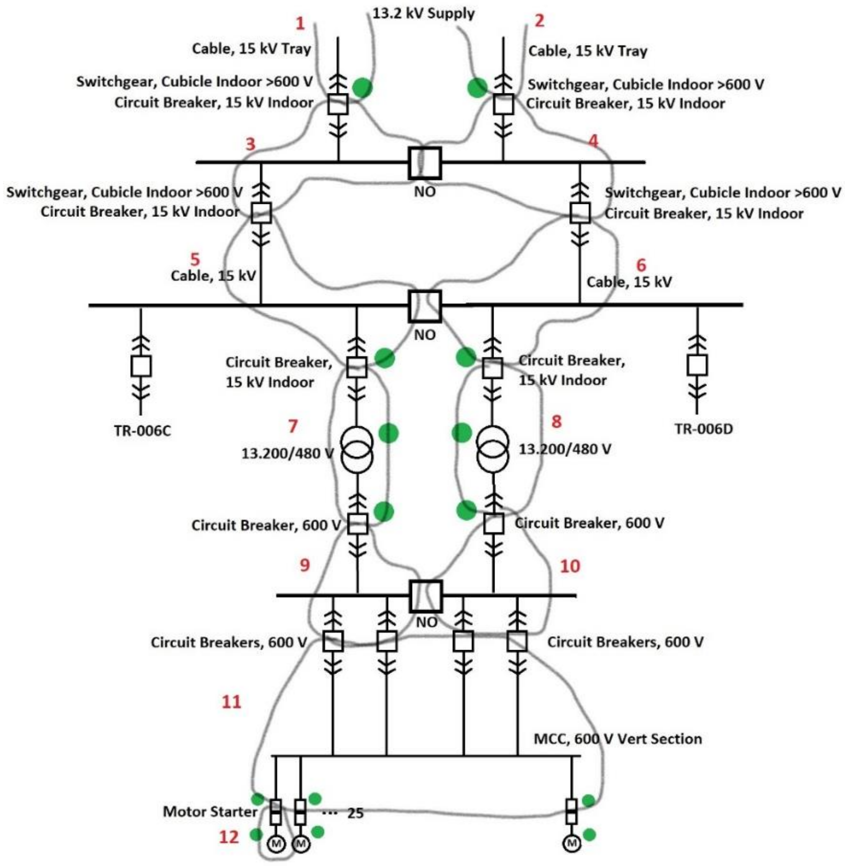


Figure 20 Case 1 SLD of a part of a chemical industry

The list of equipment is presented in table 19 with its failure rate, failure in service and MTTR data. The failure in service factor is set at 5% for LV circuit breakers, 10% for MV circuit breakers and 90% for transformers. The installation is less than 15 years old, so the related data are utilized.

Table 19 Case 1: Equipment of a part of a chemical industry

Equipment	Failure rate (f/yr)	MTTR (h)	Failure in Service (%)
Cable, 15 KV Tray < 15 yr	0.00360000	48.00	98
Circuit Breaker, 15 KV Indoor < 15 yr	0.00360000	8.00	10
Circuit Breaker, 600 V ID Metalclad < 15yr	0.00500000	16.00	5
MCC, 600 V Vert Section < 15yr	0.00100000	72.00	80
Starter MCC, motor 600V < 15yr	0.01390000	24.00	80

Equipment	Failure rate (f/yr)	MTTR (h)	Failure in Service (%)
Switchgear, Cubicle Indoor > 600v <15 yr	0.00191700	36.00	8
Switchgear, Cubicle InDoor 600v <15 yr	0.00720000	36.00	8
Transformer 300 - 10000 KVA <10yr, Monitored	0.0010000	300.00	90
480 v Motor	0.08000000	8.0	94
Utility U1 and U2	0.22222222	0.63	100

6.3.1. Reliability analysis

Based on the approach the lambda factor is adjusted to include the impact of a predictive maintenance (PdM) system on the monitored assets. The efficiency of the system is set to 67%. Thus, the lambda factor is considered as:

- 0.3769, 62.31% reduction in the case of Low Voltage Circuit Breakers
- 0.8325, 16.75% reduction in the case of Medium Voltage Circuit Breakers
- 0.732, 26.8% reduction in the case of Transformers

Table 20 summarizes the results of failure rate and forced downtime for failures related to lose of power. The forced downtime is presented in this case since it is a parameter that is included in the cost benefits analysis calculations to extract the average downtime per failure, as it was explained in chapter 4.

Table 20 Case 1: Results of failures related to system failure

Point number	Failure Rate per year without PdM	Failure Rate per year with PdM	Difference (%)	Forced Downtime (Hrs/Yr) without PdM	Forced Downtime (Hrs/Yr) with PdM	Difference (%)
Point 1	0.222576	0.222576	0.0000%	0.155881	0.155881	0.0000%
Point 2	0.222576	0.222576	0.0000%	0.155881	0.155881	0.0000%
Point 3	0.223089	0.223029	-0.0270%	0.164282	0.163799	-0.2936%
Point 4	0.223089	0.223029	-0.0270%	0.164282	0.163799	-0.2936%
Point 5	0.22367	0.223609	-0.0270%	0.055917	0.055902	-0.0270%
Point 6	0.22367	0.223609	-0.0270%	0.055917	0.055902	-0.0270%
Point 7	0.22493	0.224568	-0.1609%	0.056232	0.056142	-0.1608%
Point 8	0.22493	0.224568	-0.1609%	0.056232	0.056142	-0.1608%
Point 9	0.22518	0.224662	-0.2298%	0.060232	0.057649	-4.2881%
Point 10	0.22518	0.224662	-0.2298%	0.060232	0.057649	-4.2881%
Point 11	0.245683	0.245165	-0.2107%	0.06142	0.061291	-0.2107%
Point 12	0.332003	0.331485	-0.1559%	0.92982	0.929691	-0.0139%

The calculations indicate a really small improvement in the failure rate per year of the installation. That can be attributed to the low failure rate of the equipment, the failure in service factor, the configuration and the high impact of the source failure rate, which cannot be improved. Regarding the force downtime difference an improvement up to 4.28% is observed. One point that requires attention in this configuration is the repair time. The system includes three tie breakers which enable the switch between the sources at different points. To incorporate the impact of tie breakers in the calculations, a 0.25 hours repair time is inserted manually in the points after the tie breakers. Thus, the values of MTTR on those points are not based on formulas and a predictive maintenance system does not have any impact. That point is important during the cost benefit analysis.

Table 21 summarizes the calculations of failure rate of standard failures. The results will be used during the cost benefit analysis to calculate the average reduction of the fixed expenses parameter.

Table 21 Case 1: Results of standard failures

Point number	Failure Rate per year without PdM	Failure Rate per year with PdM	Difference (%)
Point 1	0.224344	0.224344	0.0000%
Point 2	0.224344	0.224344	0.0000%
Point 3	0.229861	0.229393	-0.2036%
Point 4	0.229861	0.229393	-0.2036%
Point 5	0.235446	0.234978	-0.1988%
Point 6	0.235446	0.234978	-0.1988%
Point 7	0.240046	0.23884	-0.5024%
Point 8	0.240046	0.23884	-0.5024%
Point 9	0.245046	0.24074	-1.7572%
Point 10	0.245046	0.24074	-1.7572%
Point 11	0.280054	0.275745	-1.5386%
Point 12	0.373954	0.369645	-1.1522%

In this case, as it was previously explained, the impact of a predictive maintenance system on the standard failures is higher.

6.3.2. Cost benefit analysis

To evaluate the impact of predictive maintenance in financial terms the revenue requirement (RR) method, as it was described in chapter 4, is utilized. The focus during the analysis is on the points that a failure will have significant financial consequences thus, in this case point 11 of the SLD will be investigated.

Based on the reliability analysis the reduction of failures per year related to downtime due to PdM is 0.2107%. Regarding the repair time, as it was previously explained, there is no difference due to tie breakers. In the case of standard failures per year at point 11 there is a reduction of 1.53% and of 0.7215% on average at the installation. To calculate the fixed expenses percentage that average value is used.

Concerning the financial terms of the installation and according to [43], the initial capital investment is 728.000 $ and it is increased by 1.8% due to the predictive maintenance system installation. The margin between losses and savings is 6000 $ per hour and the plant restart time after a failure is set to 72 hours. Lastly, the extra expenses incurred per failure are considered to be 27.500 $ (average value) with a 30% reduction due to PdM. That last reduction is assumed, and a sensitivity analysis will be performed to support better the results. Regarding the fixed investment charges factor, none of the parameters is affected by the implementation of PdM except the fixed expenses per dollar of investment. That value initially is considered to be 8.25% and includes property taxes, fixed maintenance cost and insurance. When PdM is applied the percentage is calculated considering the standard failures (related to fixed maintenance cost) and the subscription fee of the PdM system. The summary of the RR methodology parameters is presented in table 22.

Since only a part of the system is analyzed, the calculation of the fixed expenses percentage assumes that 90% is related to fixed maintenance cost and the rest to the other factors. Then, in the initial value the subscription fee percentage has to be added and the fixed maintenance cost should be reduced based on the failure rate reduction and the extra expenses incurred per standard failures. The same 30% reduction is assumed for the extra expenses incurred for the standard failures.

Table 22 Case 1: Summary of RR method values

Parameter	Description	Value without PdM	Value with PdM	Difference	Comment
C	Capital investment	$ 728,000	$ 741,104	1.8%	Calculated
X	Failure rate	0.245682672	0.245164957	-0.2107%	Calculated
	Extra expenses incurred per failure	$ 27,500	$ 19,250	-30%	Assumed
	Revenues lost per hour of plant downtime	$ 22,000	$ 22,000	0%	
	Variable expenses saved per hour of plant downtime	$ 16,000	$ 16,000	0%	
	Repair or replacement time after a failure	0.249998247	0.249998251	0%	No change due to tie breakers
	Plant start-up	72	72	0%	

Parameter	Description	Value without PdM	Value with PdM	Difference	Comment
	time after a failure				
F	Minimum acceptable earnings per $ of investment	0.15	0.15	0%	
	Years prior to start-up that an investment is made	1	1	0%	
	Life of investment	20	20	0%	
	Risk adjustment factor	1	1	0%	
	Income tax depreciation, levelized per $ of investment	0.05	0.05	0%	
	Income taxes per $ of investment	0.05	0.05	0%	
	Fixed expenses per $ of investment [insurance, property taxes, fixed maintenance cost]	8.25%	7.00%	-15.185%	Calculated

Based on the calculations the percentage of fixed expenses is reduced by 15.18%. The subscription fee yearly adds 1.01% percent (7.500 $/year) although, a reduction of 30.5% of the cost of standard failures due to PdM is leading to the final percentage of 7% from the initial value of 8.25% without PdM applied. The calculation can be described by the following formula:

$$e_{new} = [fixed\ insurance\ and\ property\ taxes] + [reduced\ standard\ maintenance\ cost] + [subscription\ fee] \Rightarrow$$

$$e_{new} = 10\% \cdot 8.25\% + 90\% \cdot 8.25\% \cdot (1 - 30.5\%) + 1.01\%$$

The calculations related to the standard failure cost reduction are presented in table 23. In summary from the amount of 6.883 $ per failure per year the new variable cost due to PdM goes to 4.784 $ reaching a reduction of 30.5%. Since standard failures are not causing downtime, savings, losses, repair, replacement and restart time are not considered in the calculations. The variable expenses are the product of the failure rate with the expenses due to a failure. For the failure rate of standard failures, the average value is considered in fixed maintenance cost calculations.

Table 23 Case 1: Variable cost of standard failures

Description	Value without PdM	Value with PdM	Difference	Comment
Failure rate	0.250291028	0.248498214	-0.7215%	Calculated
Extra expenses incurred per failure	$ 27,500	$ 19,250	-30%	Assumed
Variable expenses due to standard failures per year	$ 6.833	$ 4.783	30.5%	Calculated

Finally, considering all the calculations above, the results of the RR method are presented in table 24.

Table 24 Case 1: Results of the RR method

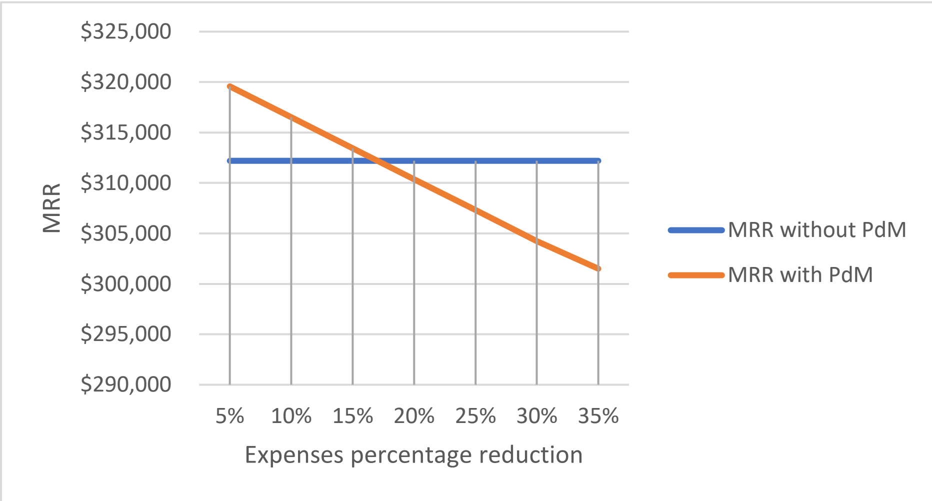
Description	Value without PdM	Value with PdM	Difference
Capital investment (C)	$ 728,000	$ 741,104	1.8%
Variable expenses (X) [$/year]	$ 113,259	$ 110,998	-2%
Fixed investment charges factor (F)	0.27326	0.26074	-4.58%
Fixed investment charges ($C \cdot F$) [$/year]	$ 198.936	$ 193.233	-2.87%
Minimum revenue requirements ($G = X + C \cdot F$) [$/year]	$ 312.196	$ 304.231	-2.55%

In summary, to apply a predictive maintenance system a 1.8% of the capital investment is required and a subscription fee of 7.500$ (1.01%) per year. That would result in a 2% reduction of the variable expenses and 2.87% of the fixed investment charges per year. Consequently, the minimum revenue requirements (MRR) are reduced by 2.55% from 312.196 $ per year to 304.231 $ per year. Thus, based on the RR methodology described in the IEEE 493-2007 [13] standard the installations that includes a predictive maintenance system is preferable since it presents lower MRR.

6.3.3. Sensitivity analysis

To evaluate the impact of the assumed reduction of the extra expenses incurred per failure, a sensitivity analysis regarding this parameter is conducted in this section.
The 30% reduction applied on the calculation is an estimation based on use cases [42] and expert experience [43]. Although, this number is not accurately calculated thus, in figure 21 a graph comparing MRR with the extra expenses incurred per failure percentage reduction is presented.

Figure 21 Case 1: MRR against extra expenses incurred per failure reduction percentage



According to the graph, when a reduction between 15 and 20 percent is applied the MRR of the PdM installation becomes the preferable choice. That percentage, although not precisely calculated, can be achieved considering the cost and the collateral damages of a failure that was not predicted (e.g. in a transformer). Additionally, the assumed percentage is supported by different sources such the US Department of Energy [5].

6.4. Case 2: Chemical industry in US circuit 2

A second part of the installation of the same chemical industry is analyzed in this section. The SLD along with the protective zones is presented in figure 22. The green dots indicate the equipment under monitoring.

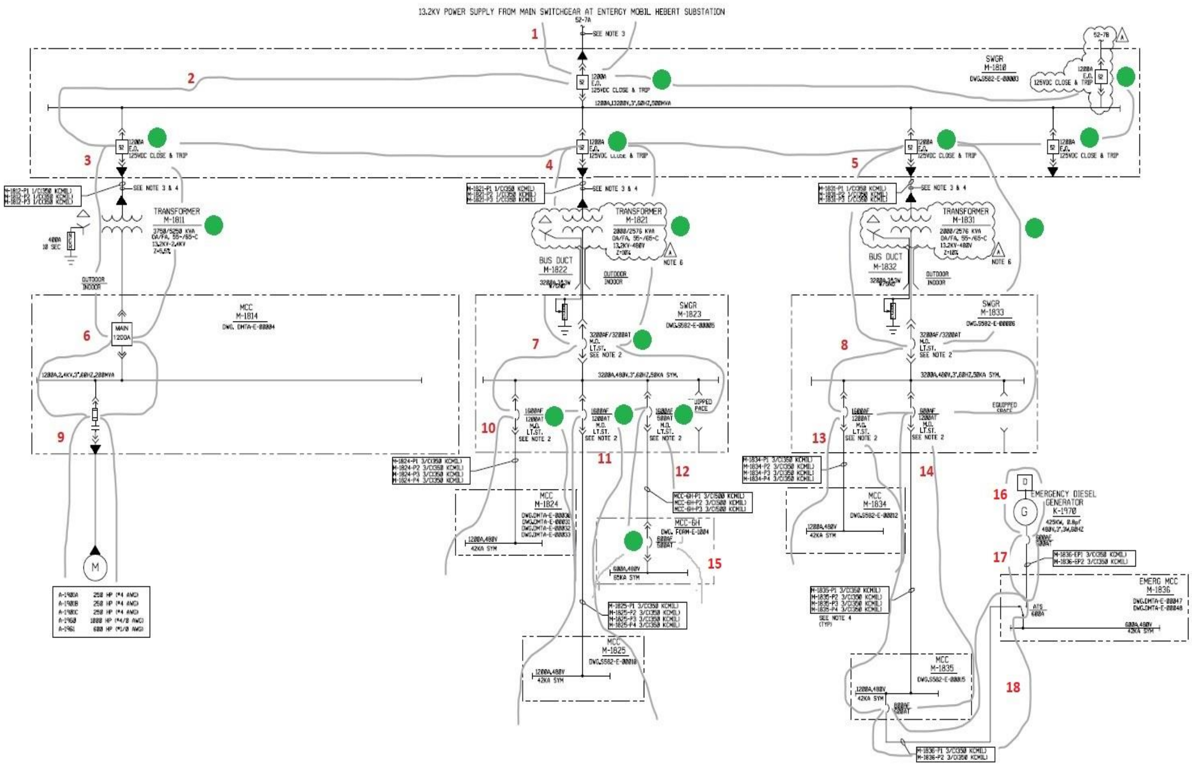


Figure 22 Case 2: SLD of a part of a chemical industry

The equipment of the installation and the corresponding data are summarized in table 25. In this case that the installation is less than 15 years old thus the corresponding data are used according to the RAM table.

Table 25 Case 2: Equipment of a part of a chemical industry

Equipment	Failure rate (f/yr)	MTTR (h)	Failure in Service (%)
Cable, 15 KV Tray < 15 yr	0.00360000	48.00	98
Bus Duct, Outdoor, 600v < 15yr	0.00033300	9.50	40
Cable in Conduit/OH 15 KV < 15 yrs	0.00400000	48.00	98
Cable, 600 V Tray	0.00400000	5.00	98

Equipment	Failure rate (f/yr)	MTTR (h)	Failure in Service (%)
Circuit Breaker, 15 KV Indoor < 15 yr	0.00360000	8.00	10
Circuit Breaker, 600 V OD Metalclad <15yr	0.00580000	16.00	5
Generator, Diesel Standby 250KW-1.5MW Packaged	0.13386922	35.9	100
MCC, 600 V Vert Section < 15yr	0.00100000	72.00	80
Starter, motor E-2 < 15yr	0.00500000	24.00	75
Switch, Automatic Transfer 0-600 amp	0.07800326	6.31	95
Switchgear, Cubicle Indoor > 600v <15 yr	0.00191700	36.00	8
Switchgear, Cubicle Indoor 600v <15 yr	0.00720000	36.00	8
Transformer 300 - 10000 KVA 10yr	0.00100000	300.0	90
480 v Motor	0.08000000	8.0	94
Single Circuit Utility Supply	1.95600000	1.32	100

6.4.1. Reliability analysis

The same lambda factors are utilized, and the system efficiency is set to 67%. The failure rate and the MTTR are summarized in table 26 for this case.

Table 26 Case 2: Results of failures related to system failure

Point number	Failure Rate per year without PdM	Failure Rate per year with PdM	Difference (%)	MTTR (Hrs/Event) without PdM	MTTR (Hrs/Event) with PdM	Difference (%)
Point 1	1.956222727	1.956222727	0.0000%	1.325316399	1.325316399	0.0000%
Point 2	1.956736087	1.956674887	-0.0031%	1.32926205	1.329053405	-0.0157%
Point 3	1.958062905	1.957697505	-0.0187%	1.46936162	1.43189804	-2.5497%
Point 4	1.958196105	1.957830705	-0.0187%	1.469907899	1.432446964	-2.5485%
Point 5	1.958196105	1.957830705	-0.0187%	1.469907899	1.432446964	-2.5485%
Point 6	1.959728905	1.959363505	-0.0186%	1.510453131	1.473029068	-2.4777%
Point 7	1.959062105	1.958516905	-0.0278%	1.482211271	1.44343296	-2.6162%
Point 8	1.959062105	1.958696705	-0.0187%	1.482211271	1.444769195	-2.5261%
Point 9	2.038678905	2.038313505	-0.0179%	1.791201563	1.755277375	-2.0056%
Point 10	1.960002348	1.959277348	-0.0370%	1.494636556	1.454545613	-2.6823%
Point 11	1.960002348	1.959277348	-0.0370%	1.494636556	1.454545613	-2.6823%
Point 12	1.959426348	1.958701348	-0.0370%	1.484493229	1.444386746	-2.7017%
Point 13	1.960002348	1.959636948	-0.0186%	1.494636556	1.45721476	-2.5037%
Point 14	0.002484002	0.002482019	-0.0798%	12.9399786	12.9323188	-0.0592%
Point 15	1.960292348	1.959387548	-0.0462%	1.496782437	1.455363679	-2.7672%
Point 16	0.133869218	0.133869218	0.0000%	35.88	35.88	0.0000%
Point 17	0.13423346	0.13423346	0.0000%	35.8199717	35.8199717	0.0000%
Point 18	0.208912556	0.208912556	0.0000%	25.35303039	25.35303039	0.0000%

As it was explained in subsection 6.2.2, the high failure rate of the source has an impact on the calculations. Any improvement on the lower decimals points due to PdM is shadowed by the failure rate of the single source which cannot be affected. Specifically, in point 7 which is of interest only a 0.0278% reduction is achieved. Regarding the MTTR a maximum reduction of 2.76 at point 15 is observed. Points 15 to 18 show no improvement since they are related to the emergency diesel generator with no PdM applied.

Table 27 summarizes the calculations of failure rate of standard failures. The average values of the results are used to calculate the fixed expenses factor during the cost benefit analysis.

Table 27 Case 2: Results of standard failures

Point number	Failure Rate per year without PdM	Failure Rate per year with PdM	Difference (%)
Point 1	1.956227273	1.956227273	0.0000%
Point 2	1.961744273	1.961132273	-0.0312%
Point 3	1.966412455	1.964918455	-0.0760%
Point 4	1.966745455	1.965251455	-0.0760%
Point 5	1.966745455	1.965251455	-0.0760%
Point 6	1.980412455	1.978918455	-0.0754%
Point 7	1.979745455	1.974655455	-0.2571%
Point 8	1.979745455	1.978251455	-0.0755%
Point 9	2.065412455	2.063918455	-0.0723%
Point 10	1.992821212	1.984135212	-0.4359%
Point 11	1.992821212	1.984135212	-0.4359%
Point 12	1.985621212	1.976935212	-0.4374%
Point 13	1.992821212	1.991327212	-0.0750%
Point 14	0.020238897	0.020235602	-0.0163%
Point 15	1.998621212	1.986339212	-0.6145%
Point 16	0.133869218	0.133869218	0.0000%
Point 17	0.139744975	0.139744975	0.0000%
Point 18	0.224948234	0.224948234	0.0000%

The impact of PdM is higher compare to the failures related to downtime but is general is low compare to the previous cases due to the impact of the high failure rate of the source compare to the rest of the equipment of the installation.

6.4.2. Cost benefit analysis

In this case, the focus of the revenue requirement method calculations will be on point 7 of the installation since a downtime failure there is having significant financial losses for the industry. The reliability analysis at this point indicated a reduction of the failure rate per year by 0.0278% and by 2.61% for MTTR. Regarding the standard failures an average reduction of 0.19% is observed.

The initial capital investment of this part of the installation is 817.125 $ and 26.965 $ (3.3% increase) are required for the implementation of the PdM system. The subscription fee is 5.175 $ while the margin between losses and savings is doubled, compare to the previous case, to

12.000$. Finally, the average extra expenses due to a failure are 27.500 $ and a 30% reduction due to PdM is also assumed.

Any change on the fixed investment charges factor is dictated by the fixed expenses per dollar of investment parameter since any other parameter remains the same. The calculations of that value are exactly the same with the previous case. The initial percentage is 8.25 which is reduced to PdM implementation by 19.69%. The summary of the RR methodology parameters is presented in table 28.

Table 28 Case 2: Summary of RR method values case 2

Parameter	Description	Value without PdM	Value with PdM	Difference	Comment
C	Capital investment	$ 817,125	$ 844,090	3.3%	Calculated
X	Failure rate	1.959062105	1.958516905	-0.0278%	Calculated
	Extra expenses incurred per failure	$27,500	$19,250	-30%	Assumed
	Revenues lost per hour of plant downtime	$28,000	$28,000	0%	
	Variable expenses saved per hour of plant downtime	$16,000	$16,000	0%	
	Repair or replacement time after a failure	1.481720114	1.442967292	-2.6154%	Calculated
	Plant start-up time after a failure	72	72	0%	
	Minimum acceptable earnings per	0.15	0.15	0%	

Parameter	Description	Value without PdM	Value with PdM	Difference	Comment
	$ of investment				
F	Years prior to start-up that an investment is made	1	1	0%	
	Life of investment	20	20	0%	
	Risk adjustment factor	1	1	0%	
	Income tax depreciation, levelized per $ of investment	0.05	0.05	0%	
	Income taxes per $ of investment	0.05	0.05	0%	
	Fixed expenses per $ of investment [insurance, property taxes, fixed maintenance cost]	8.25%	6.63%	-19.690%	Calculated

The calculations related to the standard failure cost reduction are presented in table 29. In summary from the amount of 43,243 $ per failure per year the new variable cost due to PdM goes to 30,212 $ reaching a reduction of 30.13%. For the failure rate of standard failures, the average value is considered in fixed maintenance cost calculations.

Table 29 Case 2: Variable cost of standard failures

Description	Value without PDM	Value with PDM	Difference	Comment
Failure rate	1.572483228	1.569455268	-0.1929%	Calculated
Extra expenses incurred per failure	$ 27,500	$ 19,250	-30%	Assumed
Variable expenses due to standard failures per year	$ 43,243	$ 30,212	30.13%	Calculated

Finally, considering all the calculations above the results of the RR method are presented in table 30. It is obvious that the costs are higher in this case due to the higher failure rate that this part of the installation presents.

Table 30 Case 2: Results of the RR method

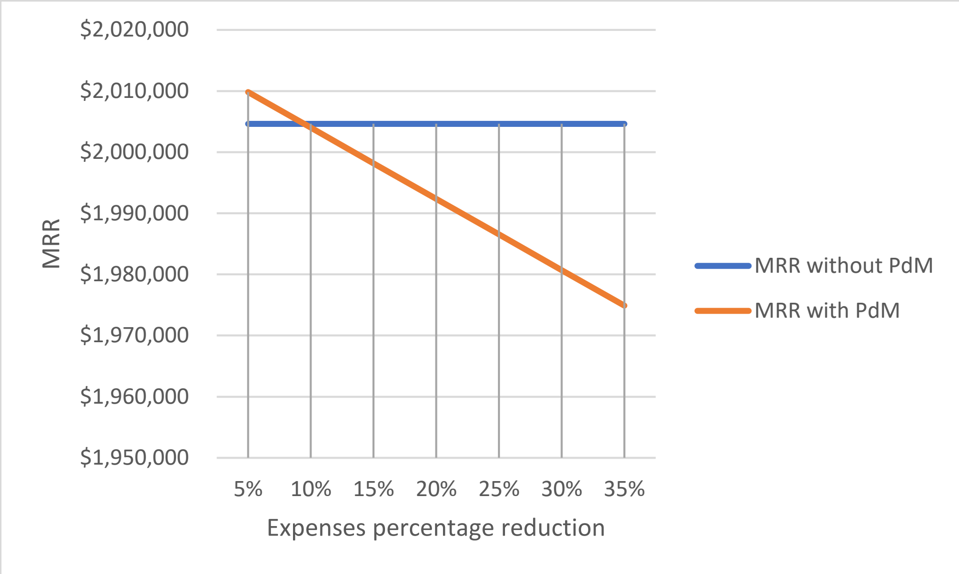
Description	Value without PDM	Value with PDM	Difference
Capital investment (C)	$ 817,125	$ 844,090	3.3%
Variable expenses (X) [$/year]	$ 1,781,337	$1,763,772	-1%
Fixed investment charges factor (F)	0.27326	0.25702	-6.31%
Fixed investment charges ($C \cdot F$) [$/year]	$ 223,291	$ 216,948	-2.84%
Minimum revenue requirements ($G = X + C \cdot F$) [$/year]	$ 2,004,628	$ 1,980,721	-1.19%

The results suggest that the configuration of the system that includes predictive maintenance should be the favourable choice according to the RR method and the IEEE 493-2007 [13]. The implementation of PdM requires 3.3% of the capital investment and an annual subscription fee of 5.175 $. Consequently, the variable expenses due to a failure are reduced by 1% and the minimum revenue requirements are also lower by 1.19%.

6.4.3. Sensitivity analysis

A sensitivity analysis on the extra expenses incurred per failure percentage reduction is conducted in this case too. In figure 23 the results of the MRR for different percentages of reduction are presented.

Figure 23 Case 2: MRR against extra expenses incurred per failure reduction percentage



In this case, a bit less than 10% reduction on the extra expenses incurred per failure, when a predictive maintenance system is applied, is enough to justify its installation. That number considering the prevention of a crucial failures is not hard to be achieved indicating the preference for a PdM system.

Conclusions

According to the proposed approach new failure rates are calculated for the equipment under monitoring when a predictive maintenance is applied. Those values are then inserted in the spreadsheet tool to evaluate the impact of the implementation of such a system. Additionally, cost benefit analysis was conducted utilizing the revenue requirement method. The overall methodology was applied in two theoretical and two real industrial networks.

The results indicate that the failure rate of the system decreases when the number of monitored equipment increases although, implementation cost should be considered in the different cases. Additionally, the impact is higher to standard failures compare to the failures related only with downtime due to the different failure rate considered percentage (failure in service factor). The results are also affected by the type of the equipment under monitoring and the configuration of the system. Furthermore, the prediction efficiency of the system affects linearly the reliability indices at the different points of the installation. Finally, the cost benefit analysis on actual cases indicates that a PdM system should be preferred even with lower reduction percentage of extra expenses incurred per failure, than the one assumed.

As a general conclusion, it can be noted that the low failure rate of the equipment along with the high of the utility sources lead to a small improvement on the reliability of the installation. The impact of predictive maintenance appears only on the selected equipment under monitoring which presents low failure rate values per year. On the other hand, the high failure rate of the sources, that cannot be affected by the system, dictates the calculations thus, the overall impact appears to be low. Despite that, the cost benefit analysis suggests the preference on PdM regardless of that low impact on the failure rate. That justifies the overall benefits of a predictive maintenance system.

The limitations on available data and consequently of the suggested approach leads only to the consideration of the mitigation of causes of failures by a predictive maintenance system. An approach that can incorporate the predictive maintenance along with the preventive maintenance actions that take place, might indicate different results on the reliability indices. Finally, it should be noted that all the calculations are in an annual basis and assume a constant failure rate in time. Consequently, the accumulated calculated impact is higher and becomes even more when an increased failure rate is considered.

Future Work

The presented static approach attempted to quantify the impact of predictive maintenance on an industrial system. Although, further improvements can be made to justify and provide better results.

The base of the approach is constructed around the statistical information of causes of equipment failure. That utilized knowledge came from IEEE surveys that date back some decades and consequently, that information could be revised and updated by new and more accurate studies. Additionally, a deeper failure mode analysis would enable a better understanding of the failure mechanisms and would allow a more accurate and broader link between the functions of a predictive maintenance system. A project could be just dedicated to study that relationship. Furthermore, the upcoming development of such a system with more capabilities would require the update of the approach.

Regarding the utilized methodologies, time dependent functions could be used in the future to provide more holistic results as it was explained in section 5.4. However, that process would require a big amount of data related to the failure rate and the failure mechanisms for the studied equipment. Additionally, different approaches that enable the analysis of big data might be required.

Finally, to be able to perform the presented approach or any other alternative to more industrial installations, access to financial parameters is necessary to conduct cost benefit analysis. Moreover, further investigation on the revenue requirement parameters can be conducted to justify better the assumed values. Lastly, other benefits of predictive maintenance could be included such as the timecard savings, equipment lifetime (increase of the lifetime investment parameter of RR method) and any other cost reduction and benefit.

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