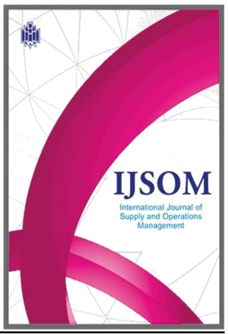
International Journal of Supply and Operations Management

IJSOM

November 2018, Volume 5, Issue 4, pp. 319-337
ISSN-Print: 2383-1359
ISSN-Online: 2383-2525
www.ijsom.com



Improving Maintenance Strategy by Physical Asset Management Considering the Use of MFOP instead of MTBF in Petrochemical

Farid Najari [a], Mohammad Ali Sobhanallahi [a,*] and Mohammad Mohammadi [a]

[a] *Department of Industrial Engineering, Faculty of Engineering, Kharazmi University, Tehran, Iran*

Abstract
The aim of this study is to compare the aviation derived reliability metric known as the Maintenance Free Operating Period (MFOP) with the traditionally used reliability metric called Mean Time between Failure (MTBF), which has its innate disadvantages in the field of maintenance. This is mainly due to MTBF's inherent acceptance of failure and the unscheduled maintenance directly associated with it. Moreover, MFOP is successfully applied to a Petrochemicals-specific case study. To date, no other application of the MFOP concept to the Petrochemicals sector is known. In this study, first, an extensive review of the literature is presented. This section covers concepts relevant to the study and helps to contextualize the problem, revealing the major shortcomings of the commonly accepted MTBF metric. Then, for the analysis of MFOP performance of the systems, a methodology that makes use of failure statistics to analyze both repairable and non-repairable systems is presented. Validation makes use of a case study, which applies the MFOP methodology to a system, specifically in the Petrochemicals sector. It was shown that MFOP could be applied to the data obtained from the Petrochemicals sector, producing estimates, which were accurate representations of reality. These findings provide an exciting basis for facilitating a paradigm shift in the mindset of maintenance personnel, setting reliability targets, and dealing with unscheduled maintenance stops.

Keywords: Maintenance strategy; Petrochemicals; Physical asset management; Repairable system; and Non-repairable system.

1. Introduction

Physical Asset Management (PAM) is one of the fast-growing engineering disciplines in the world. By reliance on recent conception and implementation of the British Standard Publicly Available Specification 55 (PAS 55), specifically dealing with PAM, the concept has become an area of much research and discussion in both industry and academia. This has been even further bolstered by the upcoming creation of the standard set by an International Organization for Standardization (ISO) on PAM from the PAS 55 standard, to be known as ISO 55000, which at the time of writing this paper was still being developed. Within PAM and PAS 55, there are certain primary requirements for the optimization of asset management activities. These requirements include acquiring, utilizing, maintaining, and renewing.The scope of the research closely associate with the PAS 55 is the "maintain" asset management activity. Maintenance engineering truly began to be taken seriously by the majority of the industry in the early 1980s by the advent of the formulation and introduction of maintenance management theories, such as Total Productive Maintenance (TPM) and Reliability Centered Maintenance (RCM). As with most industries, in maintenance, there is a tendency for constant improvement of the status quo. Mobley (2002) pointed out that maintenance is one of the driving factors involved in reliability and efficient operation (Khalilpourazari & Khalilpourazary 2018; Mohammadi & Khalilpourazari 2017). However, many industries still knowingly perform ineffective maintenance action. Due to this fact, there is a constant push, especially in the engineering discipline, to optimize methodologies and practices. Heng et al. (2009) state that plants in the United States spent more than the US $600 billion to maintain their systems in 1981 and this figure has been doubled in the last 20 years. Thus, today maintenance is not a multi-billion-dollar industry, but actually a trillion-dollar industry.

Corresponding author email address: sobhanallahi@yahoo.com

This is a massive industry, not only in terms of expenditure, but also in terms of maintenance activities; therefore, there is a need for optimized maintenance activities in order to gain maximum benefit for the operator at the lowest cost. Old concepts; therefore, need to be challenged with new thought patterns, in order to best perform this task and to continue to improve maintenance, and thereby the greater scope of PAM.

2. Literature Review

This sector introduces the related literature and attempts to contextualize the problem described in the introduction. PAM, the umbrella term under which this research falls, is considered first, Asset Management (AM) and an overview of the holistic approach to AM is then described. After gaining an overview of AM, the PAS 55 standard is briefly discussed in the following subsection. After this, ACPs are reviewed and a number of relevant subsections follow. Maintenance interval metrics play a central role in this study and are elaborated on after ACPs, together with relevant items regarding maintenance intervals. Thereafter, two important maintenance management philosophies are discussed, in order to place the research in context and to show its wider application. To begin to understand the term AM in the context of engineering, from Engineering-specific perspective, Davis (2007, p.?) defined an engineering-AM as “a continuous process-improvement strategy for improving the availability, safety, reliability, and longevity of plant assets, i.e., systems, facilities, equipment, and processes”. However, in order to gain an understanding of the complete and more general application of the term AM, it would be appropriate to compare the above definition to the definitions of the word pair, given by the Oxford English Dictionary (OED), first, the definition of an asset is given as “All the property of a person or company, which may be made liable for his or their deaths”. (OED, 2007). Management is also defined by the OED as”organization, supervision, or direction; the application of skill or care in the manipulation, use, treatment, or control (of a thing or person), or in the conduct of something”. (2007) An authoritative definition of AM is the so-called accountant's view of assets. In the accountant's definition, assets are split into fixed and current assets. Hastings (2010) defines a fixed asset as a physical item, which has value over a period exceeding one year. Examples of these include land and buildings, as well as plant and machinery. Faster moving assets, such as cash and inventory are defined as the current assets (Khalilpourazari et al. 2018; Khalilpourazari & Pasandideh, 2018). Amadi-Echendu et al. (2010) state that one should clearly differentiates "engineering" asset objects from "financial" asset objects, as all assets can be classified into one of these two object categories. Financial objects, for example, could be securities traded on the stock exchange or patent rights, both of which only exist as contracts between legal entities. Engineering objects can be items, such as inventories, equipment, land, and buildings. These objects can exist independently of any organization or contract. Amadi-Echendu et al. (2010) point to a diagram, reproduced in Figure 1 below, in which the author describes the base of a pyramid comprising of the realm of Engineering Asset Management (EAM), with financial and all other assets being built at the top of it. The OED (2007) also more specifically defines AM as”the active management of the financial and other assets of a company, etc., esp. in order to optimize the return on investment”.

Hastings (2010) gives another definition of AM that is more aligned with a businessobjectives, where AM is the set of activities associated with:
- identifying what assets are needed,
- identifying funding requirements,
- acquiring assets,
- providing logistic and maintenance support systems for assets,
- Disposal or renewal of assets.

Amadi-Echendu (2004) and Woodhouse (2003) also state that aligning utilization and management with the stakeholder-desired performance is a key challenge for physical asset management. Effective asset management requires: (i) The appropriate integration of the corporation between established disciplines and emerging technologies; and (ii) the application of the integrated synergies towards achieving the value profile, desired at the respective lifecycle stages of the asset. Amadi-Echendu (2004) also points out that PAM is fundamentally accountable for the triple bottom line of business reporting of economic, environmental, and social responsibilities. In this regard, Woodhouse (2003) mentions that integrated AM represents the best-sustained mix of both asset care (maintenance and risk management) and asset exploitation (use of the asset to meet some organizational objective). Vanier (2000) presents the "Six What’s" of asset management, in order to describe examples of decision support tools for asset management, as well as to show the discrete levels for asset management implementation:
1. What do you own?
2. What is it worth?
3. What is the deferred maintenance?
4. What is its condition?
5. What is the remaining service life?
6. What do you fix first?

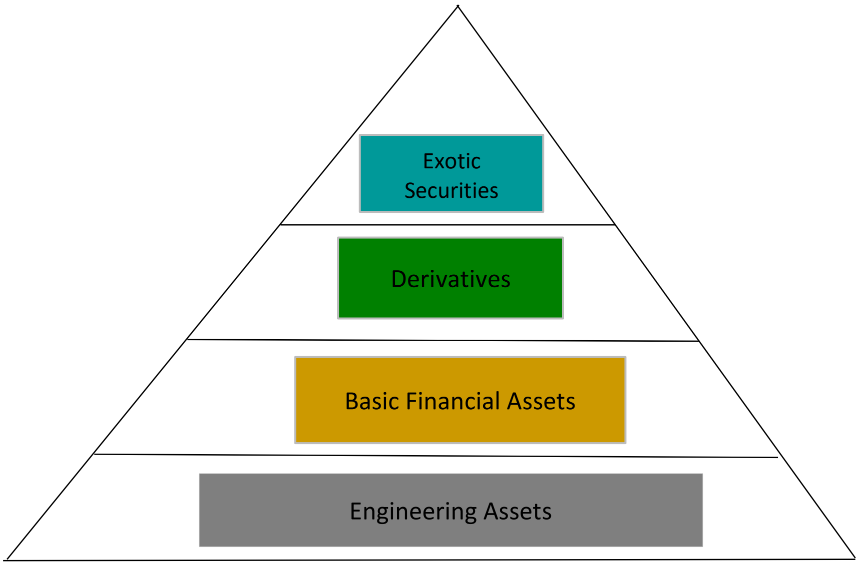


Figure 1. Nature of EAM within the context of other assets. Retrieved from Amadi-Echendu et al. (2010)

The British Standards Institution (2008) PAS 55 standard on physical asset management, also defines five key asset management areas within organizations:
1. Financial Assets
2. Physical Assets
3. Human Assets
4. Information Assets
5. Intangible Assets

Vanier (2001) and FHWA (1999) define asset management as "... a systematic process of maintaining, upgrading and operating physical assets cost-effectively. It combines engineering principles with sound business practices and economic theory, and it provides tools to facilitate a more organized, logical approach to decision-making. Thus, asset management provides a framework for handling both short- and long-range planning". Even though this definition is older, similarities can still be drawn to PAS 55 and Woodhouse (2001).
Wenzler (2005) called keeping assets healthy and operational as a core activity. Wheelhouse (2009) also states a number of items that should be included within a plant asset care plan:

- Servicing and Maintenance
- Inspection
- Shutdowns
- Spares Management
- Asset Strategy
- Performance Monitoring

The MTBF is a reliability metric that is often used to describe equipment or system reliability. Smith (2005) defines MTBF as a stated period in the life of an item, the mean value of the length of time between consecutive failures, computed as the ratio of the total cumulative observed time to the total number of failures (Fazli-Khalaf et al. 2017; Khalilpourazari & Khalilpourazary 2017;). Modarres et al. (1999) define the MTBF as the Probability Density Function (pdf) of time, between the first failure and the second failure, the second failure, and the third failure, and this process goes on. The unit of MTBF is hours per failure, however, most statements about MTBF are made in terms of some time unit (Ireson et al., 1996). When an item goes through a renewal process, it is assumed to be perfect. This means that when the item goes through repair or maintenance, it is assumed to exhibit the characteristics of a new item. Modarres et al. (1999) state that the as-good-as-new assumption made here is sufficient for the vast majority of reliability cases. Ireson et al. (1996) argue that MTBF does not indicate how high the failure rate is, nor does it indicate how long the infant-mortality period will last. Knowles (1995) also mentions that defining reliability in terms of MTBF is neither beneficial to the customer nor to the supplier. Kumar (1999) states that MTBF has been widely used for the past five decades in many commercial and defense industries for measuring reliability, but there are many difficulties in using MTBF for maintenance planning and it fails to engineer a solution to maintenance problems. The use of MTBF has been questioned by a number of researchers. Knowles (1995), Dinesh Kumar et al. (1999), and Hockley and Appleton (1997) listed a number of drawbacks of MTBF: (1) It is almost impossible to predict MTBF if the time-to-failure distribution is not exponential; (2) The methodology used widely to predict MTBF and the failure rate, is based on the exponential distribution. This distribution is used to model failure times, not for any scientific reason, but primarily for its mathematical simplicity. Mitchell (2000) also makes a statement similar to both Knowles (1995) and Dinesh Kumar et al. (1999), in that MTBF assumes an exponential failure rate, meaning that random failures are inevitable. Hockley (1998) and Mitchell (2000) make the point that MTBF and the use thereof, has created a culture of acceptance of failure with little or no motivation to understand the mechanisms of when and why failures occur, but instead to concentrate on random failure. MFOP is defined by Mitchell (2000), Brown and Hockly (2001), Dinesh Kumar et al. (1999), Manzini et al. (2009) and Long et al. (2009) as a period of operation during which the system must be able to carry out all of its assigned missions without any maintenance action and without the operator being restricted in any way due to system faults or limitation. Another term that goes hand in hand with MFOP is the Failure Free Operating Period (FFOP), which can be equated to ROCOF vis-à-vis MTBF. FFOP is defined by Brown and Hockly (2001) and Mitchell (2000) as a period during which the equipment shall operate without failure; however, faults and maintenance, both planned and unplanned, are permissible, i.e. all planned operations and cycles are completed unchanged. Brown and Hockly (2001) state that MFOP also utilizes fault-tolerant, redundant, and re-configurable systems that allow for continuous operation. It is very importantly noted by Dinesh Kumar et al. (1999), Kumar (1999), and Mitchell (2000) that during a MFOP, the system is allowed to undergo any planned minimal maintenance, and also that redundant components can fail during an MFOP. Without forcing any corrective maintenance, this ties into Brown and Hockly’s previous statement. Long et al. (2009) point out some MFOP concept change drivers, these changes could be in design, operation, and maintenance planning. This is done to realize success in the operational environment with minimal maintenance inside a MFOP, achieved through the use of failure anticipation, avoidance, and maintenance delay. Brown and Hockly (2001) state that MFOP measures the probability of being able to successfully complete an operation or a series of operations, without maintenance degrading the ability to conduct the next operation or series of operations. A key point differentiating the reliability metric or maintenance interval MFOP from that of MTBF is that MFOP assumes, from the outset, that success is attainable and that the probability of success can be accurately forecast from entry into service. Brown, and Hockly (2001) state that MFOP specifies customer needs in unambiguous terms.

3. Problem Statement

Physical Asset Management (PAM) has become an increasingly important area of research and discussion in both industry and academia. The British Standards Institution (2008) PAS 55 states that PAM constitutes those systematic and coordinated practices that support an organization, to optimally and sustainably manage their asset systems over their entire life cycle. Due to the interdisciplinary nature of PAM, PAS 55 emphasizes an integrated and holistic view of PAM, in order to come to terms with its complexity. A detailed overview of PAM and PAS 55 is given in the literature, and the overall high-level research influence is given in Figure 2. In order to help with the assessment of this complexity and the overarching nature of the field, seventeen Key Performance Area (KPA) have been defined in the literature. These shed a light on the current status of an organization's AM performance and AM maturity. One of the KPAs defined is called an Asset Care Plan (ACP). ACP is the high-level term coined to describe the mix of tactical and non-tactical maintenance activities performed within a maintenance strategy. Here tactical maintenance is the group of Preventive Maintenance (PM) activities, and non-tactical is the group of Corrective Maintenance (CM) activities, where PM is being favored among maintenance specialists. Maintenance management strategies, such as RCM and TPM also fall under ACPs and can even be said to operate on the same level as an ACP.

In order to schedule and specify maintenance activities, and analyze historical failure data on equipment, statistical maintenance interval metrics are defined and used. The most notable maintenance intervals used today are MTBF and Mean Time to Failure (MTTF), depending on whether the system is repairable or non-repairable. The use of MTBF to predict and specify failures goes back nearly to half a decade and it is used extensively in industry. The aviation industry is widely considered to be at the forefront of maintenance methods. In recent years, a study commissioned by the Royal Air Force found a number of underlying and fundamental problems by the use of the maintenance interval metric MTBF, specifically for aircraft. Long et al. (2009) highlight the fundamental problem with MTBF. The author states that the use of MTBF in predicting failure accepts that failure cannot be accurately forecast or avoided. It assumes random failures and this assumption has negative knock-on effects, as it creates the need for unscheduled maintenance activities to be performed during normal operating hours. Other problems have been highlighted by Knowles (1995), Appleton (1996), Hockley and Appleton (1997) and Dinesh Kumar et al. (1999), for example, that it is almost impossible to predict MTBF if the failure distribution does not follow an exponential one. The exponential distribution is used within the prediction of MTBF, not for scientific reasons, but mainly for its mathematical simplicity. In a very clear assessment provided by Trinidad and Nathan (2006), there is a need for better reliability metrics that account for trends in the failure data.

The above-stated problems with MTBF have resulted in the Royal Air Force defining a new maintenance interval that addresses the elementary problems that arise when using MTBF. The interval or reliability metric that has been defined is called MFOP (Appleton, 1996). MFOP, which is elaborated on in the literature, is a period of operation, where no unscheduled maintenance activities are allowed, thereby replacing unscheduled maintenance activities with scheduled ones, essentially making it a warranty period. It exploits systems that are fault-tolerant and have redundancies. There exists a problem, specifically within asset-intensive industries, in the application and use of MTBF for the scheduling of maintenance activities.

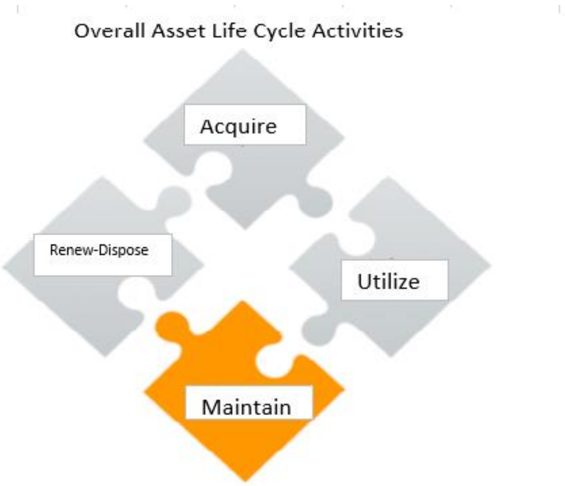


Figure 2. Asset life cycle activities, highlighting an overall area of research

Characteristically the Petrochemical industry needs equipment to work continuously, and any unscheduled downtimes or interruptions during production time create massive losses in revenue and hamper the quality of the final product. It would, therefore, be advantageous to use MFOP as reliability metric and give machines or equipment a set MFOP, within a predefined confidence interval. This would potentially allow for better production scheduling, a better downtime planning that could reduce the logistic footprint and yield a steadier throughput within a plant or system.

Hypothesis
The central research question is defined below:
Is the use of Maintenance Free Operating Periods a more appropriate reliability metric for the assessment of physical assets in the Petrochemical sector?
From the central research question the null hypothesis can be derived, it is defined in Table 1:

Table 1. The Null Hypothesis (H_0, H1)

H_0: The use of Maintenance Free Operating Periods is not a more appropriate reliability metric for the assessment of physical assets in the Petrochemical.
H1: More appropriate reliability metric for the assessment of physical assets in the Petrochemical is the use of Maintenance Free Operating Periods.

The methodology is to be set out for the calculation of MFOP lengths, thereby modeling a chosen system. This methodology is then applied in an industry case study, where the research can be validated and the null hypothesis can be either rejected or accepted.

4. Case Study

In the sections that follow the study is performed on data collected from Petrochemicals. A brief outline of the specific problem is given first, thereafter more is said about the case study and the system analyzed is formally introduced. Practicalities of data gathering are then discussed, with data requirements, collection, and classification playing a prominent role. Now that the case study has been defined, the analysis can be conducted. Three identical systems were analyzed, general and coherent analysis steps were followed throughout, these are shown in Table 2.

Table 2. Analysis steps followed for each system

No.	Step
1	Analysis of failure data set
2	MTBF calculations for actual system
3	MFOP calculations for actual system
4	MFOP calculations for hypothetical system
5	Summary of results

4.1. The Problem

The global problem, as stated previously, is that current reliability metrics, MTBF that is widely used, do not provide an unambiguous and untainted view of the performance and operation of the equipment. MTBF remains a simple mean and has created a widely accepted view that random failures are completely unavoidable. In this specific study, it is to be researched if there is an application within Petrochemicals for the proposed solution to the shortcomings of MTBF, MFOP originating from the aviation industry. Having found a research partner, Petrochemicals, a system or equipment needed to be found so that the hypothesis could be tested. After a visit on-site and discussions with various key players from the plant, a system is established. The equipment that is chosen to be studied is a grouping of cone crushers used in ethylene operations. The group of Pumps consisted of three individual and identical pumps, Turbine, and Compressor. These pumps were vital to the overall process. Due to smaller sized pumps, Turbine, and Compressor in the process, a failure at this station in the process would have had far-reaching consequences in proceeding stations. Another factor that is taken into consideration is that this grouping of pumps, Turbine, and Compressor had seen some unreliability in the past, a better picture of them is therefore desired. The aim of this case study is to investigate the idea of using the aviation-derived concept of MFOP within a Petrochemicals environment. Here a specific item of the total Petrochemicals system is chosen, its failures are modeled, and the MFOP concept then applied to the chosen item, in this case, a grouping of pumps. The failure distribution of the pumps, Turbine, and Compressor is found and thereafter the relevant MFOP statistical formulas are applied to the distribution, in order to find the maintenance free time of operation, specific for that item. It can then be seen if this period is feasible and could be applied to the item. The modeling of the pumps, Turbine, and Compressor failure distributions is an additional sub-aim of the study additionally. Ultimately, a better understanding of applying the MFOP concept should be gained, thereby testing the school of thought of MFOP against that of the traditionally used reliability metric MTBF. After detailed discussions with the concentrator plant manager on the system and its subcomponents, a decision is made on which equipment to use for the analysis. This decision is based on the plant manager's in-depth knowledge of the complete system and the complexities thereof. Also taken into account, where conditions, such as equipment criticality to continue uninterrupted operations, based on non-operational output loss. The chosen equipment is an arrangement of three pumps 201 A-B-C. These pumps were pivotal to the smooth operation of the complete system and the equipment.

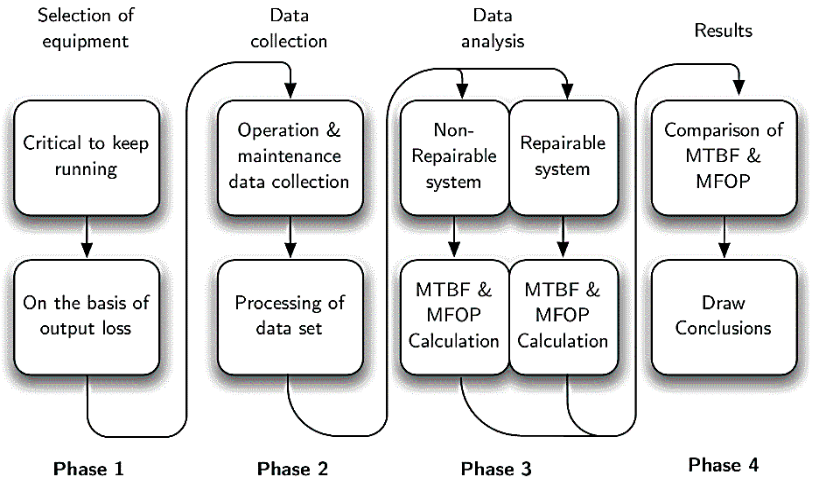


Figure 3. Application methodology, employed in Case Study

Down streaming from them. They were, however, to different degrees, susceptible to breakdowns and therefore unplanned maintenance activities had to be conducted, thereby hampering the continuous operation of the system. Due to their susceptibility and varying reliability, this system is chosen for the study. Figure 3 shows the methodology that was used so far. As stated in the previous section, the system chosen for the study is a grouping of three pumps that are used in Ethylene production operations in Figure 4.

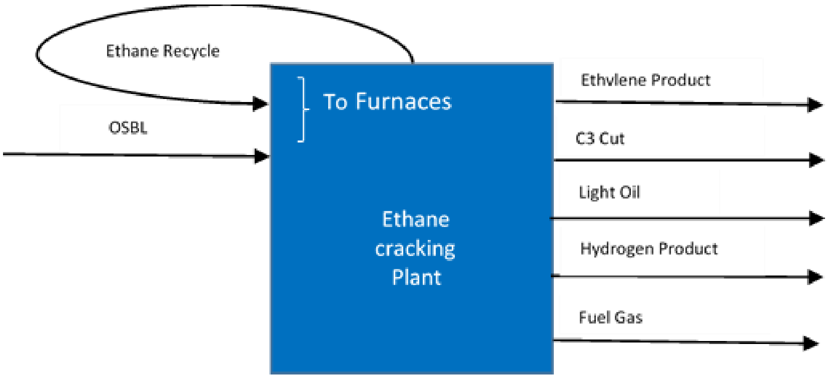


Figure 4. Relative position of the ethylene retrieved in petrochemical process

This unit consists of five main parts:
1. Cracking furnaces
2. Cooling of cracking gas and recovery of diluted steam in the cooling Tower
3. Compressor and wash with caustic
4. Pump & Cooling Section for recovery of C2 cut
5. Hydrogenation and purification of ethylene are formed.

Ethan enters this unit as a feed of the adjacent petrochemical plant. This feed comes with the ethanol from the unit itself to the cracking in furnaces. The furnace output is immediately cooled and moved into the compressor section. The moisture content of the exhaust gas is taken from the compressor in moisture absorbers and then enters the cooling section. After cooling, cracking gas enters the distillation towers to separate the various carbon slices. Finally, the C2 Cut tower enters the hydrogenation reactor and after converting acetylene into ethylene andthe Ethylene separating tower, ethylene is distilled from ethanol, and pure ethylene is sent from the top of the tower for use downstream of the polyethylene or storage tank for export.

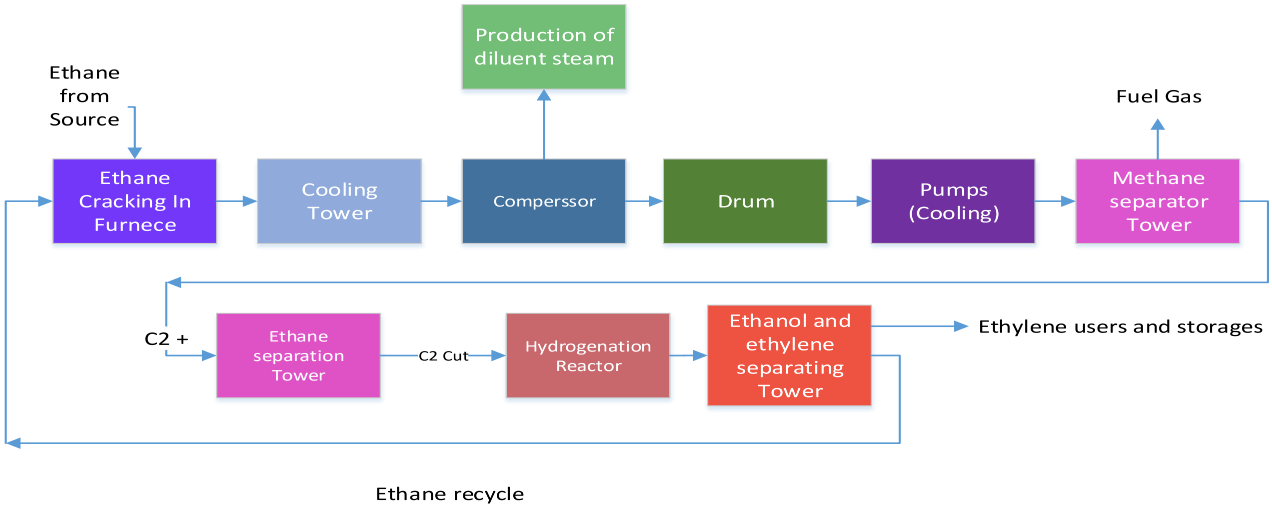


Figure 5. Ethylene Production Steps retrieved in petrochemical process

The data used in this study were failure and maintenance data of the system of pumps 201. This data come from secondary sources, being from petrochemical data recorder system, which records a large amount of data and variables. From this system, maintenance data on the pumps were pulled and stored in Microsoft Excel. Data were obtained from 2016 to 2017, at a resolution or in increments of 10 minutes over the entire period; a higher resolution would have become impractical within the Microsoft Excel environment, due to the large amounts of data points. Data could not be obtained earlier than October 1, 2015, due to no data on failures being available before that point. Table 3 shows the number of events found for each pump from the stated period.

Table 3. Number of Events Found in Data.

row	level	Number of failures
1	Pump 201-A	60
2	Pump 201-B	51
3	Pump 201-C	26

4.2 Analysis of the Failure Data Set for Pump 201-A

The first calculation performed on the data is the Laplace trend test. The result of the Laplace test for the found data is $U_{L\text{-}P\text{-}201\text{-}A} = -2.5648$, which is clear in the reliability improvement area of the test that displayed a trend; therefore, making the Lewis–Robinson trend test superfluous. The results are outlined in Table 4.

The Power Law NHPP is used in this analysis. The data set for Pump 201-A can be analyzed using repairable systems theory. Here a power law NHPP is used to model the system in order to find expected failure times. The power law's parameters, λ, and δ were found through the least-squares method, the parameters were found by using the solver function in Microsoft Excel.

Table 4. Results of Trend Tests applied to P-201-A data

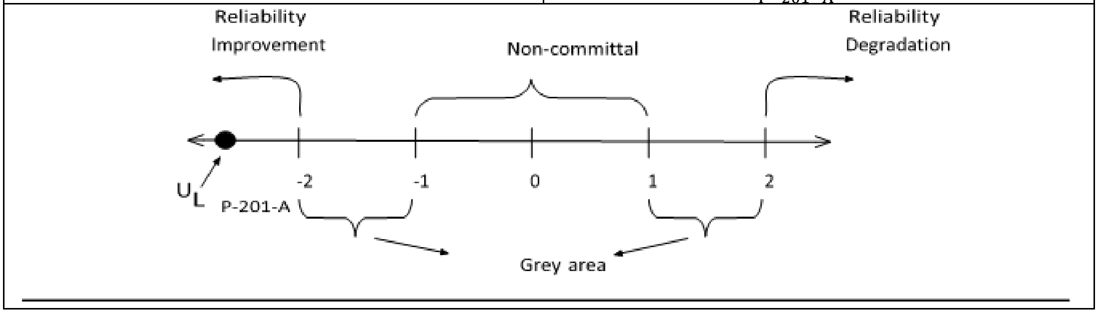
Trend Test	**Result**
Laplace Test	$U_{L_{P-201-A}} = -2.5648$
Lewis-Robinson Test	$U_{LR_{P-201-A}} = N/A$
	

Table 5. Power law parameters found for P-201-A

Parameter	**Value**
λ	0.6593
δ	0.4023
$\rho_{CR1} = (0.6593) \cdot$	$0.4023t^{0.4023-1}$

The outcome of using the Power Law NHPP, in order to model the failure data is shown in Figure 6. Figure 6 plots the actual found failure events, together with the predicted or modeled failure events, found through the use of the Power Law NHPP.

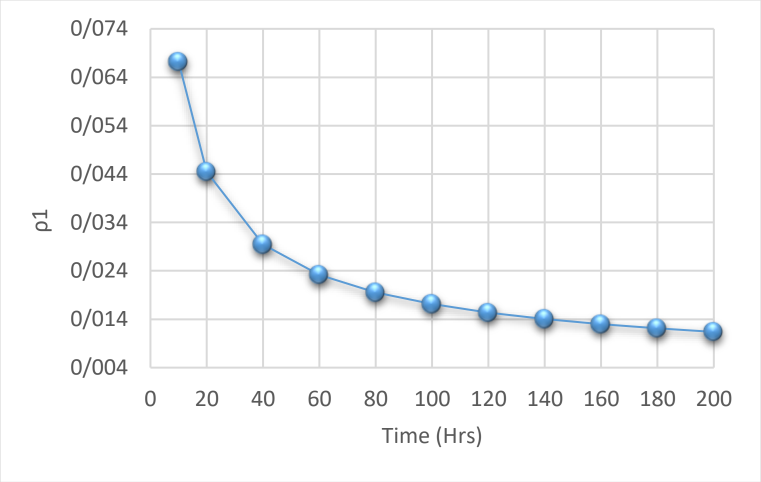


Figure 6. Modeled failure times using the Power Law NHPP

4.3. MTBF Calculation for Pump 201-A

The historical and future MTBF of Pump 201-A is determined for comparative purposes and in order to have a reference in the analysis that is used.

The historic MTBF for Pump 201-A is found to be 57.12 hours, using Equation (1):

$$MTBF_{\rho1}(t_1 \rightarrow t_2) = \frac{(t_2-t_1)}{\lambda(t_2^{\delta}-t_1^{\delta})} \qquad (1)$$

For a non-repairable system, the historic MTBF can be calculated by using Equation (1) this section still makes up phase 3 of the methodology layout shown in figure 3. $MTBF_{\rho1}(t_1 \rightarrow t_2)$: Mean time between failures estimated by power law NHPP from $t_1 to\ t_2$

$t_1 and\ t_2$: Between any two points in time

λ and δ : parameters for the power law NHPP

The future MTBF is calculated by using Equation (2):

$$E\left((T_{r+1}|t=T_r)\right) = \left(\frac{1+\lambda T_r^{\delta}}{\lambda}\right)^{1/\delta} \qquad (2)$$

Providing a better representation of the current state of the system is the future MTBF. If the system is put back in operation after the last recorded failure, then the next failure of the system can be predicted,$(\mathrm{r}+1)^{th}$, This yields the next expected failure, T_{r+1},in order to attain the future MTBF, λ and δ parameters for the power law NHPP to be estimated using the least-squares method. Here T1, T2,…, Tr = arrival times of failures, r = total number of observations. And is found to be 62.64 hours, results are summarized in Table.

Table 6. Summary of both historic and future MTBF found for Pump 201-A

MTBF type	Hours
Historic MTBF	57.12
Future MTBF	62.64

4.4. MFOP Calculations for Pump 201-A

MFOP calculations specific to Pump 201-A are shown in this section. It is established that Pump 201-A followed a repairable system and is modeled accordingly, using the power law NHPP. Using Equation 3, and the previously determined power law NHPP parameters, the MFOP of Pump 201-A could be determined. This is shown graphically in Figure 7.

$$MFOPS(t_{mf}) = e^{-\lambda\left((t_{mf}+T_r)^{\delta}-(T_r)^{\delta}\right)} \tag{3}$$

Tr is the global time unit of the last known failure event andλ and δ parameters for the power law NHPP are estimated using the least-squares method. In putting a number of values for *tmf* in this example from 1 to 200 is shown in Figure 7. As shown in Figure 8, it can be seen that Pump 201-A did not yield particularly high MFOPS probabilities for long MFOP. The comparison of the historic MTBF, to the equivalent MFOP of the same length, gave the following results that were found by the application of failure statistics and are not just a mean. At Pump 201-A's MTBF of approximately 57.12 hours, the probability of achieving this, or the MFOPS, is about 53 %, without requiring any corrective maintenance actions. A further MFOP length that could be taken, as it is easy to comprehend, is the length of a full day or 24 hours. Inspecting Figure 8, it is found that Pump 201-A had a MFOPS of 70 % at an MFOP of 24 hours.

4.5. MFOP Calculations for Hypothetical Pump 201-A

In order to better perceive the MFOP principle, a hypothetical Pump 201-A is modeled. This crusher used the same data set found for pump 201-A, but removed the top two failures from the data set. Even though this is a hypothetical system, it does not seem unrealistic in the targets it achieves. In the case of pump 201-A, the top two failures that were removed were the categories of the lube system and feedback faults, made up of approximately 70 % of the failures of Pump 201-A. Now that a new data set is formed, the analysis began again with the application of trend tests to the failure data set. Using the Laplace trend test, it is established that the hypothetical pump 201-A is laid in the grey area of the test. Therefore, no conclusive statement can be made as to whether there is a trend present or not. The Lewis–Robinson trend test is then applied to the data set, here, again no conclusive result is found, the data is still in the grey area.

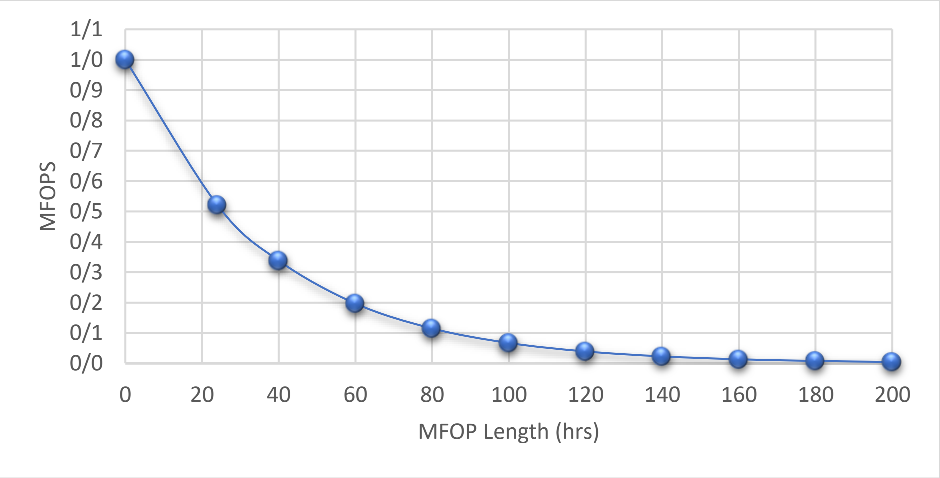


Figure 7. Probability of achieving MFOP length for Pump 201-A

At this point an assumption needs to be made, plotting the data, it can be seen that the system looks like a repairable system with a distinct reliability improvement; it is therefore decided to model the system accordingly.

The power law NHPP is therefore used to model the new data set, with the power law parameters, λ, and δ, being found numerically, using the least squares method. The results for the parameters are shown in Table 7.

After the parameters for the power law NHPP were known, the MFOP analysis could begin. Plotted in Figure 7, is a comparative plot of the MFOP length and equivalent MFOPS for both the current Pump 201-A and the hypothetical Pump 201-A system.

Table 7. Power law parameters found for the hypothetical Pump 201-A

Parameter	Value
λ	0.6037
δ	0.3256

4.6. Summary of Results of Pump 201-A

Pump 201-A is the only Pump 201-A of the three that could be modeled as a repairable system, due to the results of the Laplace trend test. The greatest cause of failure for Pump 201-A is the lube system, accounting for nearly 40 % of all failure. MFOP calculations performed on the Pump 201-A showed that the Pump 201-A at an MFOP length is equal to that of its MTBF (57.12 hours), where the MFOPS is approximately 53 %. In essence, giving Pump 201-A 70 % chance of completing its found MTBF, without requiring unscheduled maintenance. A different outlook of pump 201-A is given in the hypothetical case that is modeled. Here the top two failures were removed from the data and a new failure data set is defined.

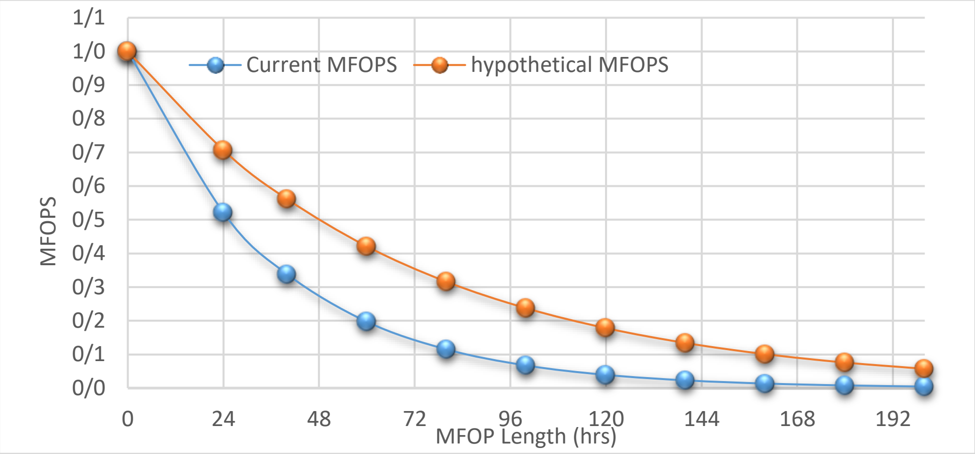


Figure 8. Probability of achieving MFOP length for both hypothetical and current Pump 201-A

4.7. Analysis of the Failure Data Set for Pump 201-B

The first calculation performed on the failure data for Pump 201-B is the Laplace trend test. The result of the Laplace test for the found data is $U_{L_{P-201-B}} = -1.49$. This puts Pump 201-B into the grey area of the Laplace trend test and the test could therefore not provide a definitive answer as to whether there is a trend or not. The Lewis–Robinson trend test is then applied to the data. The outcome of the Lewis–Robinson test is found to be $U_{LR_{P-201-B}} = -0.85$. This took Pump 201-B back to the noncommittal or no trend area of the Laplace trend test. The results are outlined in Table 8. Due to the fact that the Lewis–Robinson test showed that Pump 201-B had no apparent trend within the data, Pump 201-B is analyzed using non-repairable systems theory.

Table 8. Results of Trend Tests applied to PUMP 201-B data

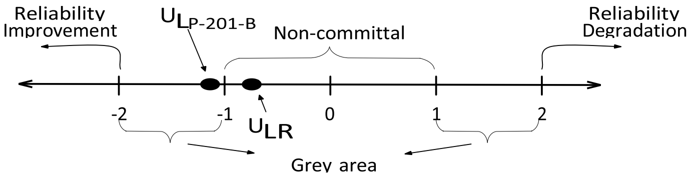
Trend Test	Result
Laplace Test	$U_{L_{P-201-B}} = -1.49$
Lewis-Robinson Test	$U_{LR_{P-201-B}} = -0.85$
	

Table 9. Weibull parameters found for PUMP 201-B

Parameter	Value
β	2.554
η	74.366

This creates the specific distribution for PUMP 201-B given in Equation 4 below:

$$f(x) = \frac{\beta}{\eta}\left(\frac{x}{\eta}\right)^{\beta-1}.\,\exp\left(-\left({}^{x}/_{\eta}\right)^{\beta}\right)$$

$$f(x) = \frac{2.554}{74.366}\left(\frac{x}{74.366}\right)^{1.554}.\,\exp\left(-\left(\frac{x}{74.336}\right)^{2.554}\right) \qquad (4)$$

Here β is the shape parameter and η is the scale parameter of the Weibull distribution, with η> 0 and β > 0. These parameters are required in order to later calculate the MFOP of the system selected. Equation 4 provides the probability of system failure at instant x and is plotted in Figure 9. Analyzing the shape parameter, β, of PUMP 201-B, which is also known as the Weibull slope, as the value of β, is equal to the slope of the probability density function shown in Figure 9. Even though PUMP 201-B is not a non- repairable system, it behaves like one, with the current β > 1; PUMP 201-B displayed a probability of failure that decreases with time. The analysis determined the scale parameter, η, which has the effect of stretching out the probability density function, or the same effect as a change in the abscissa scale. The peak value of the probability density function curve could decrease, as the area under the probability density function remained a constant one. An increase in η, while keeping β constant, stretches the curve out towards the right and its height decreases. A decrease in η, while keeping β constant, pushes the distribution to the left and its height increases. Now that parameter estimators are known and systems reliability is modeled, including graphically, the MFOP calculation can begin.

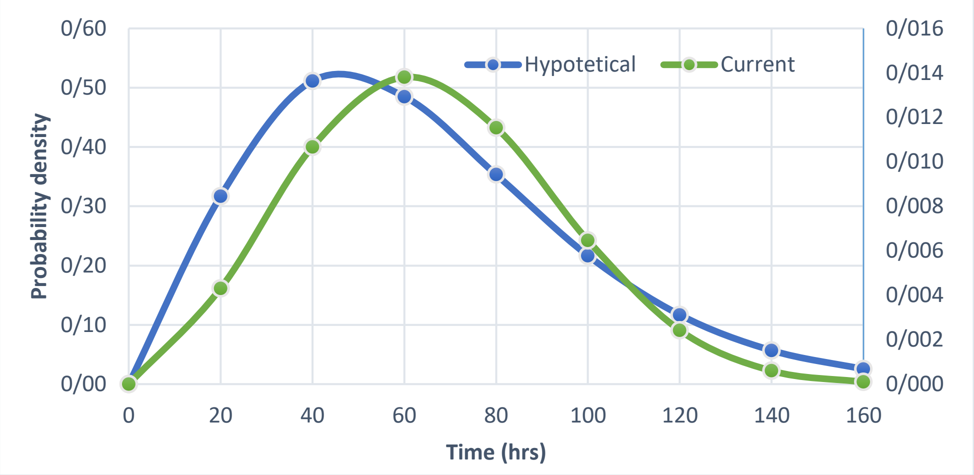


Figure 9. Weibull pdf for PUMP 201-B Current & Hypothetical

4.8. MTBF Calculation for PUMP 201-B

The historic and future MTBF of PUMP 201-B is determined simply for comparative reasons and in order to have a currently used reference in this analysis. For the non-repairable system of PUMP 201-B, the calculation of the MTBF is clearly the average of the failure times found in the collected failure data. From the data, the average Xi is calculated and then divided by the total number of observations, in this case, 51. The historic MTBF of PUMP 201-B is then found to be 64.98 hours and the future MTBF, found by applying Equation 5, is determined as 66.02 hours. The results are summarized in Table 10.

$$E[X_{r+1}] = \frac{\int_0^\infty x.f(x)dt}{\int_0^\infty f(x)dx} \qquad (5)$$

Here the integral of f (x) will converge to 1 and the integral of x .f (x) will converge to the future MTBF of the system.

Table 10. Summary of both historic and future MTBF found for PUMP 201-B

MTBF type	**Hours**
Historic MTBF	64.98
Future MTBF	66.02

4.9. MFOP Calculations for PUMP 201-B

MFOP calculations are shown in this section. These calculations are specific to PUMP 201-B. PUMP 201-B has been found to act like a non-repairable system previously, thereby necessitating a Weibull analysis of the system, which is done in the previous section. The shape and scale parameters for the Weibull distribution of PUMP 201-B were found.

These are needed for further analysis. In order to determine the MFOP and MFOPS of PUMP 201-B, a system that can be Weibull modeled on Equation 6 is used.

$$MFOPS(t_{mf}) = exp\left(\frac{t^{\beta}-(t+t_{mf})^{\beta}}{\eta^{\beta}}\right) \tag{6}$$

λ and δ parameters for the power law NHPP be estimated using the least-squares method. In putting a number of values for tmf in this example from 1 to 120 this is shown in Figure 10. Using Equation 6 and the previously determined Weibull shape and scale parameters, the MFOP of PUMP 201-B is calculated. It is immediately obvious that PUMP 201-B, in its current state, does not provide a particularly high MFOP at a high probability of achievement at that MFOP length. In comparison to the MTBF found in the previous section, which is approximately 64.98 hours of operation, MFOP yields additional information calculated through formal failure statistics and is not just a Mean as in MTBF. Results present us with the fact that if PUMP 201-B is given a MFOP length equal to that of the MTBF (64.98 hours), PUMP 201-B would only have an approximately 50 % probability of completing that period without requiring any corrective maintenance actions. Another MFOP length of interest, which is easy to comprehend, is the length of 24 hours or a full day. Again, by finding 24 hours on the x-axis of the plot and then reading off the equivalent probability, it is found that PUMP 201-B has an approximately 95 % probability of achieving an MFOP of 24 hours.

4.10. MFOP Calculations for hypothetical PUMP 201-B

Results for the Weibull parameters are shown in Table 11.

Table 11. Weibull parameters found for hypothetical PUMP 201-B

Parameter	Value
β	6.780
η	95.000

Comparing the current MFOP of PUMP 201-B and the hypothetical one in Figure 10, it is immediately noticeable that the hypothetical system provided a substantially improved MFOP, at a far higher probability of success. Studying the 64.98-hour MTBF value that is established previously, it now becomes apparent that the new system has a far higher chance of achieving this period, from 50 % to 92 %.

4.11. Summary of Results of PUMP 201-B

P-201-A and PUMP 201-B have very similar MTBF values, 57.12 hours and 64.98 hours respectively, but behave very differently and therefore need to be modeled in a different way. The greatest cause of failure for PUMP 201-B, as for all pumps, is the rotor system, accounting for nearly 50 % of the total failures within the analysis period. Owing to the results of the Laplace and Lewis-Robinson trend tests, the pump is modeled using the Weibull distribution with parameters found, as seen in Table 10 and Table 12. The MFOP calculations performed on pump two demonstrated that the crusher at an MFOP length is equal to that of its found MTBF had a MFOPS of approximately 50 %. Therefore, giving the pump a 50 % chance of achieving its found MTBF.

In order to show another perspective of the PUMP 201-B system, a realistic hypothetical case is constructed. The top two failures found in the Pareto analysis were removed from the data set and a new failure data set was compiled. The conceived system displayed a significant improvement in its attainable MFOP and MFOPS, gains of an MFOP of 65 hours from a previous MFOPS of 50 % to one of 92 % are seen in Figure 10.

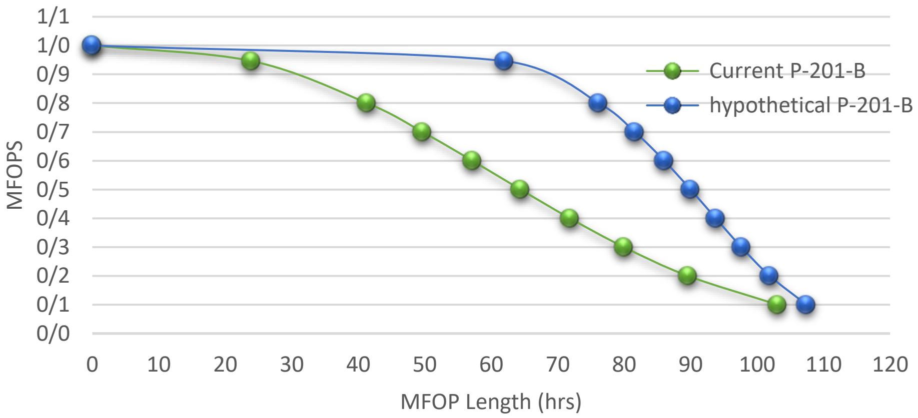


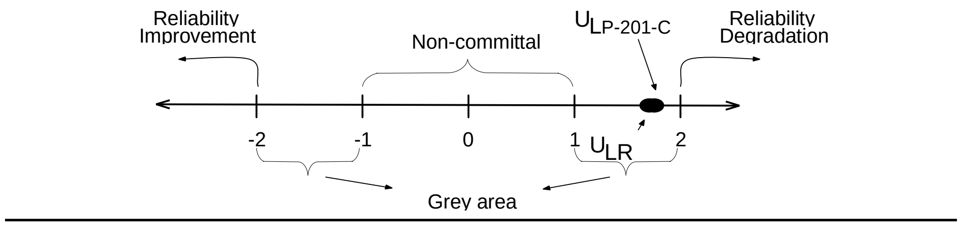
Figure 10. Probability of achieving MFOP length for both hypothetical and current PUMP 201-B

4.12. Analysis of the Failure Data Set for Pump 201-C

The result of the Laplace trend test in the dataset was found to be$\mathrm{U}_{\mathrm{L}_{\mathrm{P-201-C}}} = 1.878$. This put P 201-C, as with PUMP 201-B, in the grey area of the Laplace trend test, the test thus provided an inconclusive result and did not deliver an answer as to whether there is a trend present within the dataset. The Lewis-Robinson trend test, a modification of the Laplace trend test, is then applied to that data set. The test uses the same test scale as the Laplace test, the result of the Lewis-Robinson test is found to be $\mathrm{U}_{\mathrm{LR}_{\mathrm{P-201-C}}} = 1.948$. This did not show a significant change and is still within the grey area of the test metric, revealing no further details about whether the data set has an underlying trend or not.

Table 12. Results of Trend Tests applied to P 201-C data

Trend Test	**Result**
Laplace Test	$\mathrm{U}_{\mathrm{L}_{\mathrm{P-201-C}}} = 1.878$
Lewis-Robinson Test	$\mathrm{U}_{\mathrm{LR}_{\mathrm{P-201-C}}} = 1.948$



No further details about whether the data set has an underlying trend or not. This information is needed in order to ascertain whether the pump should be modeled as a repairable or non-repairable system. As both trend tests did not divulge a definitive answer, the data is looked over again It is assumed that no trend is present. P 201-C is therefore modeled in a Weibull distribution and as a non-repairable system, provides a satisfying result.

Table 13. Weibull parameters found for P 201-C

Parameter	**Value**
β	0.752
η	44.887

Substituting the found shape and scale parameters into Equation $f(x) = \frac{\beta}{\eta}\left(\frac{x}{\eta}\right)^{\beta-1}.exp\left(-\left(\frac{x}{\eta}\right)^{\beta}\right)$, he specific equation for P 201-C shown below in Equation 7.

$$f(x) = \frac{0.752}{44.887}\left(\frac{x}{44.887}\right)^{-0.248}.\exp\left(-\left(\frac{x}{44.887}\right)^{0.752}\right) \tag{7}$$

Here β is the shape parameter and η is the scale parameter of the Weibull distribution, with η> 0 and β > 0. These parameters are required in order to later calculate the MFOP of the system selected. Analyzing the found Weibull shape parameter, β, of P 201-C, it is found that it is close to a value of 1. If the β is equal to 1, then the effect would be a constant failure rate or one which is consistent with the exponential distributions. Even though β is still less than 1 for P 201-C, the pump displays a very slightly decreasing failure rate, but close to a constant one. The Weibull pdf is shown in Figure 11 and the failure probability function is shown in Figure 12.

4.13. MTBF Calculation for PUMP 201-C

From the data, the average X_i is calculated, thereby yielding the historic MTBF of P 201-C. The historic MTBF of P 201-C is found to be 48 hours and the future MTBF is determined as lasting for 53 hours. The results are summarized in Table 14.

Table 14. Summary of both historic and future MTBF found for P 201-C

MTBF type	**Hours**
Historic MTBF	48
Future MTBF	53

4.14. MFOP Calculations for Pump 201-C

In order to determine the MFOP and MFOPS of P 201-C, Equation 6, as with P 201-C is used. The shape and scale parameters are substituted into the equation to calculate the MFOP and are shown graphically in Figure 13.

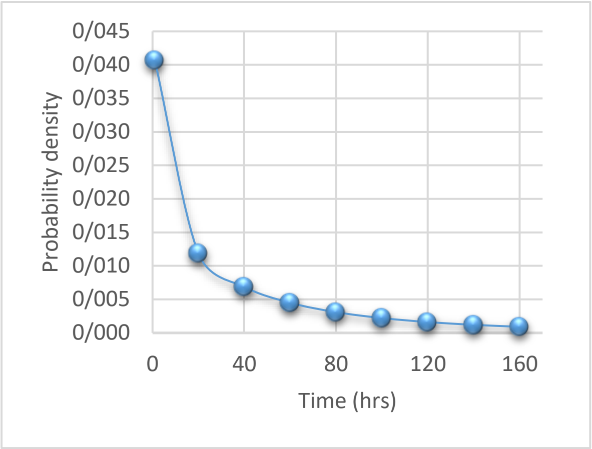


Figure 11. Weibull Pdf for P 201-C

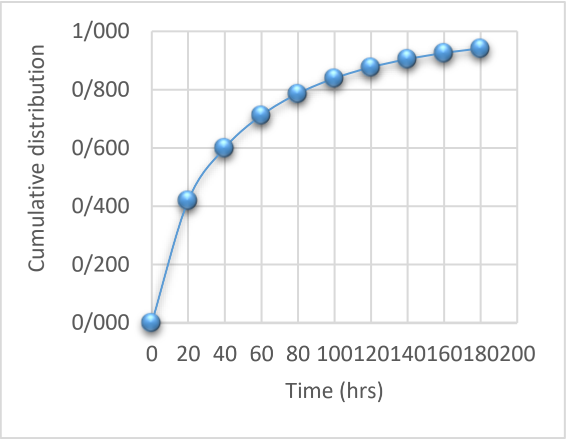


Figure 12. Weibull Cdf for P 201-C

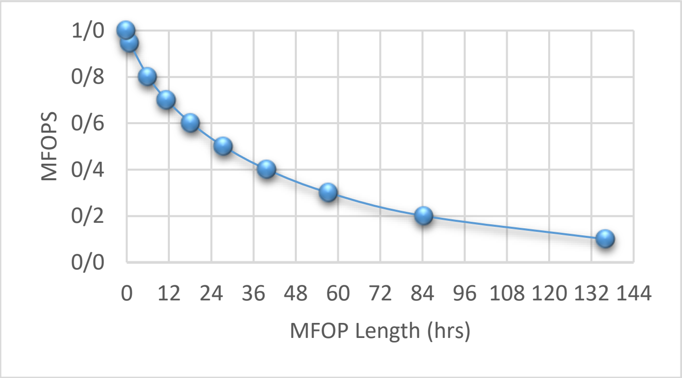


Figure 13. Probability of achieving MFOP length for P 201-C

Table 15. Weibull parameters found for hypothetical P 201-C

Parameter	Value
β	0.752
η	44.877

As with PUMP 201-B, P 201-C does not provide a particularly high MFOP at a high probability of achievement. However, immediately noticeable is that P 201-C is more reliable than PUMP 201-B. Comparing P 201-C's previous MTBF, 48 hours, with the found MFOP, it was found that P 201-C only had an approximately 50 % chance of completing this period without requiring any corrective maintenance actions. As with PUMP 201-B, looking at a 24-hour period is relatively easy to comprehend. Figure 13 shows that the pump had a 50 % chance of completing a full day without requiring corrective maintenance actions.

4.15. MFOP Calculations for hypothetical PUMP 201-C

A hypothetical P 201-C is modeled, again, in order to better demonstrate the MFOP concept. Even though this system is hypothetical, it is not unrealistic. With reference to the Pareto chart shown in Figure 10, the hypothetical case removed the top two failure cases from the data set. In the case of P 201-C, these were the categories of lube system failures and other/unplanned maintenance. The latter failure is classified by failures, such as sequence stops or data points that are simply named "unplanned maintenance". These two failure categories made up over 70% of failures for P 201-C. Once a new data set had been formed, the analysis started again with a trend test. The Laplace trend test established that there is no underlying trend present in the new data set and therefore the hypothetical pump could again be modeled using the Weibull analysis. Weibull parameters were then found by using the Maximizing the Likelihood Method, parameters β and η, shown in Table 16. As the Weibull parameters, β and η, of the hypothetical system are now known, an MFOP calculation could be performed. The results were plotted together with the current MFOP performance, shown in Figure 14. By comparing the two systems, a vast difference can be seen in the probability of achievement of MFOP length. The supposed system is immensely more reliable than the current system. Taking the previously established current systems MTBF of 48 hours, P 201-C had a 37 % chance of completing this period. The proposed system would now have a 57% chance of making the same period, a sizeable improvement.

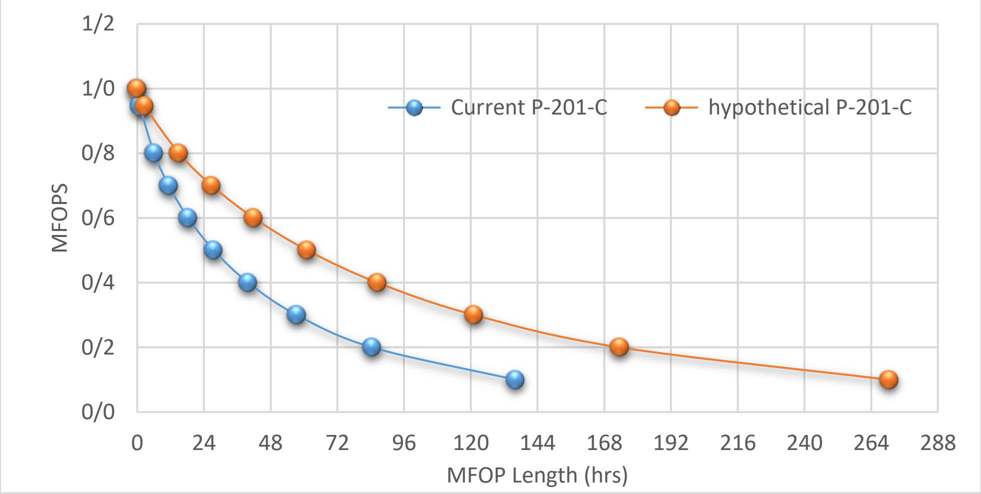


Figure 14. Probability of achieving MFOP length for both hypothetical and current P 201-C

4.16. Summary of Results of Pump 201-C

It can be ascertained that P 201-C is the most reliable pump of the three pumps analyzed. Of the 26 events that were found during the analysis period, the Pareto analysis established that the rotor system is by far the greatest cause of failure, accounting for over 60 % of failures. The data set is analyzed and it is found that it could be characterized by a Weibull distribution. Weibull parameters were found with results provided in Table 14. P 201-C displayed a probability of failure that decreased with time. The MFOP of P 201-C was calculated and it was found to be 37 % at the crusher's MTBF of 48 hours. Here the operator of the equipment immediately had more information at hand about the current performance of the system. A hypothetical or proposed P 201-C is then modeled, with the top two causes of failure removed from the data set, and a new failure data set found. A considerable and realistic improvement is found in both the MFOP and MFOPS, as seen in Figure 14, with the pump achieving an MFOP of over 48 hours at an MFOPS of more than 57 %.

4.17. Final Remarks

Now that the MFOP analysis for all pumps has been performed, a final comparison can be conducted. Starting with the familiar MTBF values found for each pump, shown in Table 16. The most striking element is the fact that P-201-A and PUMP 201-B have an MTBF that is virtually the same, P 201-C.

Table 16. Historic and future MTBF values for all pumps in their current state

Future MTBF (hrs.)	Historic MTBF (hrs.)	pumps
62.64	57.12	201-A
66.02	64.98	201-B
53.03	48.01	201-C

Even though P-201-A and PUMP 201-B have more or less the same MTBF, their reliability characteristics are vastly different.

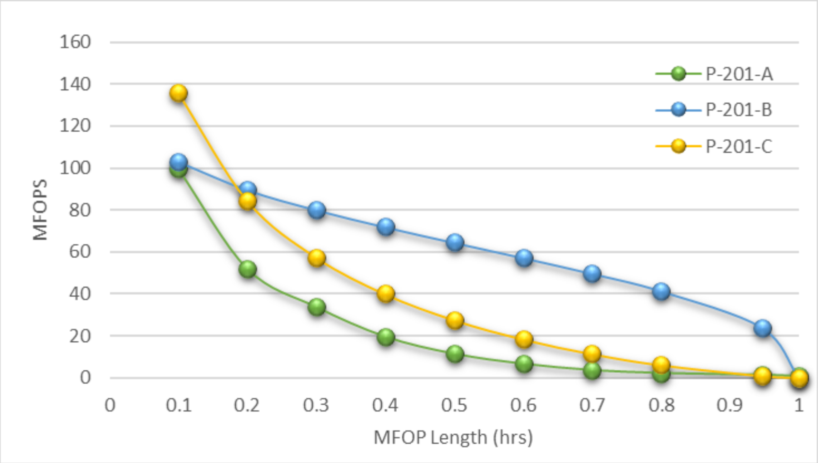


Figure 15. Comparison of all three pumps current MFOP performance

At the exactly the same MFOP of 30 hours, (Figure 15), P-201-A has an MFOPS of 35 %, whereas PUMP 201-B has a MFOPS of only 80 %. This illustrates the vastly different reality of the crushers, performances and provides a more "complete" picture.

5. Conclusion

The research conducted above has been successfully applied to the data obtained from Petrochemicals; however, in order to ascertain the practical value of the research, a number of external industry experts were approached. The first validation was done by senior engineering manager at large Petrochemicals who studied the results and approved the validity of the research in writing. Stating that he preferred the metric MFOP over MTBF, finding it more beneficial to describe reliability. Another validation was conducted; this was done by way of an interview an external person and introducing him to the research and case study results. For this purpose, Maintenance Specialist was interviewed. Maintenance Specialist is a consultant working for the asset management consulting company, and has extensive experience in reliability and maintenance topics in the industry and specifically in Petrochemicals. The review of the literature demonstrated that there is a definite problem with the use of the maintenance interval metric Mean Time Between Failures (MTBF). This problem is not isolated from the Petrochemicals industry. The aviation sector has defined a new maintenance interval metric to address the intrinsic issues that MTBF presents. The maintenance interval metric that was defined is called Maintenance Free Operating Period (MFOP) and was introduced in the literature. It was chosen to investigate this aviation-derived metric and is used in the Petrochemical industry. After an application methodology was introduced, the principle was applied in a case study presented in this chapter. From the analysis, it could be clearly seen that historic MTBFs found for each pump did not describe the system completely, it did provide indications that the system seems unreliable, but this would have been known by simply observing the system for a short time physically on-site, no more valuable information is provided. The future MTBF that was found for each pump also failed to show any more information, except for showing that P-201-A is more reliable that P 201-C which is actually not the case. It could be seen from the analysis that the MFOP principle provides a far better and more accurate picture of the analyzed system's performance, enabling maintenance engineers to make better-informed maintenance decisions on the pumps, the system that was analyzed. Engineers perform smarter and more focused maintenance, setting reliability targets that can be visually tracked.

In today's extremely competitive industrial environment, optimized maintenance decisions and programs are becoming increasingly important to asset-centric organizations. Preventive maintenance remains the most popular maintenance strategy, followed by a vast number of organizations, especially in the Petrochemicals sector. An intrinsic and essential part of maintenance is maintenance interval metrics or reliability metrics, as they yield information of the reliability performance of a certain system or equipment. The most commonly found and used maintenance interval metric is MTBF, which is used widely in various industries including the Petrochemicals sector. A number of inherent problems with the definition and application of MTBF have been found and a proposed solution to these problems has come from the aviation sector. The aviation sector is highly regulated, safety conscious, and asset-intensive, bearing many similarities to the Petrochemicals industry. The solution put forward is to define a new maintenance interval metric called MMFOP. This study investigated the school of thought of the widely used maintenance interval metric MTBF, against that of MFOP and applied it in the Petrochemicals sector. Following the literature study, an application methodology was derived in order to apply the MFOP concept to a system and compare the results to an ordinary MTBF approach. This methodology is based on the use of failure statistics, in order to result in a MFOP for both repairable and non-repairable systems. The methodology was then applied in the case study, with data being provided from Petrochemicals. In the case study, three pumps used for ethylene production were analyzed and both MFOPs and MTBFs were calculated for the pumps. Part and parcel of any scientific study are limitations. Raw data plays a large part in the application and use of MFOP and the calculation thereof. If no historical data were available for the system, then it would be difficult or impossible to model the system. The calculation, and thereby the application of MFOP, requires a certain amount of background knowledge in failure statistics. If this knowledge is not available, then the MFOP methodology cannot be applied effectively.

There are still areas where future research could improve results:

1- A general comment for future research is that data quality obtained from the Petrochemicals industry remains a problem. There should be a concerted effort to improve data recordings. In case of this study, failure data was readily available through the modern PI data capturing system, except that the maintenance data input was at times ambiguous or incomplete, specifically as to the root cause of the failure. It would, therefore, be desirable for future studies to have better data quality. Through consistent data capturing, this would further improve the results.

2- Future research may investigate the incorporation of the MFOP concept, and the MFOPS probability associated therewith, into the criticality analysis. This would be beneficial to a criticality analysis, as commonly, the educated guesses of an employee are simply used to determine which system is critical to the operation. The

MFOPS of different systems could be used within the criticality analysis to better establish which system is most critical to the operation.

The recommendations listed above could provide interesting windows for future research projects conducted in the field of PAM.

References

Abate, M., Lijesen, M., Pels, E., and Roelevelt, A. (2013). The impact of reliability on the productivity of railroad companies. *Transportation Research Part E: Logistics and Transportation Review*, Vol.51, pp.41-49.

Bohoris, G. A. (1996). Trend testing in reliability engineering. *International Journal of Quality & Reliability Management*, Vol.13 (2), pp.45-54.

Bourouni, K. (2013). Availability assessment of a reverse osmosis plant: Comparison between reliability block diagram and fault tree analysis methods. *Desalination*, Vol.313, pp.66-76.

Cox, T., Houdmont, J., and Griffiths, A. (2006). Rail passenger crowding, stress, health and safety in Britain. *Transportation Research Part A: Policy and Practice*, Vol.40 (3), pp.244-258.

Elsayed, E.A. (2012). Reliability engineering. New Jersey, Wiley Publishing.

Fritzsche, R., Gupta, J. N. D., andLasch, R. (2014). Optimal prognostic distance to minimize total maintenance cost: The case of the airline industry. *International Journal of Production Economics*, Vol. 151, pp.76-88.

Fazli-Khalaf, M., Khalilpourazari, S., and Mohammadi, M. (2017). Mixed robust possibilistic flexible chance constraint optimization model for emergency blood supply chain network design. *Annals of Operations Research*, pp.1-31.

Fritzsche, R. (2012). Cost adjustment for single item pooling models using a dynamic failure rate: A calculation for the aircraft industry. *Transportation Research Part E: Logistics and Transportation Review*, Vol.48 (6), pp.1065-1079.

Gulati, R. (2013). Maintenance and reliability best practices, New York, Industrial Press.

Huisman, D., Kroon, L. G., Lentink, R. M., and Vromans, M. J. (2005). Operations research in passenger railway transportation. *Statistica Neerlandica*, Vol.59 (4), pp.467-497.

Hashemian, H. M., and Bean, W. C. (2011). State-of-the-art predictive maintenance techniques. *IEEE Transactions on Instrumentation and measurement*, Vol.60 (10), pp.3480-3492.

Karanikas, N. (2013). Using reliability indicators to explore human factors issues in maintenance databases. *International Journal of Quality & Reliability Management*, Vol.30 (2), pp.116-128.

Khalilpourazari, S., and Pasandideh, S. H. R. (2018). Multi-objective optimization of multi-item EOQ model with partial backordering and defective batches and stochastic constraints using MOWCA and MOGWO. *Operational Research*, pp.1-33.

Khalilpourazari, S., Pasandideh, S. H. R., and Ghodratnama, (2018). A. Robust possibilistic programming for multi-item EOQ model with defective supply batches: Whale Optimization and Water Cycle Algorithms. *Neural Computing and Applications*, pp.1-28.

Kingham, S., Dickinson, J., and Copsey, S. (2001). Travelling to work: will people move out of their cars. *Transport policy*, Vol.8 (2), pp.151-160.

Milutinović, D., and Lučanin, V. (2005). Relation between reliability and availability of railway vehicles. *FME Transactions*, Vol. 33(3), pp.135-139.

Mohammadi, M., and Khalilpourazari, S. (2017, February). Minimizing makespan in a single machine scheduling problem with deteriorating jobs and learning effects. In *Proceedings of the 6th International Conference on Software and Computer Applications* (pp. 310-315). ACM.

Mann, H. B. (1945). Nonparametric tests against trend. *Econometrica: Journal of the Econometric Society*, Vol. 13(3), pp. 245-259.

Xu, M., and Wu, Y. (2015). Evolutionary Maintenance Based on Maintenance Free Operating Period Philosophy. *Procedia Engineering*, Vol.99, pp.587-592.

Waeyenbergh, G., and Pintelon, L. (2002). A framework for maintenance concept development. *International journal of production economics*, Vol.77 (3), pp.299-313.

Regattieri, A., Giazzi, A., Gamberi, M., and Gamberini, R. (2015). An innovative method to optimize the maintenance policies in an aircraft: General framework and case study. *Journal of air transport management*, Vol.44, pp.8-20.

Pintelon, L. M., and Gelders, L. F. (1992). Maintenance management decision making. *European journal of operational research*, Vol.58 (3), pp.301-317.

Pham, H., and Wang, H. (1996). Imperfect maintenance. *European journal of operational research*, Vol.94 (3), pp.425-438.

Khalilpourazari, S., and Khalilpourazary, S. (2018). A Robust Stochastic Fractal Search approach for optimization of the surface grinding process. *Swarm and Evolutionary Computation*, Vol. 38, pp. 173-186.

Khalilpourazari, S., and Khalilpourazary, S. (2017). An efficient hybrid algorithm based on Water Cycle and Moth-Flame Optimization algorithms for solving numerical and constrained engineering optimization problems. *Soft Computing*, pp.1-24.

Saleh, J. H., and Marais, K. (2006). Highlights from the early (and pre-) history of reliability engineering. *Reliability engineering & system safety*, Vol. 91(2), pp.249-256.

Rietveld, P., Bruinsma, F. R., and Van Vuuren, D. J. (2001). Coping with unreliability in public transport chains: A case study for Netherlands. *Transportation Research Part A: Policy and Practice*, Vol.35 (6), pp.539-559.

Scarf, P. A. (2007). A framework for condition monitoring and condition based maintenance. *Quality Technology & Quantitative Management*, Vol.4 (2), pp.301-312.

Sherwin, D. (2000). A review of overall models for maintenance management. *Journal of quality in maintenance engineering*, Vol.6 (3), pp.138-164.

Slife, B. D., Williams, R. N., and Williams, R. N. (1995). *What's behind the research?: Discovering hidden assumptions in the behavioral sciences*. SAGE, pp.1-251.

Smith, A. and Hinchcliffe, G. (2004). RCM: Gateway to World Class Maintenance. Butterworth-Heinemann.

Smith, D. J. (2017). Reliability, maintainability and risk: practical methods for engineers. Butterworth-Heinemann.

Stanley, N. and Heap, H. (1979). Reliability-centered maintenance. Tech. Rep., AD-A066-579.

Suzuki, T. (1992). New directions for TPM. Productivity Press Cambridge, MA. Swanson, L. (2001). Linking maintenance strategies to performance. International Journal of Production Economics, Vol.70 (3), pp.237–244.

Todinov, M. T. (2003). Minimum failure-free operating intervals associated with random failures of non-repairable components. *Computers & industrial engineering*, Vol.45 (3), pp.475-491.

Trindade, D. and Nathan, S. (2005). “Failure rate” which one? Tech. Rep., Sun Microsystems Inc., Newark, CA.

Trindade, D. and Nathan, S. (2006). Statistical analysis of field data for repairable systems. In: Reliability and Maintainability Symposium (RANS). Orlando, Florida.

Tsang, A. H. (1998). A strategic approach to managing maintenance performance. *Journal of Quality in Maintenance Engineering*, Vol.4 (2), pp. 87-94.

Van der Lei, T., Herder, P., and Wijnia, Y. (2014). *Asset Management: The State of the Art in Europe from a Life Cycle*. Springer Verlag. Stellenbosch University http://scholar.sun.ac.za

Van der Westhuizen, J., and Van der Westhuizen, N. J. (2009). Optimisation of railway asset life cycle performance through a continuous asset improvement process as part of the maintenance management programme. *SATC 2009*.

Vanier, D. J. (2000, September). Advanced asset management: tools and techniques. In *Innovations in Urban Infrastructure Seminar of the APWA International Public Works Congress*, pp. 39-56.

Vanier, D. J. (2001). Asset management a to z. *Innovations in Urban Infrastructure*, pp.1-16.

Venkatesh, J. (2007). An introduction to total productive maintenance (tpm). The Plant Maintenance Resource Center.

Vlok, P. J. (2011). Introduction to practical statistical analysis of failure time data: Long term cost optimisation and residual life estimation. *Self-Published, Course notes*.

Vanderhaegen, F. (2001). A non-probabilistic prospective and retrospective human reliability analysis method—application to railway system. *Reliability Engineering & System Safety*, Vol.71 (1), pp.1-13.

Wang, P. and Coit, D.W. (2004). Repairable systems reliability trend tests and evaluation. Rutgers, State University of New Jersey.

Wenzler, I. (2005). Development of an asset management strategy for a network utility company: Lessons from a dynamic business simulation approach. *Simulation & Gaming*, Vol. 36*(*1*)*, pp.75-90.

Wessels, W. R. (2011, January). Mechanical Engineering Design-for-Reliability. In *ASME 2011 International Mechanical Engineering Congress and Exposition* (pp. 469-477). American Society of Mechanical Engineers.

Wessels, W. (2012). Design-for-mechanical reliability to risk of failure. *RMS Partnership: A Newsletter for Professionals*.

Wheelhouse, P. (2009). Creating value from plant asset care. *Plant and Maintenance Asset Care*.

Willmott, P., and McCarthy, D. (2000). *TPM-A Route to World Class Performance: A Route to World Class Performance*. Elsevier.

Woodhouse, J. (2001). Combining the best bits of RCM, RBI, TPM, TQM, Six-Sigma and other 'solutions'. *J. Woodhouse.-The Woodhouse Partnership Ltd.-2003*.

Woodhouse, J. (2003). Asset Management: concepts & practices. *The Woodhouse Partnership Ltd*.

Xie, M., and Lai, C. D. (1996). Reliability analysis using an additive Weibull model with bathtub-shaped failure rate function. *Reliability Engineering & System Safety*, Vol. 52(1), pp.87-93.

Ren, Z., and Wu, Y. (2015). Modeling the Performance of Aircraft Utilizing Maintenance Free Operating Periods. *Procedia Engineering*, Vol.99, pp.214-218.