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 **MAINTENANCE** 

IncoME-III 2018

**Proceedings of
3rd International Conference on
Maintenance Engineering
IncoME-III 2018**

**September 6-7, 2018
University of Coimbra, Portugal**

Editor

**Jyoti K. Sinha
Filipe Didelet**

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IncoME-IV 2019

4th International Conference on
Maintenance Engineering

April 24-25, 2019

The University of Manchester
Middle East Centre - Dubai



Preface

This is first time the IncoME-III 2018 conference is organised out side the University of Manchester UK since 2016. It is likely that the IncoME-IV 2019 will be organised in Dubai, UAE.

The conference has received more than 50 papers from academic institutions and industries from several countries worldwide. The conference proceedings contains peer full papers and a few abstracts related to industrial maintenance activities. Prof Torres Farinha (Polytechnic Institute of Coimbra, Portugal) and Mr Dakheel Alharthi (Saudi Aramco, KSA) will be presenting the keynote lectures in the conference.

The organisers of IncoME-III would like to thank the keynote speakers, authors, presenters, committee members, invited guests, participants and session chairs for taking part and contributing to the success of this conference. Sincerest appreciation goes to Mrs. Ana Valeira, Mr. Hugo Santos, Ms. Noélia Marques and Mr. Pedro Neves (conference secretaries) for managing efficiently the event of IncoME-III 2018. The support by Dr Keri Elbhah, the University of Manchester UK during the preparation of the conference proceedings is also acknowledged.

Prof Jyoti K. Sinha
The University of Manchester, UK

Prof Filipe Didelet
Polytechnic Institute of Setubal, Portugal

About Coimbra

Coimbra is located in the middle of Portugal, in a region called *Beiras*. *Beiras* is the traditional name of a region running south of Douro River and north of Tagus River. This region is made up of two contrasting areas. The extensive beaches and fishing villages that lies along the Atlantic coastline, while in interior the mountains dominate the landscape.

In the heart of this hinterland rises the Serra da Estrela (Estrela Mountain Range), the highest in continental Portugal. This is where the Mondego River rises, later running down to the city of Coimbra. Here, the river that over the centuries has so many odes composed to it by generations of university students flows out into the Atlantic Ocean by the lengthy Figueira da Foz beach.

Coimbra has an area of 316,8Km² and around 140 000 inhabitants and a rich history. Six of Portugal's Kings were born here. In the Middle Ages, from 1139 until 1256, Coimbra was the capital of Portugal. The original name in the Roman period was Aeminium but it was changed to Coimbra influenced by the greater nearby town at the time - Conimbriga (today Conimbriga is a large archaeological site of great interest).

The University of Coimbra (UC) is one of the oldest in the world, having been founded in 1290 by King Dinis. UC was classified as a World Heritage by the United Nations Committee for Education, Science and Culture (UNESCO).

Known as the "city of students" here the daily life is marked by the students. Academic traditions are very important in the town and student's life. During special celebrations, students use black academic gowns, giving a special ambient to the streets. The city is divided into two distinct areas, the *baixa* (lower town) by the river, where most of the city's commercial activity is concentrated, and the *alta* (upper town), the older part. The upper town consists of steep narrow streets, where the *Repúblicas* (typical students' residences) are found, as well as some of the city's most important buildings.

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IncoME-III 2018 photographs



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ME2018_K02: Life Cycle Cost *versus* Life Cycle Investment, a New Paradigm

José Torres Farinha

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Abstract The first of approach of this paper is to present an overview of all phases of the physical assets life cycle. Based on this, it is discussed a new methodology to evaluate the financial life cycle of the assets.

The investment analysis in physical assets is usually done based only in the perspective of Economist view, considering the initial investment, the expected benefits throughout time and the functioning and maintenance costs throughout time.

Regardless of the first approach, it is extremely important to consider the maintenance policy and the overall Life Cycle Cost (LCC) throughout the entire life of the physical asset. These costs may be extremely variable and they may change dramatically the time for the Return of Investment (ROI).

However, the preceding involves an enormous contradiction because of the following: the initial cost of the physical asset is called investment, but the remaining costs throughout its life are only called costs.

It is important to clarify these concepts, calling the initial cost the Initial Investment and the remaining costs throughout time as the Variable Investments which implies changing the acronym LCC to Life Cycle Investment (LCI).

Key words: Physical Assets; Life Cycle Cost; LCC; Life Cycle Investment; LCI; Return on Investment; ROI.

1.0 Introduction

This paper makes a global approach of the Life Cycle of Physical Assets structured in two parts: the first one analyses the management of their global Life Cycle, since acquisition to withdrawal; the second one presents a new approach for their financial life cycle, based on econometric specific models, called Life Cycle Investment (LCI).

About the econometric models to evaluate the LCI, i.e., all costs and benefits are considered, since the initial investment until the withdrawal, including all the variable investments (usually called costs) to guarantee their normal functioning.

The paper is structured in the following way:

- Section 2 describes the State of the Art;
- Section 3 describes a global vision of the Physical Assets Life Cycle;
- Section 4 describes The Life Cycle Cost, i.e., The traditional Investment Analysis;
- Section 5 describes the new approach called Life Cycle Investment;
- Section 6 presents the conclusions.

2.0 State of The Art

The interest about the Physical Asset Management area is increasing more and more, namely after the publication of ISO 5500X (ISO 55000, ISO 55001, ISO 55002), and previously encouraged by the PAS 55.

Farinha [1] presents, in his most recent book, a global view of the Life Cycle of Physical Assets integrating the preceding standards.

According to Ljiljana, Dragutin & Zelimir, “Asset Management is a relatively new discipline that provides methods and tools for effective management of Physical Assets to maximize their utilization during entire Life Cycle. Asset Management evolved from Maintenance Management to provide a holistic approach to managing the life of a physical asset. This management is important for the performance of any organization, particularly Physical Asset intensive organizations. Therefore, it is no wonder that asset management professionals around the world work on the development of new models and concepts such as engineering asset management, integrated strategic asset management or asset governance, in order to find the best solutions to meet the changing nature and challenges of organizations and society... Today, we recognize that asset governance is a key point for leading role in the development and implement asset management in the company and it is evidence in PAS 55 and the ISO 55000 standards”, [2].

Stimie & Vlok present a mechanism that can assist Physical Asset Management (PAM) experts and academics with the early detection and management of PAM Strategy Execution Failure (PAMSEF). The authors present a mechanism to assist experts with the early detection and prevention of PAMSEF. The mechanism is referred to as a “Physical Asset Management Strategy Execution Enforcement Mechanism” (PAMSEEM), which corresponds to a double-loop feedback system consisting of: four iterative phases; four major decisions; and a number of implementation processes or steps, [3].

The relevance of evaluating the Life Cycle of the Physical Assets is referred by Eicher in the following way: “Investing in hospital infrastructure is not just a financing activity. It is important to consider the whole life cycle of an asset. For example, it is necessary to think about the operating life of an asset before building it, because this can influence investment costs and follow-up costs substantially”. There are several models of investments in assets. Regardless of this case being based in a hospital, he presents 12 investment models from which some models can be extrapolated to other types of business. The paper also discusses the models for assets maintenance, namely the option insourcing versus outsourcing, [4].

Katicic, Lisjak & Dulcic (2014) say that Asset Management is a new discipline that provides methods and tools for management of Physical Assets to maximize their use during the entire lifecycle. The Physical Asset Management evolved from the Maintenance Management to provide a holistic view to manage the Life of the Physical Asset. The authors also mention that nowadays it is recognized that Physical Asset governance is a key point for a leading role in the development and implementation of Asset Management in the companies and in according to the ISO 5500X standards, [5].

Banyani & Then (2014) present a study that shows how the Physical Facilities Management in an industry can be perceived at different levels of maturity based on personal judgement. This situation is due to a lack of a tool that can be used in assessing maturity levels. The study proposed an Integrated Feeder Factors Framework (I3F) as a yardstick, [6].

Volker, Telli & Ligtvoet (2011) refer that an asset management system for the transportation sector requires system-level performance measures, models, interoperable databases used by asset groups to make evidence-based decisions, [7].

About passenger urban transport, the following references emphasize the importance of maintenance included in several econometric models, [8], [9].

According to the Center for Transportation Research and Education (CTRE), the transportation agencies are facing many of the same challenges and could benefit from the adoption of asset management principles. The organizations lack the resources and/or experience that allow them to initiate and grow an asset management program. To face this challenge, the document presented by CTRE shows a guide to support transportation organizations in their implementation of Physical Asset management program. The document also presents a guide focused on the various levels of the transportation organization’s maturity in undertaking the activities that comprise the asset management framework. The levels of maturity presented are the following [10]:

- Organizational goals and objectives;
- Inventory of pavements, bridges, and other major infrastructure assets;
- Knowledge of the age, condition, and deterioration of these assets;

- Availability of information to undertake Life Cycle cost analysis for all major asset types and asset classes;
- Information to undertake risk management analysis at the enterprise and program level;
- Information to develop the organization's financial plan to support investment;
- Development of investment strategies to manage the network for its whole life.

3.0 The Global Physical Assets Life Cycle Analysis

Farinha presents, in his book, a new integrated vision for the *Physical Asset Management* and emphasizes some tools to manage the entire life cycle of *Physical Assets* [1]. The author's approach for all phases of *Physical Assets* life cycle can be summarized in the followings times and steps:

- t₁ - Decision for Acquisition;
- t₂ - Terms of Reference;
- t₃ - Market consultation;
- t₄ – Acquisition;
- t₅ – Commissioning;
- t₆ - Starting Production / Starting Maintenance;
- t₇ - Economic / Lifespan;
- t₈ - Renewal / Withdrawal.

Additionally, the author establishes the relation between Life Cycle of Physical Assets, the standards ISO 5500X (55000, 55001, 55002) and some maintenance standards, like the NP4492 and the associated ones, [1].

Figure 1 represents the author's graphical approach for the Life Cycle of Physical Assets including the referred standards.

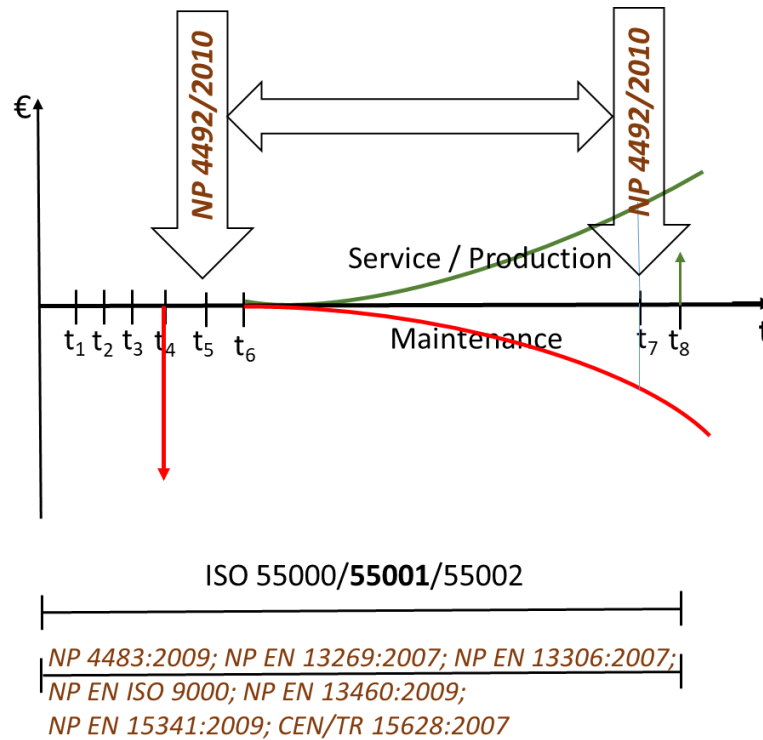


Figure 1 – Times of a Physical Asset life cycle

4.0 The Life Cycle Cost

The LCC is the sum of all capital spent in support of that asset from its design and manufacture, through the operation and until the end of its useful life. It is understood that the life time goes from the physical asset commissioning to the equipment withdrawal.

The LCC of a physical asset can be significantly higher than the value of the initial investment and, in many cases, it is already set in the design phase.

One of the main objectives of the LCC analysis is to support decisions about the alternatives of investment by estimating the total cost of the physical asset during its life cycle. This calculation increases the visibility of the equipment total costs and helps to choose the best solution.

The Table 1 and Figure 2 show a simulation of an initial investment with variable costs (investments) of functioning and maintenance during 20 years. The Interest Rate is of 25%.

Table 1 – Values of investment and Functioning of an initial investment

Time	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Initial Investment	1200																				
Functioning	200	200.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00
Present Value (FPV)	160.00	160.00	128.00	102.40	81.92	65.54	52.43	41.94	33.55	26.84	21.47	17.18	13.74	11.00	8.80	7.04	5.63	4.50	3.60	2.88	2.30
Accumulated FPV	1960.00	1520.00	1648.00	1750.40	1822.32	1897.86	1950.28	1992.23	2025.78	2052.63	2074.10	2091.28	2105.02	2116.02	2124.82	2131.85	2137.48	2141.99	2145.59	2148.47	2150.70
Maintenance	250	250.00	300.00	360.00	432.00	518.40	622.08	746.50	895.80	1074.95	1289.95	1547.93	1857.52	2229.03	2674.83	3209.80	3851.76	4622.11	5546.53	6605.83	7987.00
Present Value (MPV)	200.00	192.00	184.32	176.95	169.87	163.07	156.55	150.29	144.28	138.51	132.97	127.65	122.54	117.64	112.93	108.42	104.08	99.92	95.92	92.08	88.40
Accumulated MPV	300.00	392.00	576.32	753.27	923.14	1086.21	1242.76	1393.05	1537.33	1675.84	1808.80	1936.45	2058.99	2176.63	2289.57	2397.99	2502.07	2603.98	2697.90	2789.99	2879.19
Accumulated Total Costs	1560.00	1912.00	2224.32	2503.67	2755.46	2984.07	3193.05	3385.28	3563.11	3728.46	3882.90	4027.73	4164.02	4292.65	4414.38	4529.84	4639.55	4743.97	4843.49	4938.46	5028.76
Benefit	2000	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00
Present Value (BPV)	960.00	768.00	614.40	491.52	393.22	314.57	251.66	201.33	161.06	128.85	103.08	82.46	65.97	52.78	42.22	33.78	27.02	21.62	17.29	13.84	10.96
Accumulated Total Benefits	960.00	1728.00	2342.40	2833.92	3227.14	3541.71	3793.37	3994.69	4155.75	4284.60	4387.68	4470.15	4536.12	4588.89	4631.12	4664.89	4691.91	4713.53	4730.82	4744.66	4755.00
BPV-FPV	-600.00	-184.00	118.08	330.25	471.68	557.64	600.32	609.41	592.64	556.14	504.78	442.41	372.10	296.24	216.73	135.05	52.37	-30.44	-112.67	-193.80	-274.80

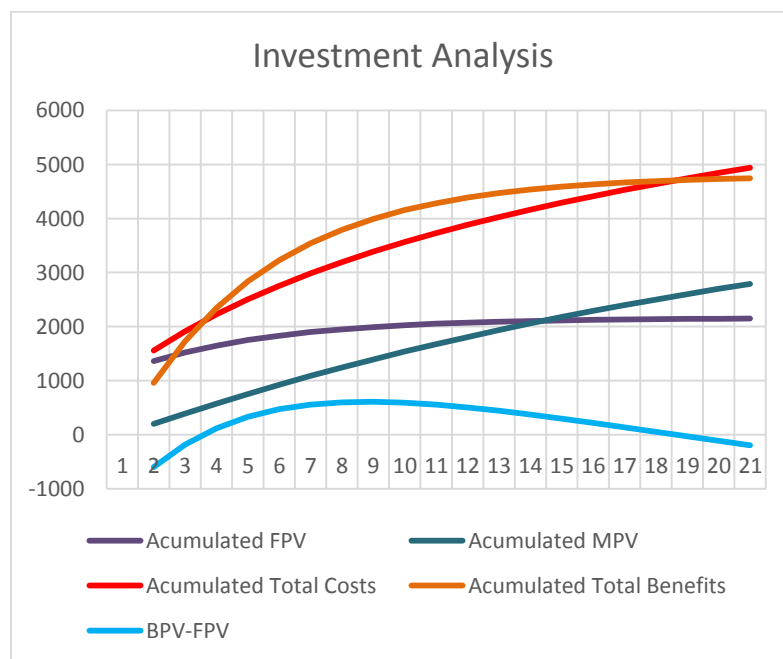


Figure 2 – Graphical variation of the values represented on Table 1

5.0 The Life Cycle Investment

It is important to clarify the usual contradiction between investment and costs of physical assets, namely the following:

- The initial cost of the Physical Asset is called Investment, but the remaining costs along its life are, usually, called Costs.

It is important to clarify these concepts and to call the Initial Cost the Initial Investment and the Remaining Costs throughout time as Variable Investments which implies changing the acronym LCC to Life Cycle Investment (LCI).

Taking into consideration this concept, some simulations over the data on Table 1, that considered the following values, were made:

- Internal Rate of Return - 0.25;
- Availability - 0.89.

Based on these values, a positive cycle of results can be observed since the 3rd year until the 17th year.

However, if we consider a diminishing in the Maintenance Investment of the Physical Asset, reaching an Availability only of 0.82, the results are presented in Table 2 and Figures 3 and 4, showing that the positive cycle of results is shorted in three years, i.e., it occurs between the 2nd year and the 12th year.

These results demonstrate the importance of the maintenance activity and, by consequence, the importance of the maintenance investment to maximize the profits of a Physical Asset.

Table 2 – Values of investment, several costs and benefits, with an Availability=0.82

Time	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Initial Investment	1200																				
Functioning (F)	200	200.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00
Present Value (FPV)		160.00	160.00	128.00	102.40	81.92	65.54	52.43	41.94	33.55	26.84	21.47	17.18	13.74	11.00	8.80	7.04	5.63	4.50	3.60	2.88
Accumulated FPV		160.00	1520.00	1648.00	1750.40	1832.32	1897.86	1950.28	1992.23	2025.78	2052.63	2074.10	2091.28	2105.02	2116.02	2124.82	2131.85	2137.48	2141.99	2145.59	2148.47
Maintenance (M)	250	250.00	300.00	360.00	432.00	518.40	622.08	746.50	895.80	1074.95	1289.95	1547.93	1857.52	2229.03	2674.83	3209.80	3851.76	4622.11	5546.53	6655.83	7987.00
Present Value (MPV)		200.00	192.00	184.32	176.95	169.87	163.07	156.55	150.29	144.28	138.51	132.97	127.65	122.54	117.64	112.93	108.42	104.08	99.92	96.92	92.08
Accumulated MPV		200.00	392.00	576.32	753.27	923.14	1086.21	1242.76	1393.05	1537.33	1675.84	1808.80	1936.45	2058.99	2176.63	2289.57	2397.99	2502.07	2601.98	2697.90	2789.99
Non Production (NP)	250	250.00	300.00	360.00	432.00	518.40	622.08	746.50	895.80	1074.95	1289.95	1547.93	1857.52	2229.03	2674.83	3209.80	3851.76	4622.11	5546.53	6655.83	7987.00
Present Value (NPPV)		200.00	192.00	184.32	176.95	169.87	163.07	156.55	150.29	144.28	138.51	132.97	127.65	122.54	117.64	112.93	108.42	104.08	99.92	96.92	92.08
Accumulated NPPV		200.00	392.00	576.32	753.27	923.14	1086.21	1242.76	1393.05	1537.33	1675.84	1808.80	1936.45	2058.99	2176.63	2289.57	2397.99	2502.07	2601.98	2697.90	2789.99
Accumulated Total Costs		1700.00	2304.00	2800.64	3256.93	3678.59	4070.28	4435.81	4778.33	5100.44	5404.30	5691.71	5964.18	6223.01	6469.29	6703.95	6927.82	7141.61	7345.95	7541.40	7728.45
Benefit (B)	2000	1639.34	1639.34	1639.34	1639.34	1639.34	1639.34	1639.34	1639.34	1639.34	1639.34	1639.34	1639.34	1639.34	1639.34	1639.34	1639.34	1639.34	1639.34	1639.34	1639.34
Present Value (BPV)		1311.48	1049.18	839.34	671.48	537.18	429.74	343.80	275.04	220.09	176.02	140.82	112.65	90.12	72.10	57.68	46.14	36.91	29.53	23.69	18.90
Accumulated Benefits BPV		1311.48	2360.66	3200.00	3871.48	4408.66	4838.40	5182.20	5457.23	5677.26	5853.28	5994.10	6106.76	6196.88	6268.98	6326.66	6372.80	6409.72	6439.25	6462.88	6481.78
BPV-FPV-MPV-NPPV		-448.52	56.66	399.36	614.54	730.05	768.12	746.39	678.90	576.82	448.98	302.40	142.57	-26.13	-200.31	-377.29	-555.02	-731.90	-906.70	-1078.52	-1246.67

The detailed mathematical analysis of the models that support the simulations presented in the sections 4 and 5 can be found in the references [1], [8], [9] and [11]. Figure 4 shows the financial flows throughout time for a value of Availability of 0.82.

6.0 Conclusions

The Physical Assets were always very important investments to the Organizations and Society. However, time after time they become strategic and more and more complex to analyse.

The paper has discussed and proposed three key points for Physical Asset analysis: The several steps throughout its life, from acquisition to withdrawal; the traditional Life Cycle Cost; A new approach called Life Cycle Investment.

The paper also demonstrates the relevance of the maintenance investment throughout the Life Cycle of Physical Assets through the Availability indicator that is one of the most pragmatic ways to measure the maintenance efficacy.

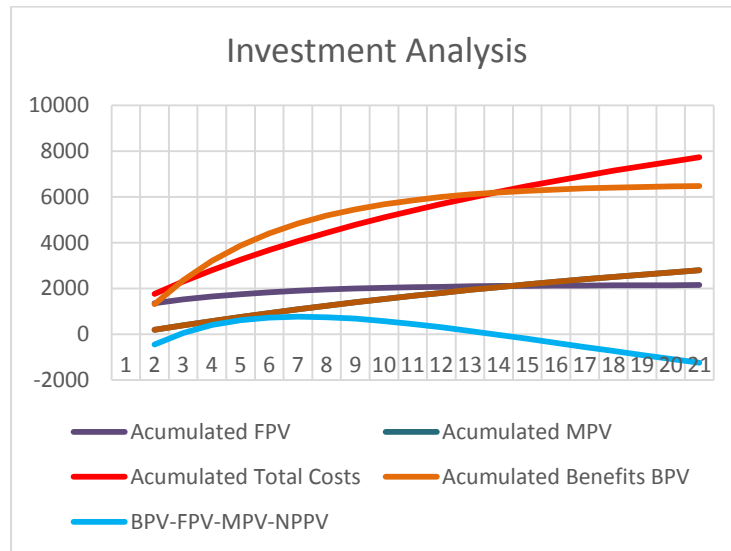


Figure 3 – Values of investment, several costs and benefits

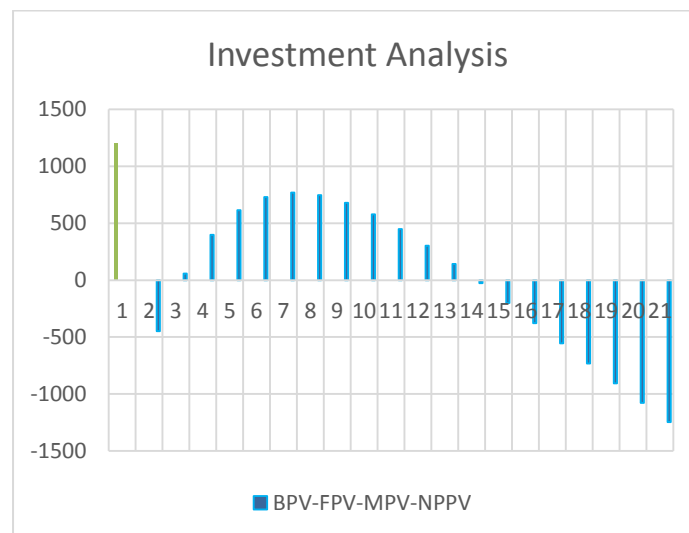



Figure 4 – Annual financial results of a physical asset investment

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Authors' Biography

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ME2018_1103

Rotating Equipment Energy Conservation Initiatives

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Abstract Riyadh refinery has developed separate comprehensive program for each of the following categories: Compressor re-rates, Fin Fan Blade Upgrade Hydraulic Re-rates & Non-metallic Wear Parts. This paper aims to highlight comprehensive energy assessment carried out on different types rotating equipment to identify energy saving opportunities and candidate equipment under each category. Successful cases histories are also shared in brief to highlight the benefits realized in terms of energy saving and improvement in equipment reliability.

Key words Rotating Machines, Energy Efficiency, Energy Conservation.

1.0 Introduction

With the surge in local demand for energy and higher capital cost of new energy generation projects, energy conservation has become an area of high importance for the industry as a whole and the Oil and Gas processing industry in particular. In refineries, energy cost may reach up to 50% of the total plant operating cost. There is an ever growing need to find out on constant basis where the energy dollars are going and how to save it as much as possible. Rotating equipment are the largest consumers of the energy in a Refinery and studies have shown that over 20% of the energy consumed by these systems could be saved through equipment or control system changes. At Saudi Aramco Riyadh Refinery, Reliability Unit has embarked on a drive to improve rotating equipment reliability and efficiency as a part of ongoing efforts by refinery to improve its Energy Intensity index (EII). Rotating equipment energy conservation initiatives are broadly categorized as under:

1. Compressor re-rates
2. Fin-fan Upgrades
3. Hydraulic re-rates of pumps
4. Use of non-metallic wear parts in pumps

2.0 Compressor re-rates

This program is basically focusing on compressors potential saving by surveying the plant compressors and analyzing the power consumption.

Any potential improvement of power consumption, it will be evaluated to select proper technique based on the study outcomes.

2.1 Case Study: Wet Gas Compressor

This is a case study of rerating one of the compressors in RRD which is Wet Gas Compressor.

The compressor was being significantly due to crude specification changed. The crude stabilisation was being processed in CSF in RRD where the compressor is handling the rated flow, but since the crude source changed, it became stabilized before feeding the refinery, hence the gases reduced as shown in Table 1.

Max	48,000 Nm ³ /h
Min	24,000 Nm ³ /h
Normal Flow	12,000 Nm ³ /h
Recycled flow	12,000 Nm ³ /h
Power Consumption	3.1 MW
Suction Pressure	0.9 Kg/cm ²
Discharge Pressure	5.0 Kg/cm ²

Table 1 Previous Parameters

Reverse engineering was carried out for the compressor, and as a result rotor & diaphragms were changed along with the inter-stage seals. Figure 1 shows a comparison of new & old shaft size.



Figure 1 Old shaft & the new shaft

As result of rerating, the compressor recycled flow reduced 12000 to 4000 m3/h.
Power consumption reduced by 45% to b

1.7 MW instead of 3.1 MW.

Total power saving is 1.4 MW equivalent to 0.5mm \$ annual cost saving.

Another Benefits:

Avoid surge problems.

Avoid flaring in summer. \$200M/Y

Total Project Cost: \$2.5 MM

The project payback period is 2.5 years

3. Fin Fan Upgrade

This initiative aims to reduce energy consumption in fin fans by improving the aerodynamic performance. This would be done by upgrading the fan blades from aluminum to curved fiber plastic as shown in Figure 2.



Figure 2 Before & after upgrade to fiber plastic

3.1 Case Study: Upgrade fan blades of R215-E24 M5

Upgrade has been implemented for R215-E24 M5 in the refinery. This fan has a number of 12 blades with 14 ft diameter and speed of 195 rpm. The air flow measured at 12 locations with 3x readings and it's approximately 230000 ACFM. Amps was also collected which's 74. The readings were taken before and after upgrade the blades from aluminum to curved fiber plastic.

As a result of the upgrade the power consumption reduced by 25% from 43.5 to 33.1 KW. This equivalent to \$3645 annual cost saving.

4.0 Hydraulic Re-rates & Power Optimisation

The main objective of this initiative is to go over all plant's pumps and evaluate for energy losses such as recycled flow or throttling or even possibility of optimisation. Based on the study outcomes, the proper technique will be selected either trim, upgrade or replace if needed. There are five pumps were upgraded from 27 potential pumps.

4.1 Case Study: Re-rate of Hydrocracker Debutanizer Feed Pump

This is a case study of Debutanizer feed pump, in Hydrocracker unit. The pump was oversized and suspected high recirculation and vibration. Table 2 shows the pump specification. It's centrifugal, between bearings. It is pumping hydrocarbon with capacity of 350 m³/h, and bhp is about 214 KW.

Type	Centrifugal, b/w Bearing
Capacity	319.3/350.9 m ³ /hr
TDH	218.9 m
Sp. Gr.	0.727
Pressure Suc./Disch	7.1/23 kg/cm ²
Liquid	Hydrocarbon
Driver	Motor, 3560 RPM
BHP	214.2 KW

Table 2 Pump specification

An outside engineering company was contacted to proceed with reverse engineering, hence new impeller & shaft were manufactured along with wear rings. Table 3 shows the old & new material of the manufactured parts.

#	Description	Original material	Upgraded material
1	Shaft	Carbon Steel SCM4	AISI 4140 HT
2	Impeller	Cast iron FC25	CA6NM
3	Impeller wear ring	SUS420 J2 HT	SUS420 J2 HT
4	Casing wear ring	SUS420 J2 HT	SUS420 J2 HT

Table 3 The old & new materials

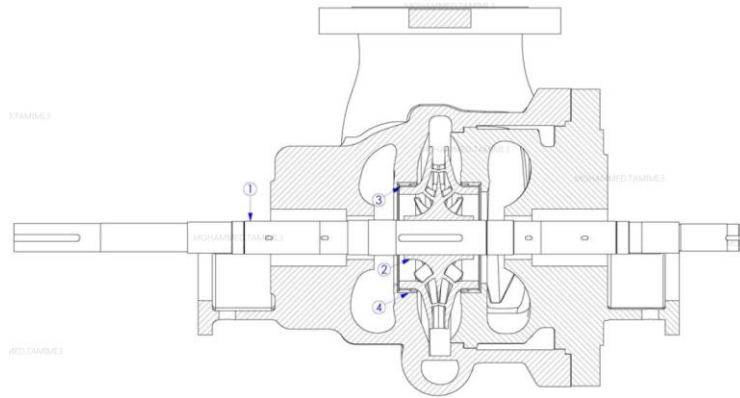


Figure 3

As a result of the re-rate, the flow reduced from 350 to 150 m³/h, which is less than 50% reduction of original flow, with minor reduction in the head as shown in Table 4.

The change in parameters, result in power consumption, where it reduced by 55% from 200 to 90 KW. Annual cost saving is \$16,000.

Performance Data	Before	After
Flow m ³ /h	350	150
Head m	219	200
Impeller OD mm	362	360
NPSHr m	4.6	4
*Consumed power KW	200	90

Table 4 results after reverse engineering

5.0 Non-metallic Wear Parts

As an ongoing effort to improve centrifugal pump reliability and efficiency, Reliability Unit has developed a program that utilizes non-metallic materials as replacement wear components in place of commonly used metals (such as wear rings, throat bushing etc.) in Figure 4. The use of non-metallic material can improve pump efficiency and reliability through utilisation of reduced running clearances and by taking advantage of significantly reduced friction. The unique properties of the material can reduce vibration and significantly decrease repair cost when a failure does occur. These improvements could help to achieve lower maintenance cost, increased mean time between failure, and reduced equipment

downtime. The centrifugal pump improvement would also result in reduced energy cost too.

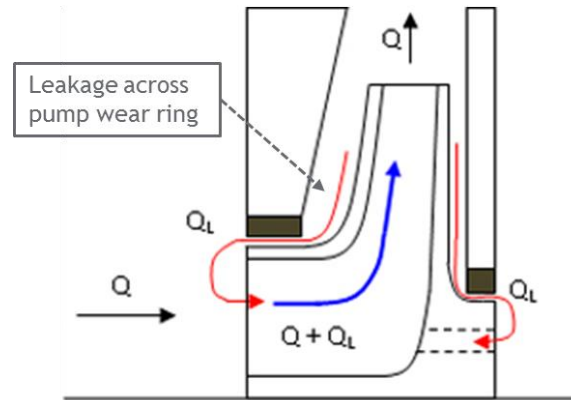


Figure 4 Non-metallic Wear Parts

There are 71 candidate pumps where they're grouped into three groups, based on S.G & the specific speed.

5.1 Case Study: Crude De-salter Water Pump

As a pilot project, Crude Unit De-salter water Pump (Z05-P3B) stationary wear rings were recently upgraded to PEEK based WR-525 non-metallic material. For Z05-P3B metal wear rings, API 610 recommends minimum diametral clearance of 0.48 mm, however with use of non-metallic material clearance was reduced by 55% to 0.21 mm. As a result of this upgrade, there is a significant reduction of 52% in vibration levels from previous baseline (3.057 to 1.477 mm/sec rms). Also, there is a noticeable increase in pump hydraulic efficiency by 5% over design which corresponds to ~10 KW of power saving. On comparison with sister pump (w/ metallic wear rings), P3B pump is drawing 17% lower current than P3A (134 Amp as against 161 Amp in P3A).

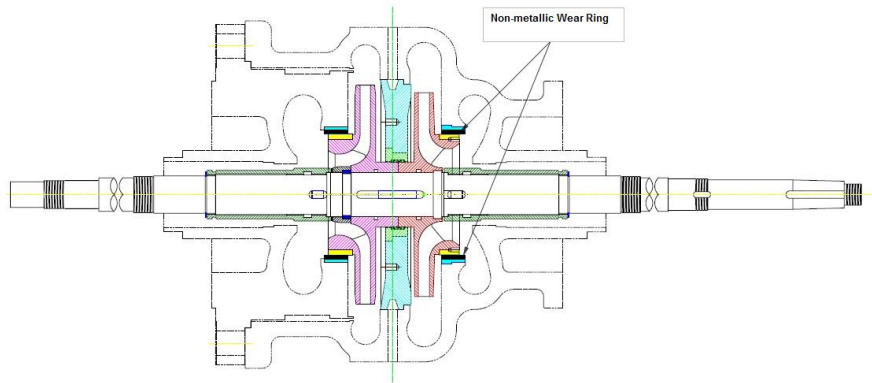


Figure 5 Cross section drawing

6.0 Conclusion

Table 5 shows the overall summary of the program for each mentioned category. The total power saved is 1800 KW with the target is to reach more than 3 MW.

Initiatives	Power Saving KW		Progress %
	Completed	Plan	
Compressor Re-rates & Power Optimisation	1400	-	100%
Fin Fan Upgrade	215	212.5	45%
Hydraulic Re-rates & Power Optimisation	176	950	25%
Non-metallic Wear Parts	12	303	25%

Table 5 Overall summary

Authors' Biography

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ME2018_1107: Potential risks in implementation of maintenance outsourcing projects (Case study for Russia and CIS)

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Abstract Due to drastic changes in process engineering and business organisation that have occurred in recent decades, outsourcing has become a key success factor in many industries. These changes have affected the conditions of managerial decision-making processes where primary focus has been shifted toward the promotion of organisation competitiveness that, in turn, requires continuous assessment of available technologies and for ways of performance improvement. Outsourcing is one possible solution that could help with business challenges in terms of ensuring the company competitiveness.

Key words Maintenance outsourcing, Outsourcing core team, Horizontal polarisation, Blaming culture, Equipment ownership, Human resource risks, Managerial risks, Process risks, Pre-contract work.

1.0 Introduction

A rule of thumb states: if a company is not best in-world in doing something and is doing it in-house, it is turning down competitive edge. This is precisely why nowadays outsourcing is an essential part of the business strategy for most of organisations, which enables, if handled properly, cost savings and improves processes and product quality.

Nevertheless, outsourcing is not a quick solution for the processes that have been poorly managed. There is no reason to believe that somebody else will be able to fix overnight the problems that an organisation has got for months or even years. First and foremost, it must be considered as a long-term strategic management tool.

Outsourcing activity in Russia and CIS brings a significant set of risks for service providers. Most companies recognize this and respond by adopting a thorough risk analysis process.

A purpose of the paper is to give a spotlight on some potential risks associated with outsourcing relationships within the Russian and CIS market and draw up a few ideas based on a theoretical and practically researched foundation for implementation of projects dedicated to maintenance outsourcing from the perspective of service providers, which may be used to assist companies in making informed decisions on the issue of strategic outsourcing.

The research represents three categories of risks: human resource, managerial and process.

2.0 Human resource risks

Prior to commencing any activities, it is vital to have a core team comprising of well-trained, motivated players that can keep the process positively moving forward. There are several characteristics to look for when assembling an outsourcing core team. These include diversity of skills and opinion—the team must be cross-functional, and members should have multidiscipline backgrounds. The team should be made up of people who will challenge themselves and others. The teams should contain the skills required to plan, analyse risks, negotiate effectively, design and execute comprehensive and effective contracts, customer relationships and controls. They should be self-directed and should not easily accept the status quo. The customer, product/service, and process-specific knowledge must be represented on the team. They must be able to work with people at all levels of an organisation, internally and externally.

Therefore, in organizing of the long-term collaborative partnership service providers should realistically assess capacity and capability of the local labour market, especially when considering cost savings, they could provide as a sales argument. If the local labour market suffers from shortage of skilled craftspeople and the outsourcer has no possibility to turn a wage factor to an advantage, he will find himself sooner or later, in a very difficult situation, i.e. will be faced with a problem of staff turnover. As a result, the efficiency of collaborative partnership will tend to be zero, deliverables of the project will counter with the initial plan and the service provider will start to lose customer loyalty due to staff rotation which takes the client time and effort to find a way of agreed co-operation. Whereas, employee turnover is expensive – recruitment, replacement, and training costs are measured in multiples of annual salaries or wages. A hidden expense is lowered productivity while a new employee learns how to do a job an experienced employee has left [1].

An alternative source of labour for company-outsourcer, in addition to the one from local labour market and as set out in terms and conditions of the contract, is customer manpower. In this case, the company-service provider, like the process

of selection of external manpower, should conduct interviews with each of the personnel to be transferred to assess their level of competence during preparation/transition period, and should on no condition rely on the results of a customer audit.

There is a common misconception that the transfer of customer manpower has an advantage over any manpower taken from outside and does not need to be assessed by skill level and professionalism. This opinion has been formed based on the following assumptions:

- Personnel has enough skills and experience of the working in the industry in which the company-client operates.
- Management of the company-supplier is interested in improving equipment reliability and maintenance service level therefore transfers only the most skilled and experienced employees.

Practice shows that these assumptions are far from reality. The rationale is below. As described above there are various scenarios of outsourcing projects:

- OEM Company concludes maintenance contract with the customer immediately after the commissioning of the new equipment, so called "greenfield" project.
- Company outsourcer (it could be OEM as well) concludes maintenance contract with the customer of the existing plant or equipment, so called "brown-field" project.

Accordingly, there are risks common to both types of projects:

1. **The customer does not transfer or delays the moment of transfer of personnel, whereas it is stated in the maintenance contract.** Quantitative and qualitative composition of the personnel to be transferred should be negotiated and agreed in the early phases and must be fixed in the contract. Sometimes the customer may insist to include in the contract only the identification of employees' transfer, whereas quantity and quality will be addressed in due course after commencement of the project. Such a decision is unacceptable for the service provider because it can lead to procrastination of the preparation period for transferring (the staff should be aware of transition in advance, and each of them must be interviewed), as well as the personnel reshuffle. That sort of activity is typical for "greenfield" projects when the company-client expects to obtain from the erection and commissioning of new production facilities the replacement of old plants by preserving the latter and transferring the existing staff to new jobs. Accordingly, personnel who are engaged in maintenance of old production facilities are transferred into the company-outsourcer who then becomes the custodian of that function. However, if there are any changes in the erection of main or auxiliary facilities or in reaching of contractual production capacities, a customer can change his mind on the continuation of maintain old production facilities and keep the most qualified personnel to him to deliver

all the contracted orders to their customers. In a worst-case scenario, the company-outsourcer becomes hostage to a situation where, under the contract it must provide jobs to employees of the client but does not have sufficient resources to provide accomplishment of its own services.

If, eventually, the transfer of employees has happened, but preparatory work has not been carried out and the new terms were not announced, it leads to the situation when transferred personnel suffer lower morale - resenting and resisting the change and they find their position less secure. They feel that they have little in common with the outsourcer trade force and are unwilling to work in the new team.

2. **Maintenance culture within the customer entity.** It has been defined as ‘the collective mental programming of people in an environment’. It is not a characteristic of individuals; it encompasses several people who are conditioned by the same education and life experience [2].

The environment which most Russian and CIS companies' employees work in can be characterized by strong horizontal polarisation, the definition of which is shown in Figure 1.

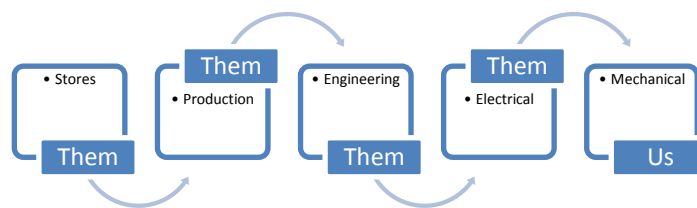


Figure 1 Horizontal Polarisation in an Administrative Structure

The horizontal polarisation indicates the presence of opposite views and attitudes across departmental boundaries. Conflict builds up across the boundaries of the main departments—viz. Production, Maintenance, Engineering, Stores—and to a lesser extent across the sub-departments, e.g., Electrical Maintenance and Mechanical Maintenance [2].

The Production–Maintenance conflict is the most well-known, when maintenance view considers that production staff only can mal-operate and never let them have the equipment for proper maintenance. The production view is that they produce money and maintenance staff does not understand their objectives when production give them the plant for a shift and they keep it for a day [2].

Thus, moving to a new environment, employees are trying to apply the same patterns of behaviour, carrying the syndrome of "us and them" into the new organisation.

Another common feature of Russian and CIS companies' work environment is the 'blaming' culture when each level in the hierarchy tries as little as possible to inform the superior level about faults or mal-operation therefore avoiding punishment. This approach educates employees with the wrong idea about the methods and principles of work, but as well, unfortunately, the lack of such information at the first stage of the feasibility study of outsourcing services, usually comes to light whilst the project matures.

The last, but not least, feature of Russian companies' maintenance culture is the little sense of plant or equipment ownership. Equipment Ownership is a factor which involves the degree to which trade force and/or operators and/or the team feel a sense of personal ownership for equipment or an area of plant. This is probably the most important single factor in achieving a high level of equipment reliability. Where ownership exists, the equipment tends to be operated and maintained correctly [1].

Thus, when auditing it is important to recognise and understand the culture of the company, establish trust-based relations with the personnel of the customer to get the most accurate picture of the current environment.

3. **Sense of subordination between the management of the customer and their former employees.** Many managers and line managers are of the habit of continuing to control the work and give instructions to employees who prior to the outsourcing implementation, were their subordinates. Such continuity cuts across with new organisational structure, and often does harm to the project. The challenge for management of the company-service provider is to bring about understanding of the boundaries of responsibilities between the client and the company.

The advantage of recruiting from the open labour market is its independence from management and cultural sensitivities of company-client, but there some risks still exist:

- The incoming personnel lack both process and equipment knowledge and any form of goodwill towards the company-client.
- The incoming personnel have little sense of plant or equipment ownership (as in the case of transferred personnel).

3.0 Managerial risks

In terms of relationship between a client and outsourcer a Murphy's Law ("if it can go wrong it will go wrong") works in the best way possible: things that might be understood wrong - will be understood wrong. In other words, any misinterpretations and understatement of contractual issues have a detrimental effect.

➤ **Distribution of authorities and processes**

As a rule of thumb, a predominant hot spot in the relationship between a client and the outsourcer becomes a difference in opinions in relation to distribution of the authorities and processes since contract initiation. As a result, a relationship loses coordination, project deadlines are to be reconsidered, services cannot be delivered in a proper manner, and both parties remain dissatisfied. Such problems arise if in pending the completion of the agreement the principles of outsourcing relationships and authority distribution for decision taking have not been established and communicated to all stakeholders. There must be no implied or generally accepted issues between client and outsourcer. All working protocols must be reflected in a contract or a service level agreement, or in any other official documents.

➤ **Lack of executive management support within company-client**

A lack of executive support within a company-client in an outsourcing project may cause an active or passive resistance of client's personnel which in turn leads to a project failure. Frequently, executive management do not go too much in detail during working out contract and profitability assessment of outsourcing, relying solely on the opinions of subordinates and not on fact-based analysis. There are two hot spots of such a situation because of non-participation of management in the process mentioned: either the leader himself ends up with an inability to implement changes or the team that are carrying on negotiations may misunderstand the value of service and its end goal.

➤ **Misinterpretation of contractual issues**

Here are issues that may occur early in a project: unprepared team of the client may interpret terms and conditions of the contract in its own way, while as outsourcing team may operate in the way they know and trust to operate not taking into consideration the specific nature of client's business.

It may also happen that too many people are involved in the implementation of any outsourcing project that are forced in a shortest time to commence performance of new functions without the adaptation period required. In turn, this results in misinterpretation of contractual issues.

➤ **Understaffed or poorly managed client's team**

There is a case when a client's team that is involved in outsourcing project is too small or poorly managed. Such a situation occurs when company-client management is concentrated solely on the commercial terms of the contract but not on the performance conditions; therefore, management does not spend enough time to foresee potential shortcomings of the project during the preparation phase to establish a proper team.

➤ **Unskilled client's team**

There is a case when client staff that stays in-house has an insufficient skill base to fulfil new functions within the framework of the project. Frequently, signing maintenance outsourcing contract the management neglect the necessity to train its local team to operate in new conditions or learn new procedures. Experience shows that 60% of employees that must deal with the service providers suffer from lack of such experience; 40% of companies do not provide any preparatory training courses for their employees responsible for contract performance; and only 20% of companies consider providing training to staff.

➤ **Inability of a client to catch up with a backlog**

It happens that during the pre-contract phase organisations try to postpone the solution to some issues planning to cut costs on themselves in the future by using support of outsourcer. However, most of the projects are overwhelmed with current issues hence there is no time left to catch up with a backlog at the end.

➤ **Resistance to change**

Frequently, Russian organisations apply for outsourcing contracts for implementation of new approaches or changes. However, along with willingness to apply changes and get return on investments as soon as possible companies disregard that most of the success depends upon how strictly the new procedures and methods will be followed by them in the first place.

➤ **Cultural clash**

By cultural clash is meant the communication within internal organisational culture as well as issues related to involvement of foreign companies in terms of outsourcing projects. There are issues concerning determination of deadlines of tasks, decisions-making styles in respect of which the outsourcer has one idea and the customer may have absolutely the opposite ideas. Working with Non-Nationals there are issues of miscommunication due to discrepancies in languages and norms of nonverbal communication and translation.

➤ **Changes do not take roots**

Old habits die hard. Therefore, even if the customer provides preparatory training of its personnel the outsourcer may still has difficulties in bringing new approaches. Over time, companies give less attention to have tracking of the change to implementation and assume that positive changes may happen by

themselves. The point is that companies pay less attention to the areas that impact the success of both outsourcing project and business.

4.0 Process risks

Even poor performers have processes, albeit these are often informal and disorderly. High performers have both efficient and effective processes that serve the needs of their people in delivering a high level of availability of their assets [3].

Two examples below show how discrepancies in the processes may impact the relationships between a client and outsourcer.

1. Company-client does not have its own well-developed processes required for management of outsourcing project, i.e. quality assurance process, continuous improvement process, scope changes management process, project management process, etc. When applied it results in the following effects:
 - Process execution of outsourcer is blocked by a lack of corresponding procedures of the customer. The simple example is a customers' inability to define performance assurance requirements (or approve requirements that were preliminary provided by service supplier) that allow reaching required level of availability of equipment.
 - Due to lack of its own sustainable processes the outsourcing process is defined and inaccurately understood by customer inaccurate. It leads to unforeseen division of authorities and responsibilities when an outsourcer finds itself responsible for the tasks that he could not accomplish.
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2. Company-client cannot assess properly the level of development of its processes and chose an outsourcer with higher process requirements. As a result, the efficiency improvements of several processes are inconsistent. It contradicts the seamless transition of outsourcing when firstly, a consistent plan of process improvement is to be made; secondly, assessment is to be carried out; finally, the plan is to be revised and approved. In the absence of such plans there are gaps in between internal and outsourced processes.

5.0 Development of effective approach

To mitigate contract management risk, it is best to develop a contract and negotiation plan to proactively document all aspects of the agreement including service level agreements (SLA), escalation procedures, product specifications, transitional requirements, roles and responsibilities, and exceptions. The more successful or-

ganisations have developed comprehensive approaches to project planning and decision making; have employed rigorous tools, frameworks, and methodologies; have demanded excellent cross-functional and cross-company teamwork; and have implemented highly effective risk management, performance management, compliance and control techniques, and disciplines.

Pre-contract consultancy also can sometimes be justified where the provider is very concerned about the risks involved. In such circumstances the provider senior management may feel that any additional cost (for much of the work would need to be done anyway if the contract goes ahead) is well justified.

If pre-contract consultancy is agreed upon, then typically, it will cover:

- The documentation of existing maintenance systems at all relevant sites to confirm the final scope of work for the outsourced services.
- A risk assessment to identify major areas of potential failure or delay in both service delivery and any new approach implementation.
- The production of detailed specification for each function to be transferred and, if relevant, a detailed project implementation plan.

However, the provider could find himself being caught-up in a lengthy pre-contract period during which time it requires to put in a great deal of resources for which he does not get paid. The last case scenario has never been fully avoided but counter-balanced.

6.0 Conclusion

Before proceeding to the outsourcing project, a time- and resource-consuming campaign of negotiation, contracting and preparation lies ahead, where success of the latter depends upon various factors as sales strategy, outsourcing teamwork and thorough analysis of customers' internal environment and procedures.

The customer environment is a given. Unless an outsourcer is by being the OEM build a new facility, the plant, technology, in most cases the people are already there. Customer's current practices, both positive and negative, or somewhere in between are also a given. If they do not match outsourcer's vision they have to be considered for adjustment or change. When the gap between the customer present reality and the supplier vision is understood, it can be closed. Closing that gap will require a collectively agreed plan that gets the client and outsourcer there, and the plan must include all the people, behaviour, system and process that will be involved in the adjustments or changes. The outsourcer should understand what drives behaviour in a client's organisation to influence changes in that behaviour. These activities are the performance drivers for delivering the change happen. They will require the most work.

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Authors' Biography

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Method for a qualitative cost benefit evaluation of process standardisation for industrial services

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Abstract Industrial service providers deliver complex technical services (e.g. inspection, maintenance, repair, improvement, installation and turnarounds) for a wide range of technical assets in process industries such as the chemical industry. Due to the versatility of assets and industries, there is also a variety of the corresponding service offerings. The demand for a high service quality and the general cost pressure leads to the need of a more efficient and standardized design of the service processes. However, cost-benefit ratio related decisions regarding the questions where and how service processes should be standardized entail great challenges for small and medium-sized enterprises. This is because there is often a lack of understanding of cost savings through process standardisation, which is caused by a lack of understanding of the correlations between process characteristics and process target values. Because of this, the goal of this paper is to develop a method for a quantitative evaluation of the cost-benefit ratio of process standardisation measures. Within this method, the relevant service performance processes are selected first. Next, the process data will be recorded with the help of questionnaires. These are then analyzed by looking for correlations between the process characteristics and the process target values. Afterwards standardisation measures are derived on the basis of these findings in order to improve deficit characteristics and thus target values. Finally, the method's practical applicability is tested and validated by applying it to an industrial service in the chemical industry.

Key words Industrial Services, Process Standardisation, Cost Benefits, Lean Services

1.0 Introduction and Objective

Companies belonging to the industrial service sector of the process industry (inspection, maintenance, repair, improvement, installation, turnarounds) are faced

with major market-related challenges in the provision of complex technical services [1]. On the one hand, process industry companies outsource their services, which do not belong to the direct value creation, more and more to external service providers. These service providers, most of them are small and medium-sized enterprises (SMEs), usually do not deliver individual services but extensive solutions which include a guarantee of plant availability [2–6]. On the other hand, the fact that the market is dominated by a few large customers leads to a high cost pressure for the small service suppliers [3,7,8]. In addition to the general competitive pressure on the market, industrial services in the process industry are subject to a high technical complexity. The service objects (machines and plants) vary greatly in type, function, configuration and wear condition. Combined with different requirements on the service creation process, this leads to a high process diversity [1,9–11].

In order to keep a strong position in this competitive market environment, industrial service companies must find a balance between high efficiency and effectiveness in the service provision whilst also offering a broad range of services [3,12]. Increasing the degree of standardisation of the service processes offers the potential of improving the competitive position of industrial services providers. The standardisation of service processes aims at minimising process variance and increasing process control [13]. This entails an increase in customer satisfaction and a decrease in wastage [14]. An improvement of the process predictability and the realisation of process optimisations can be achieved with a high degree of process control, a high process stability [15,16]. A study has shown that large industrial service providers who standardize their processes to a high degree are more successful than those who do not work with standardized processes yet [17,18]

In contrast to the large service providers, SMEs rarely repeat individual service process variants and thereby the standardisation of individual process variations only leads to small increases in efficiency for them. Furthermore, decision-makers cannot usually quantify in advance without major efforts which cost-benefit-relation results from standardisations. Thus, SMEs can only initiate standardisation measures on the basis of subjective assumptions [19]. Due to the subjective decision, there is a risk that costs and benefits will be misinterpreted. Because SMEs only have limited resources in general, they cannot afford to initiate standardisation projects that do not promise a positive return on investment. The high effort required to estimate the cost-benefit-relationship and the high risk of failure due to lack of information often keeps SMEs from driving process standardisation forward and from implementing improvements and thus enhancing their competitive situation [10].

Consequently, industrial service SMEs for the process industries often lack a well-founded, practicable and efficient method based on quantitative process data for the evaluation of standardisation potentials and the derivation of standardisation measures. To close this research gap, the aim of this paper is to develop such a method. Using this method, the existing service process is recorded, relevant pro-

cess data is collected and analyzed with regard to standardisation potentials and as a last step, standardisation measures are derived from this data-based information.

2.0 Theoretical Framework

2.1 Industrial services

In this paper, industrial services in general are defined based on their process characteristics [20]: They are independent, marketable outputs which are provided at an external factor (e.g. an object of the customer) specified by the customer. The external factor is integrated into the creation process of the service provider. This service process is beneficial for the external factor [21]. Industrial services are investment services which, as opposed to consumptive services, are not consumed by the end user, but instead are an investment into industrial companies [22]. Thus, industrial services are usually product- and machine-related services which are provided to technical objects of commercial clients [23]. Like production processes also service processes contain a logically and substantially complete chain of activities with defined input values (inputs) and process results (outputs) [24].

2.2 Standardisation of industrial services

In general, the term standardisation refers to all forms of unification of objects. With regard to processes, standardisation is commonly understood as the anticipated thinking through of activity sequences, which allows these sequences to be performed more routinely and uniformly when repeated [25]. The integration of the external factor as the process characteristic of services prevents a complete standardisation of services [26]. The possible degree of standardisation of a service process first and foremost depends on the heterogeneity and the requirements of the external factor [27]. In the technical literature, there is no commonly accepted measure for a direct evaluation of the standardisation degree of service processes. Frequently, the degree of standardisation is distinguished only qualitatively, for example by the means of the values low, medium and high [17,20]. In the process of transferring methods of lean management, Six Sigma and Lean Six Sigma, to the service sector, first approaches for a quantitative recording of the stability and quality of service processes have been developed and applied [23,28–30]. Examples for this are the recording of the cycle time, first fulfilment proportion, timeliness and query frequency [23,30]. These quantitative values, usually called key performance indicators (KPI), provide information on the quality of the regarded service process in comprised form [23]. However, the actual degree of standardisation cannot be measured by these KPI.

3.0 Method

The aim of this paper is to develop a method that can be used to investigate the predominant stability of execution processes in industrial services and to derive effective standardisation measures to increase process control.

Process-related methodological requirements are derived from the industry and application reference. First, a large number of similar but not congruent execution processes have to be analysed using the method on the basis of service orders actually performed. In addition, service orders have to be recorded using suitable characteristics with disjoint characteristics and target values of cost, time and quality dimensions. From a scientific point of view, the method has to be characterised by practicability, a high cost-benefit ratio and the use of quantitative parameters.

The method described in this paper is a solution system that models the reality by using representative data, analysis tools and measures. In practice, it is common to design such a method on the basis of a framework. The generic phases of process management are the used framework for this method. This framework consist of (1) the process identification, (2) the actual process analysis, (3) the target process design and (4) the change programme [31–33]. During the process identification phase, the core processes are identified and the area of examination is narrowed down with an evaluation of process effectiveness and efficiency. During the second phase, the selected processes are investigated further with the help of analytical methods. Making the employees a part of this analysis is an essential factor in developing problem awareness and recognizing improvement opportunities. During the third phase, possible target process scenarios are outlined based on the previously identified weaknesses. For this purpose, company-specific characteristics such as the existing organisational structure or the degree of the employees' qualifications need to be considered. In the fourth phase, measures for the realisation of the target processes are developed, prioritized and organised according to a hierarchy for further processing [31].

4. Results

Following the four phases of general process analysis, the developed method also consists of four individual steps to be performed one by one (**cf. figure 1**). During the first step, it is to be decided which area of the process is to be focused during the analysis. In a second step, the collection of process data is prepared and data is conducted. A standardized questionnaire serves as a tool for the data conduction. In the third step, the collected process data is analysed with the help of statistical methods. In a fourth step, suitable measures for process standardisation are defined based on the data analysis results, prioritized and transferred to a hierarchy. Subsequently, the applicability of the resulting standardisation method is validated in practice.

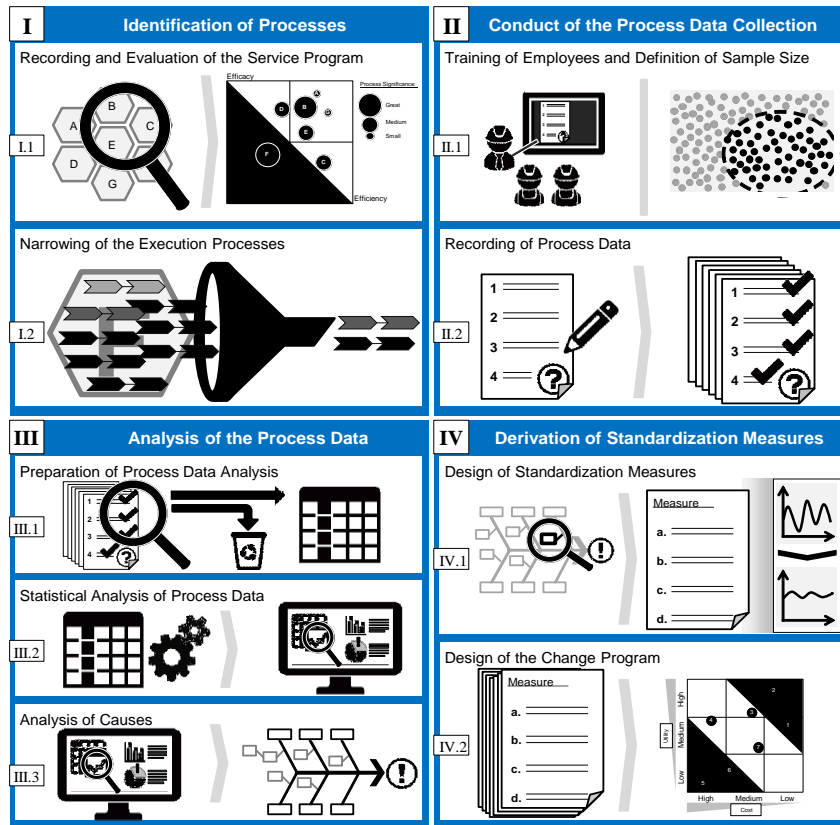


Figure 1: Scheme of the sequence of the individual steps of the method

4.1 Identification of processes

In practice, industrial service companies find themselves confronted with a low process stability of the services they offer. Because of this lack of stability, it is not advisable to decide which specific area of the process should be inspected beforehand. Instead, the first sub step of the process analysis (**sub step I.1**) is used to identify the process section of the company involved that holds the biggest potential for standardisation measures. In order to do this, the processes are recorded. Based on these records, each of the services is evaluated with regard to its profit share and execution frequency. The evaluated processes are all arranged in a portfolio to provide an overview. From this overview, those services are selected that are repeated frequently and contribute to a large share of the general turnover. In a second sub step (**sub step I.2**), the execution processes are narrowed down further with the help of nine pre-defined process characteristics with a morphology. The evaluated process characteristics are (1a) incoming type of order, (2a) information

quality regarding resources, (3a) information quality regarding location, (4a) information quality regarding the order, (5a) informative value of the customer, (6a) type of interaction, (7a) availability of technical documents, (8a) task routine and (9a) object routine. The seven target values are (1b) on-schedule performance, (2b) external inquiry rate, (3b) internal inquiry rate, (4b) interruption rate, (5b) complaint rate, (6b) internal error rate and (7b) rework rate. These characteristics and values help to describe different service scenarios clearly. They also help to ensure the comparability of the services that are analysed.

4.2 Conduct of the process data collection

As a first sub step (**sup step II.1**), the sample size to be analysed for statistically significant evidence need to be calculated and which processes are to be included. Following this, it is necessary to train the operative employees who will be in charge of the process data collection. The training they receive is aimed at establishing a better understanding of the process analysis background as well as passing on knowledge on how to collect the process data required for the analysis, so that the data of various employees documented in the questionnaire is as objective as possible. After the employees have received the training, the process data will be collected as part of the overall second sub step of the conduct of the process data collection (**sub step II.2**). Depending on the service requests of the service company, this can take weeks. In this sub step, operative employees evaluate performed service orders with the help of the questionnaire subsequently to the performed process and submit the questionnaire to an independent analyser.

4.3 Analysis of the process data

In the first sub step of the third part (**sub step III.1**), the collected process data is prepared for the following statistical data analysis. First the questionnaires are checked for completeness. Questionnaires that fall short of a previously defined degree of completeness are not used for the analysis. If questionnaires need to be excluded, the overall size of the analysis sample will have to be reconsidered in order to ensure that it remains representative. If the minimal sample size is not reached, further the data of additional processes need to be collected.

In the second sub step (**sub step III.2**), the statistical analysis of the process data is performed with the help of a contingency analysis. The aim of this is to identify and evaluate correlations between process characteristics and process target values. For this, variables pairs, consisting of one process characteristic and one process target value, are examined. In order to keep the analysis effort on an adequate level, the process characteristics with a high degree of variance and the process target values with a low degree of target achievement are identified. Subsequently, the statistical analysis is conducted for the selected process characteristics and process target values. Therefore, contingency tables are compiled and the statistical independence of the variables is examined. If the independence of the variables can be calculated, a statistic dependence will be assumed. Afterwards the corre-

lations between process characteristics and target values are evaluated using the test values ϕ (Phi), *Cramer's V*, the contingency coefficient *CC* and Pearson's *r*. The test values help to judge the strength and a possible linearity of the correlation. In the third sub step (**sub step III.3**), the causes for insufficient process performance are analysed by derivation from the time- and cost-related effects of low process performance. This sub step aims to identify the biggest improvement potentials and to uncover the reasons for low process performance. The fundamental causes for low process performance can be identified with the Ishikawa diagram method.

4.4 Derivation of standardisation measures

As the first sub step of the fourth phase, a workshop is organised in order to use the previously identified causes of low process performance to derive standardisation measures (**sub step IV.1**). When applied, the measures must decrease the variation of the process characteristics and, as a result, increase the overall process stability. For each fundamental cause, at least one standardisation measure should be derived. The designed measures then need to be evaluated with regard to the preferences of the affected stakeholders, the approach and the anticipated benefit. In the second sub step of this phase (**sub step IV.2**), the interdependencies between the measures are identified. Afterwards, the benefit and the effort of the measures with regard to the previously identified improvement potentials are estimated. Finally, the measures are compiled to a change program under consideration of their interdependencies and their effort-benefit relation.

4.5 Practice Validation of the method

In order to prove that the developed method fulfils the previously defined requirements, a validation was carried out in practice. Real data (i.e. service orders) from industrial services for the chemical process industry were used for this purpose. With the help of the method we established before, 84 service orders from the day-to-day business of industrial service companies were examined. Amongst these, most services regarded the topic of technical maintenance in accordance with DIN 31051, but some were also related to plant, container and pipeline construction [34]. Questionnaires for these processes were given to the responsible service employees. Out of a sample of 84 filled out questionnaires 76 had a sufficient extent and were used for the further analysis of the processes. The application of the designed method lead to the following results: The investigation has shown that 13 (17,1 %) of the processes didn't met the scheduled time, there were external inquiries in 15 (19,7 %) processes, internal inquiries in 10 (13,2 %) of the processes and 21 (27.6%) of the processes had to be interrupted. This deficient led to 3906 working hours per year which were not used as effectively and efficiently as possible, because processes do not yet meet the anticipated process targets. Within the analysis of the process data the process characteristics (1a) incoming type of the order, (2a) information quality regarding resources, (4a) information

quality regarding the order and (7a) availability of technical documents correlated significant with the deficient process targets. That means this characteristics have the highest standardisation potential. Based on this outcome, five suitable standardisation measures could be derived and the quantitative benefit of each possible measure was estimated. The two most beneficial of these measures are (I) a development of a standardized order acceptance form and (II) an external customer order program. If only these two measures were implemented, approx. 2100 working hours per year could already be saved and used more efficient.

5.0 Discussion and Conclusion

In this paper, a method for the analysis of service provision processes in the industrial service industry was developed. The four-phase structure of the method meets the industry- and process-related requirements. As the validation with real industrial process data proved, the method can be easily applied in an industrial context. The results of this validation showed that the application of the suggested method does lead to a very high benefit for the company involved: precise standardisation potentials were identified and quantitatively evaluated. The effort required to apply this method was less than that needed to apply conventional methods such as a fundamental standardisation of the complete service portfolio, because a large number of similar process variants could be investigated in one analysis step and only standardise the most significant characteristics for insufficient process target values, making our method quicker to use and more efficient. The requirement to use quantitative parameters for analysis for a cost-benefit assessment was also fulfilled by providing process target variables of the three dimensions cost, time and quality. By applying the method in the validation within a industrial service environment, more than half of the wasted working hours could be attributed to process characteristics and reduced by only a few standardisation measures. Restrictions of the method are, however, that typically only parts of the execution processes of a company can be analysed, since the method cannot be used parallel or sequentially to the execution of the performance processes. Furthermore, the effort for the application of the method itself should be further reduced. Designing and using the questionnaire (handing it out, filling it out and collecting it again) is time consuming and the statistical analysis should be automated for a wide use in the industry. A third challenging aspect is that the quality of the process data collected depends on the accuracy of the information provided by the surveyed employees who complete these questionnaires.

In the future, the method should be tested in other companies in the industrial services sector and other sectors and improved on the basis of this experience. The data acquisition and data evaluation should be further improved. For example, an efficient and parallel process data input and direct evaluation of the entered data would be conceivable. In conclusion, however, it should be noted that the developed method has clear advantages for the field of application of the industrial ser-

vices industry compared to other, already more common methods of process optimisation. It is a self-contained and practical approach.

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Maximilian Lukas studied industrial engineering, raw material and materials technology at RWTH Aachen University with a focus on raw material extraction and innovation management. Since 2013 he has been working as a research assistant and project manager at FIR e.V. at RWTH and is a member of the Lean Services group. His activities at FIR include the development of an industry 4.0 maturity model for manufacturing companies together with a globally active IT company. In addition, Mr. Lukas deals with the topic of service performance measurement in various industries, such as the wind energy industry and industrial services, as well as the professionalisation of after-sales service, maintenance and industrial services with established methods from the material goods industry.

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Tobias Leiting studied mechanical engineering with a focus production engineering and economic science at RWTH Aachen University. Since 2017 he has been working as a research assistant and project manager at FIR e.V. at RWTH. As part of the Lean Services group, Mr. Leiting is dedicated to the systematic improvement of (data-based) services by optimizing services with a focus on value added. In addition, he supervises studies on services in the context of digitisation.

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From 2004 to 2011 Philipp Jussen studied mechanical engineering and management at the RWTH Aachen with a focus on production engineering and financial services. Since 2011 he is project manager at FIR e.V. at RWTH Aachen (FIR) in the field of service management. The focus of his work in the Lean Services group was on the design and optimisation of service processes. Since 2013, he has headed the Lean Services division. Since 2015, he has headed the services management division of FIR. The Department researches and advises compies on the design and implementation of data-based services.

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Creating Competitive Advantage by Transforming Maintenance Organisation

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Abstract Process industry is typically characterized by high capital expenditure (CAPEX) needs, complex sites with thousands of pieces of equipment, long distances, and a large degree of interdependency between those pieces of equipment. The main aim of a site is to achieve high overall equipment effectiveness (OEE) and to achieve a healthy return on capital employed (ROCE). Maintenance is the main driver for attaining the required OEE level. The characteristics of a process site like a pulp mill make it difficult to carry out efficient and effective maintenance. This requires a well-designed manufacturing organisation, efficient processes, and a practical reliability strategy.

Key words Process industry, maintenance organisation, reliability-centered maintenance, OEE improvement.

1.0 Introduction

A newly built site in process industry requires high CAPEX. The necessary investment to develop and build a new line of a pulp mill can often be more than \$2 billion. Shareholders expect a substantial ROCE; a typical ROCE in this kind of industry is higher than 6%, best in class companies reach above 10%.

Maintenance is an important driver for reaching this target. On the one hand, maintenance strategy and execution have an important impact on OEE, which translates to how effectively the installed capacity is used and therefore how much a site can produce and sell. On the other hand, the cost of maintenance, especially for regular turnarounds (TAR), reflects a high share of operational expenditures (OPEX).

Process sites are typically characterized as follows:

1. Flow production: Nearly all equipment is linked. A problem in one item often leads to a problem for the whole site, even resulting in needing to stop of the whole production line with a highly negative impact on the total OEE.
2. Substantial amount of equipment: A process site often has more than 10,000 pieces of equipment installed
3. Large size of site: A process site often covers several square kilometers; the BASF site in Ludwigshafen, for instance, covers around 10 km².

These points make it challenging to carry out effective and efficient maintenance. Two key issues need to be addressed.

1. How to structure the maintenance organisation to cover the size of the site and the immense complexity of equipment
2. How to ensure high site reliability with a manageable effort given the high number of equipment

2.0 Case Study

One of the largest pulp mills located in Chile wanted to increase EBIT by over 20%, the main drivers being total OEE improvement and a reduction in maintenance cost.

The site covers 1.7 km², produces about 750,000 tons per year, has an installed base of more than 18,000 pieces of equipment, and employs more than 200 people in maintenance.

To achieve the target a program with three main pillars was launched (see figure 1).

1. Improve maintenance governance by implementing a best-in-class maintenance organisation as a foundation for efficient processes and effective maintenance strategy.
2. Improve maintenance execution by optimizing routine maintenance processes, eliminating root causes for equipment failures and optimisation of turnaround to reduce maintenance cost and improve OEE.
3. Improve maintenance strategy by focusing on reliability and moving towards predictive maintenance as the main driver for OEE improvement.

Transformation program with three pillars

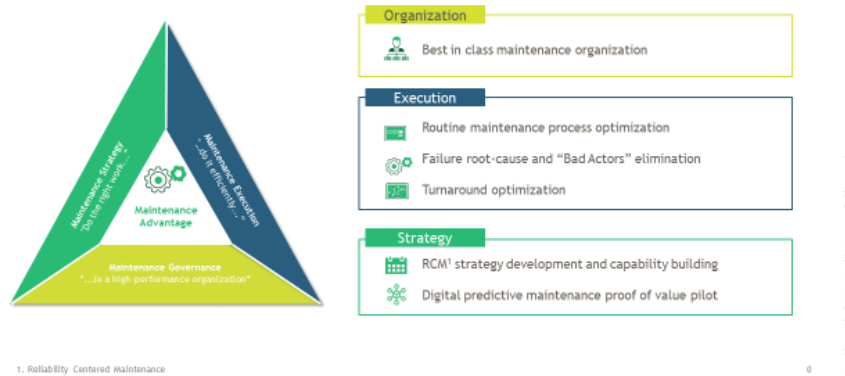


Figure 1 Maintenance transformation program

2.1 Maintenance Governance

The structure of maintenance organisations sets the foundation for high efficiency in processes and enables an effective maintenance strategy. Defining a maintenance organisation at complex production sites typically found in process industries requires the optimisation of three dimensions.

1. Focus

Three main maintenance roles can be distinguished, each role has different aims and needs different skill profiles: strategy, planning, and execution. The maintenance strategy defines what equipment should be maintained in what way to increase reliability: run to failure, planned maintenance, or predictive maintenance. Maintenance planning develops the detailed maintenance plans, in other words detailed steps and processes, tools, and spare parts. Maintenance execution goes through the processes according to maintenance plans. The organisation must allow for these activities to be focused on.

2. Specialisation

If there are a lot of different kinds of equipment installed at a site, special technical skills are required to maintain them. The maintenance organisation must then reflect these requirements.

3. Proximity

The size of the site may dictate a compromise between proximity and bundling of activities and skills. Long travel distances between pieces of equipment lead to more non-value-adding time and therefore low productivity. So local maintenance teams in close proximity to the areas

and equipment in question are better off in terms of wrench time and people management. However, this would require a high number of employees to cover the skills required, which often leads to low utilisation, thus increasing cost. Ultimately, it's necessary to strike a balance between bundling and local teams.

The Chilean pulp mill decided to structure their maintenance organisation along the three main roles,

- strategy with a reliability department,
- planning with a dedicated planning department, and
- execution with two central maintenance workshops (electrical and mechanic) and two field maintenance departments (liquid and pulp areas).

Execution already reflects the proximity and specialisation topic on the first organisational level. Within all departments the next levels are structured along required skill profiles (specialisation)—see figure 2.

Defined organization with clear focus and specialization

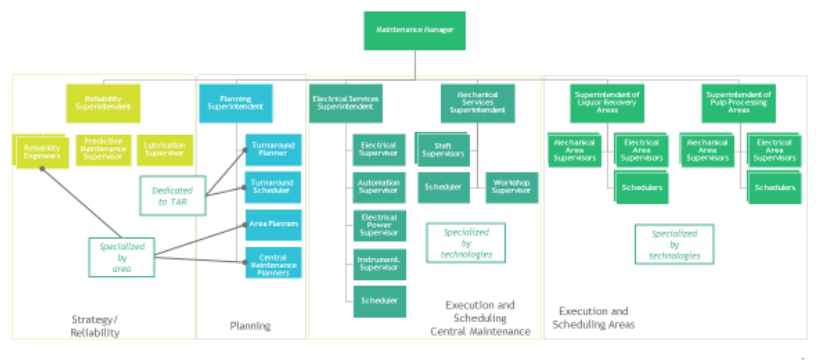


Figure 2 Maintenance organisation chosen by a pulp mill

2.2 Maintenance Execution

Maintenance execution greatly influences overall maintenance costs and also has a significant impact on OEE. To improve both—reduction in cost and improvement in OEE—three levers can be addressed.

1. Improve routine maintenance processes
In maintenance, more than 50% of maintenance activities are typically recurring activities like inspections or regular replacement of parts.

Optimizing these activities can reduce the cost of maintenance significantly. In routine maintenance, a lot of waste is hidden: long travel distances to installed equipment, missing tools and spare parts, high variance in process times and quality, and lack of knowledge of standard times in planning, all of which lead to low utilisation. Lean manufacturing [1, 2] offers a set of valuable levers that can also be transferred to maintenance. Recurring tasks can be standardized. Detailed standard operation procedures (SOP) describe step-by-step in an easily understandable way how an activity has to be done, which tools and spare parts need to be used, what the standard duration is, and which activities need close attention to avoid safety risks and quality issues. SOPs should define best practices; they are the basis for continuous improvement based on plan-do-check-act (PDCA) [3]; following is not optional, it is mandatory. To avoid stockouts in spare parts, a pull system based on kanbans can be used. Holding daily meetings within maintenance departments, as well as in cooperation with operations, delivering performance, addressing key issues, and discussing root causes and improvement activities all form the foundation for continuous improvement.

2. Establish routines for continuous improvement to eliminate root causes for failures

At process-industry production sites, many “bad actors” can be found. A bad actor is an item of equipment with either a high cost—repair costs plus cost due to downtime per single intervention—or high total cost due to high number of interventions. A typical bad actor analysis for a pulp mill is shown in figure 3.

Two groups of bad actors: Infrequent but high cost interventions and frequent low cost interventions

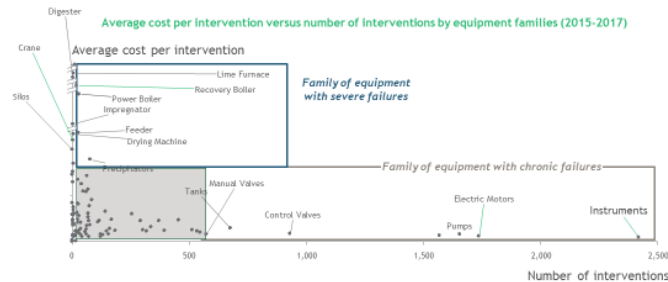


Figure 3 Bad actor analysis at a pulp mill

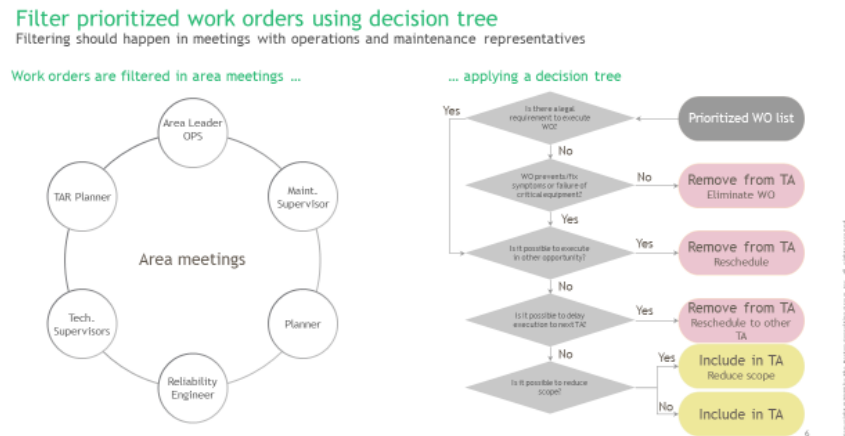
The reduction in cost caused by bad actors requires a systematic process for identifying and eliminating the root causes. The process has to be easy and fast because this is not a one-time effort—it has to be gone through

regularly to improve site performance step by step. A simple and proven approach is to employ a combination of an Ishikawa diagram [4] and the 5 Whys [2]. Within the first step, all failures of bad actors will be statistically analyzed and prioritized, and potential root causes will be identified in a combined maintenance/operations workshop facilitated by reliability engineers and using an Ishikawa diagram. For the second step, these potential root causes will be prioritized and drilled down by using the 5 Whys to find the primary root causes. Measures to prevent these root causes will be defined in the last step. Eliminating these root causes leads to a reduced cost of maintenance and higher OEE due to less breakdowns and production stops.

3. Optimize turnaround management

Cost of turnarounds are by far the highest share of maintenance costs, TAR often represents 50% of total maintenance cost. Furthermore, TAR means a regular production stop of several weeks, which leads to a loss in OEE and therefore to a loss of contribution margin. TAR optimisation has to focus on two main topics.

- Reduction of duration and frequency
For TAR, production must be stopped. The more time is spent for TARs each year, the more OEE losses are. To reduce TAR time, the duration per TAR or frequency of TARs can be reduced. Improvement in TAR management is the biggest lever to reduce duration. A TAR needs to be well planned. For preparation, every activity must be defined, the required spare parts must be ordered, and contractors must be assigned and trained (e.g., safety training). During TARs, all activities must be monitored regarding time to plan and budget to plan. Responsible are the TAR planner and scheduler; due to their dedication to TAR they can focus on these activities. The frequency of TAR can sometimes be challenged: for example, the pulp mill changed the frequency from 12 months to 18 months without a negative impact on reliability.
- Reduction of cost per TAR
The scope of a TAR is the main driver for cost per TAR. Some planned task are often not required. The implementation of a gate-keeping process (figure 4) is a powerful lever for reducing the scope to the required level. A clearly defined decision tree should be used to reduce the scope to the required level without increasing the risk for reliability of the site. The decision should be aligned between maintenance and operations.



2.3 Maintenance Strategy

Reliability-centered maintenance

High OEE is key for process-industry production sites, as explained above. That means reducing unplanned shutdowns as much as possible. A traditional approach for reducing all kinds of risk is reliability-centered maintenance (RCM). The aim of RCM is to minimize the risks for safety, health, and environment, as well as the sum of maintenance costs and loss in contribution margins due to shutdowns. Therefore for each piece of equipment, the function of the equipment is defined and potential malfunctions and root causes are identified. Each cause has to be classified based on its potential severity and probability. Significant risks have to be mitigated by countermeasures, which can include inspections or preventive or predictive maintenance activities; for low-risk equipment, run-to-failure can be the right strategy—in theory at least.

As described above, a process-industry production site can have thousands of implemented pieces of equipment, following the aforementioned approach would take considerable effort that will never be paid back. For practical reasons a lighter approach is required.

Not every piece of equipment requires the same depth of analysis. Most companies start with RCM at a site where maintenance plans are already in place and have been followed for years. This leads to four different strategies; the decision tree in figure 5 supports the decision about strategy

- Critical, single pieces of equipment
If equipment is critical (safety/health/environmental [SHE] risks, risks of production losses) a full RCM should be done to mitigate risks.
- Critical equipment families (SHE risks, cost risks)
Similar equipment, for which differences in specific functions are negligible, can be treated as a group. RCM will be done for this group instead of each single piece of equipment.
- Critical equipment (SHE risks, but low cost risk)
A general review, which means monitoring the equipment, is the right strategy; this means collecting data based on inspections and failure reports and treating them as bad actors.
- Noncritical equipment with low costs and no failures in the past
This kind of equipment does not need a special analysis, the current maintenance strategy can be kept. Monitoring this equipment will show if additional analysis is required in the future.

Decision tree defined which pieces of equipment were going to be reviewed and which ones would keep current maintenance strategy

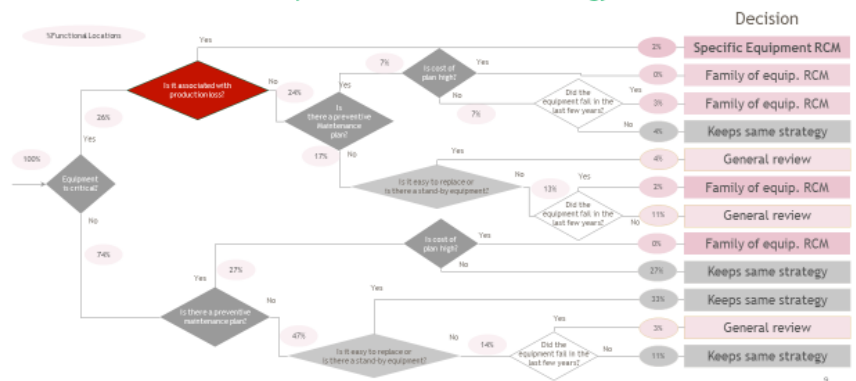


Figure 5 Decision tree for reliability-centered maintenance strategy

Predictive maintenance

The aim of predictive maintenance is to predict equipment failure and to prevent it. This is much more efficient than traditional preventive maintenance where parts are changed simply based on time of usage or similar strategies; sometimes that is too late, which leads to breakdowns, or too early, which leads to high cost. In

predictive maintenance, the condition of individual pieces of equipment is monitored to identify the right time for intervention. Monitoring can be done by visual inspections or by measuring parameters with sensors. At process-industry sites, there is typically a plethora of sensors in place, but data is not utilized effectively. Some reasons include a lack of data collection and sharing due to limitations in technology or capabilities for analyzing the data, which can easily reach the dimension of tera- or petabytes. New technologies, like cloud-enhanced sensors and edge technology that preanalyze data, and advanced analytics models offer options for getting more out of the data and enable an organisation to adopt predictive maintenance approaches. To test the power of predictive maintenance, data from pumps were collected and analyzed. The result is impressive: by using that data and developing a predictive maintenance model, 85% of failures could be predicted, which translates to a reduction of 15% in material cost and 20% in labor and service cost (see figure 6). To anchor predictive maintenance within an organisation, a specific skill set is required that is normally not found in maintenance organisations. A dedicated position for predictive maintenance is defined in reliability departments for an engineer with a data scientist background.

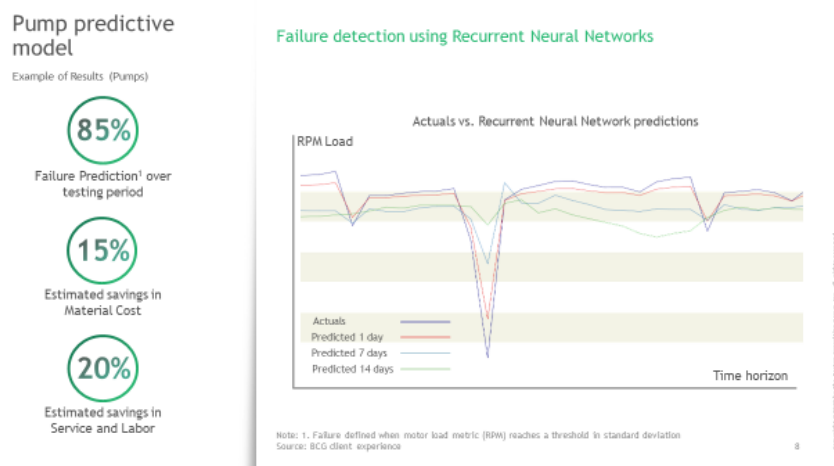


Figure 6 Decision tree for reliability-centered maintenance strategy

4.0 Conclusion

The pulp mill decided to run a full maintenance transformation program given the complexity of the manufacturing processes and site. The expected improvement of EBIT over the next years is more than 20% (figure 7). To achieve this, rigorous project management is required with close monitoring of the status and the involvement of whole organisation. A culture change is required. This can only be

achieved if you mobilize the whole organisation and change the boundaries people are used to working in. People generally act rationally [5]. If the aim is to change their behavior, the context they work in needs to change (figure 8). Some examples of how the work context was changed at the paper mill include introducing new performance metrics, implementing new daily cross-functional meetings, and introducing new roles in the organisation.

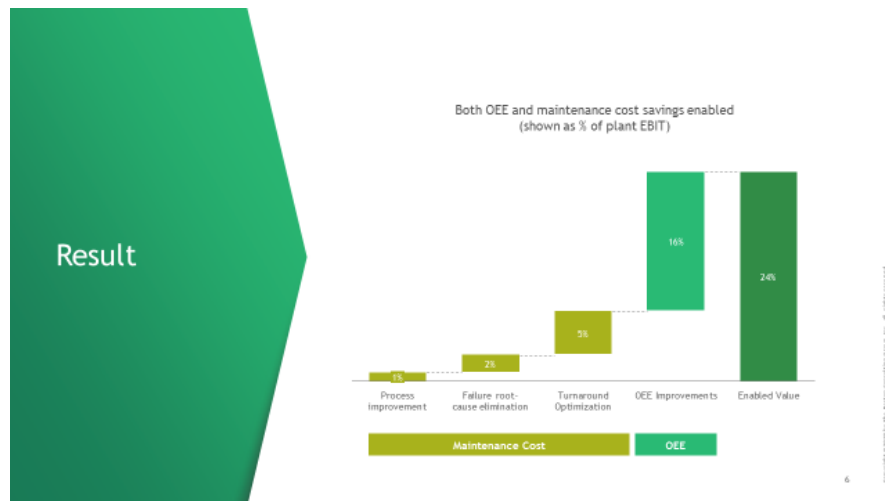
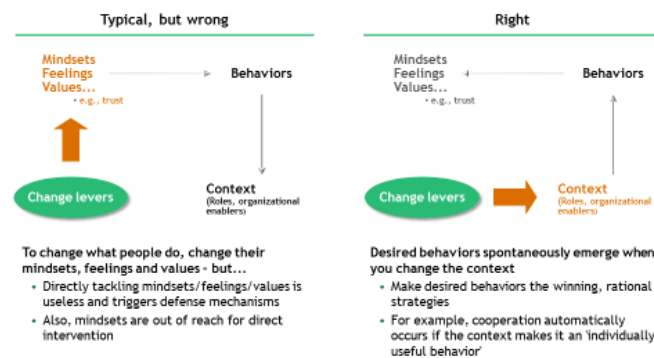


Figure 7 Financial results of transformation program

Need to change the context to change individuals behavior



Source: Y. Morieux (2011), 'Resistance to Change or Error in Change Strategy?' in: From Taylor to Today: The Multimedial Encyclopedia of Organization Theory, Edited by Jörgen Gossard, Research in Organization



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Figure 8

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ME2018_1110

Forest Maintenance Management centred on Biomass Collection

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Abstract This work intends to present a way of planning the preventive logistics management (in which the fires occurrence is concerned) similar to the maintenance work orders management. In fact the preventive actions on the forests ground must be always understood as maintenance actions.

In fact, in Portugal the problem with forest wildfires increases partially because of the consequences of climate changes. Throughout the years, the number of fires and area burned has increased. In this work the maintenance actions to be carried out upstream are focused on biomass collection and use.

Two different work orders flowcharts are presented both municipality centred being one of them initialized in the municipality forest management service and the other by forests owners' initiative.

Key words Biomass Collection, Work Order, Flowchart, Preventive Maintenance

1.0 Introduction

According to [1], consensus on the need for international co-operation to combat climate change has resulted in increased attention to the role of forests in storing carbon and the large quantity of CO₂ emissions that could be avoided if deforestation was halted. Deforestation and forest degradation are the second leading human cause of CO₂ emissions contributing to global warming. [1]

Furthermore climate changes press towards urgent solutions to get a better forest management and a preventive action in two steps. The second step concerns the forest security and the first step includes all the actions leading to the forest treatment and management in order to decrease the probability of fire deflagration. This work is focused only on the first step. On the other hand [2] states that forest

wildfires are a major problem to Portugal. And, of course, forest wildfires are a main type of forest degradation.

This problem requires a strong policy of prevention. The prevention can be done by two different approaches. The first concerns the public fire education and awareness, since more than 50% of the wildfires in Portugal are due to careless or criminal behaviour. The second depends directly on preventive silviculture, with fuel reduction, selection of species and many others actions [2]. Among these actions, preventive collection of biomass must be encouraged but prior to that a complete information system must be conceived in order to assure collection logistics, storage, analysis and, depending on analysis results, biomass processing for use (burning, incorporation as raw material for pellets, etc.).

The author intends to show how this information system can be managed as a maintenance management information system. Needs for biomass collection will be treated as maintenance work orders.

Biomass use can be a way for income generation, both for forest owners and municipalities but this is not the aim of this work and so it will not be discussed here even if the author agrees that forest owner's stimulation for biomass collection is a major factor to achieve a good result in fire prevention.

2.0 The Municipality Centred Preventive Action

Recently in Portugal the Government transferred to the municipalities the coordination of the above called first step preventive actions. So, the forest management information system is centred, at this level, in the municipalities.

All the actions to be performed by the municipality are from now on called internal actions. Most of them are new challenges and new services are needed to perform them. However some other actions must also be managed by the municipality. If so these actions must be outsourced to several external entities.

The internal services and the general outsourced entities are characterized in the following. The names used here can be different from others already used in several regions and situations.

2.1 Internal Services

A specific service for preventive maintenance forestry management must be charged of all municipality logistics (including the collected biomass storage between the collection and the processing moments) and work preparation closely linked with the forest owners and the external companies and laboratories evolved in the process. This service will be called, for instance, “Municipal Maintenance Forestry Management Service” –M3F. Under this service or under a general maintenance service a “Municipal Forestry Brigade” (MFB) must be created for the work execution on place (forest). Some other “municipal services” (MS) can be called to work in this process but may be they already exist (services already using biomass, transport services, etc.).

2.2 External Services and Plants

Besides the internal services, some external services (EXT) and process plants must cooperate in the process on a regular basis. Among these and first of all the analysis laboratory is crucial for the process. This laboratory must be charged of the collected biomass analysis in order to decide of the recommended uses.

Together with laboratory, external outsourced collection brigades (work suppliers) must be included, if necessary, when advisable in the process. The maintenance management software must be conceived in such a way that all these situations can be possible and easily managed.

The other entities to work with are the different kind of biomass users, namely boilers users, several types of process transformation plants (pellets, for instance) and so on.

All these intervenients are indicated in the next section in the flowcharts aside the actions representation.

3.0 Information System and Flowcharts

For the information system illustration two situations are represented under the form of flowcharts, the first being the work orders automatically initiated by M3F and concerning the regular and predicted forest maintenance biomass collection actions. The second type of situation is a non-predicted situation to be initiated by

the forest owner by calling to M3F and asking for the biomass non-regular collection. This can be made by phone or e-mail and always must be validated by M3F. As these are non-predicted actions they probably are completely outsourced and so the first flowchart is represented as on site action being carried out by municipal services and in the second these are represented as outsourced actions.

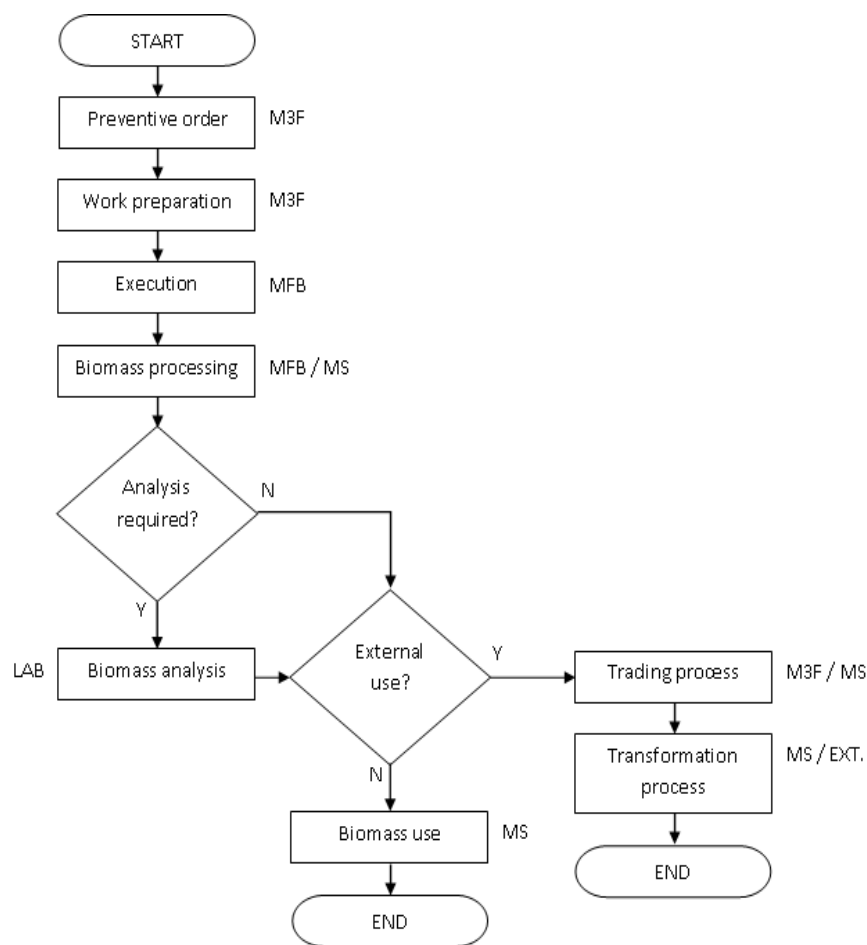


Figure 1 M3F regular work order

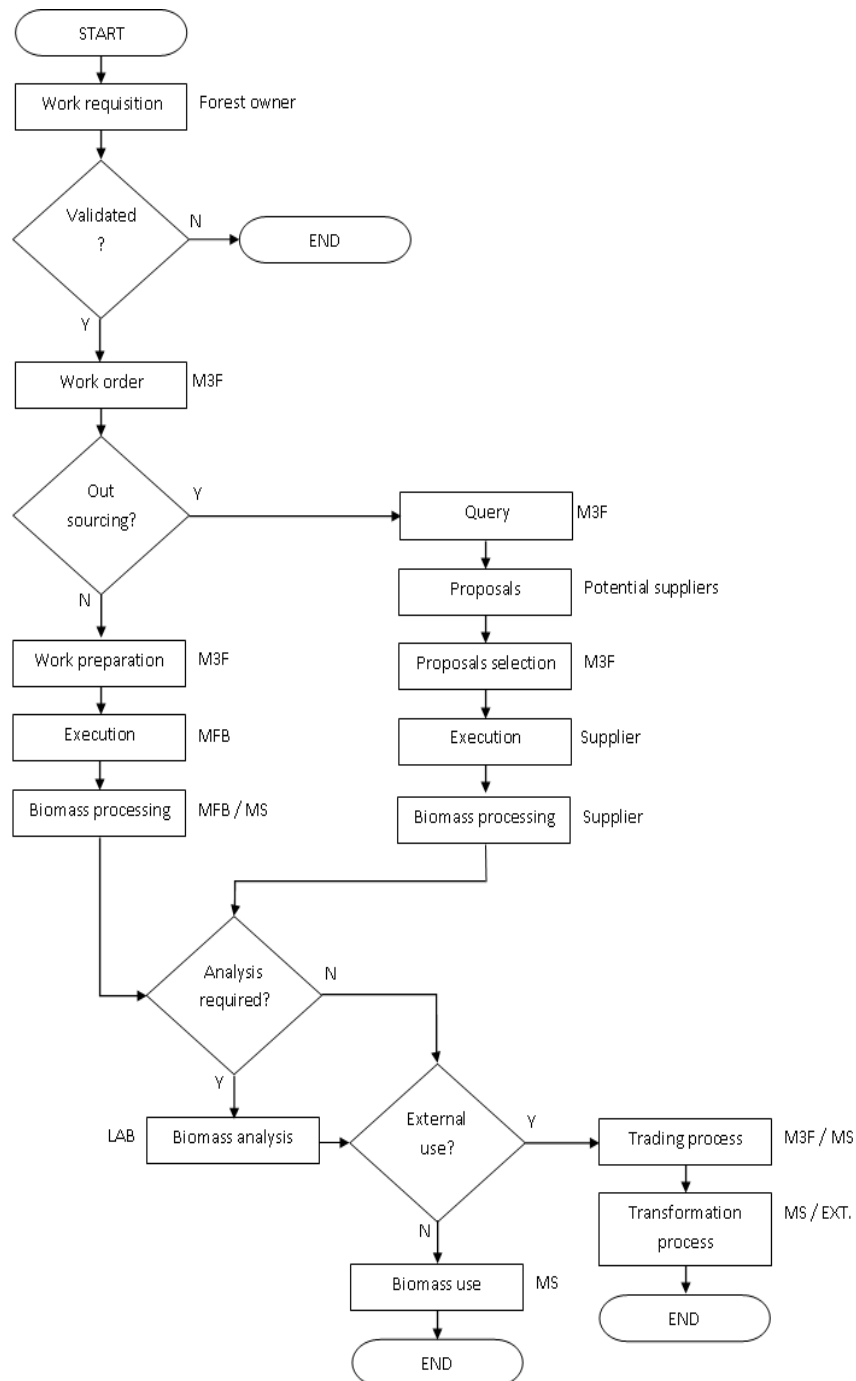


Figure 2 Forest owner request


4.0 Conclusion

The information system for a preventive forest biomass collection was designed. For the first step of prevention the action centred on the municipalities is advisable and so, the work orders can be managed according to a maintenance management system and service and through a maintenance management software. There is no need of a specific management software being possible to find completely marketed solutions.

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ME2018_1111

Solving Gearbox Frequent Failure Problem

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Abstract Power plant contains three water-cooling towers with a total of 30 fans. 27 out of the 30 fans experience frequent failures on their gearboxes. It is observed that the frequent failures lead to high maintenance cost. Vibration measurement can predict the presence of a fault at early stage so that maintenance activity can be planned before failure. Operation Deflection Shape (ODS) used to analyse the gearboxes problem and based on the observation the root cause of the frequent failure was found. Paper also highlights the findings after implementation of the modification to all fans.

Key words Power Generation; Combined Cycle Gas Turbine; Gearbox; Condition Monitoring; Operation Deflection Shape

1.0 Introduction

Power station consists of three identical turbines with total power energy of 1135MW. Each unit has its own condensate cooling tower which contains ten fans (five per row) for forced cooling of the condenser water. Figure 1(a) and 1(b) shows pictorial representation of the complete cooling tower as well as the fan and its gearbox. Each fan has 6 blades and driven by an electric motor which is situated outside the fans' stack. The electric motor is connected to the fan through a gearbox. The schematic diagram of the gearbox together with the motor and fan shafts is shown in Figure 2.



Figure 1 (a) Cooling tower, (b) a motor-gearbox-fan assembly

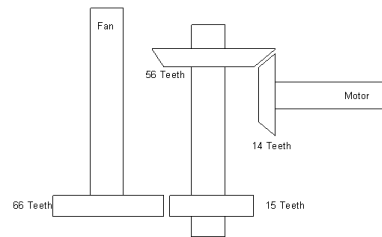


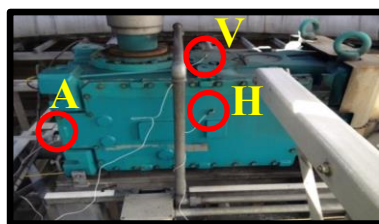
Figure 2 Schematic diagram of the gearbox

2.0 Vibration measurements & analysis

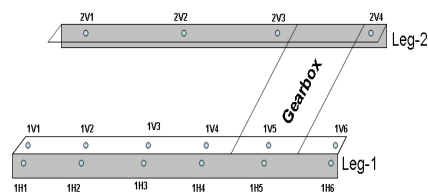
Several vibration measurements were carried out including online and offline measurements, so as to develop a robust understanding of the dynamic characteristics of the entire structure.

2.1 Spectrum analysis

Vibration data was collected at a number of locations on one of the Unit-1 cooling fans' gearboxes and its supporting steel frame. The measurement was conducted while the fan was running at its normal rotating speed [1]. Figure 3 shows the measurement locations on the gearbox as well as the supporting steel frame.



(a) The gearbox



(b) The supporting steel frame

Figure 3 Vibration measurement locations

The vibration acceleration spectra were computed for the measured vibration data acquired from all the measurement locations. Figure 4 shows the computed spectra for the measured vibration data at location 1V1 for a frequency range up to 2000Hz. The amplitude spectra for the vibration data measured at the steel frame at both vertical and horizontal directions show dominant peaks at the high gear mesh frequency (HGMF) 348Hz with its higher harmonics (696Hz; 1044Hz; 1392Hz....etc.)..

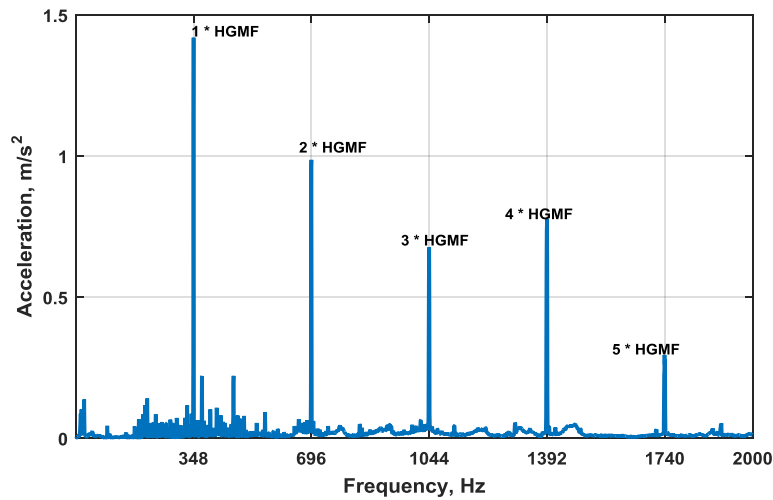


Figure 4 Typical spectrum for the vibration measured at 1V1 for frequency range 0-2000Hz

The zoomed spectra for the low frequency range up to 30Hz presented in Figure 5(a) shows the appearance of peaks at the fan blades passing frequency ($6 \times 1.4 = 8.4\text{Hz}$); its second harmonics (16.88Hz) as well as the motor speed (24.75Hz).

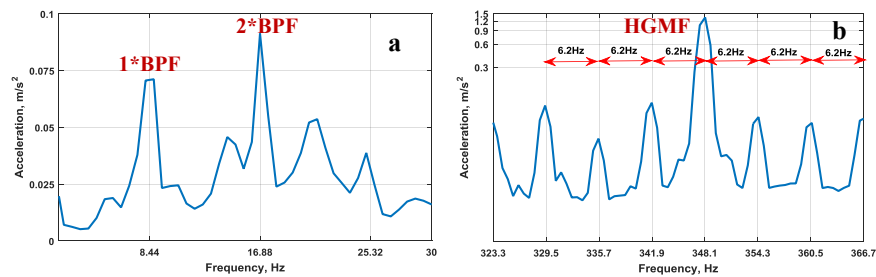


Figure 5 Zoomed view of Figure 4, (a) 0-30Hz, (b) 323.3-366.7Hz

The zoomed spectrum about the HGMF (348Hz) shown in Figure 5(b), clearly shows the HGMF peak and side band peaks spaced at equal distance of 6.2Hz (intermediate shaft frequency) or motor speed (24.8Hz), hence this indicates the defect/damage in these shafts

2.2 Operation Deflection Shape (ODS)

The collected data while the fan was on operation used to compute the averaged amplitude spectrum are used here to plot the Operation Deflection Shapes (ODS) in order to understand the motion of the supporting steel frame when the fan operates under normal condition [2]. The ODS of the steel frame were plotted at: the motor speed (24.75Hz); the low gear mesh frequency (92.4Hz) and at the high gear mesh frequency (346.5Hz). Figure 6(a) shows the steel frame's ODS at the motor speed where both legs moving in phase with low displacement near the gearbox region which may not cause any stress in the gearbox. The ODS at both gear mesh frequencies (LGMF & HGMF) shown in Figures 6(b) and 6(c), clearly indicate that both frame legs are moving out of phase at the LGMF and in phase at the HGMF with relatively high displacement near the gearbox which may induce stress in the gear box as well as the motor and intermediate shafts.

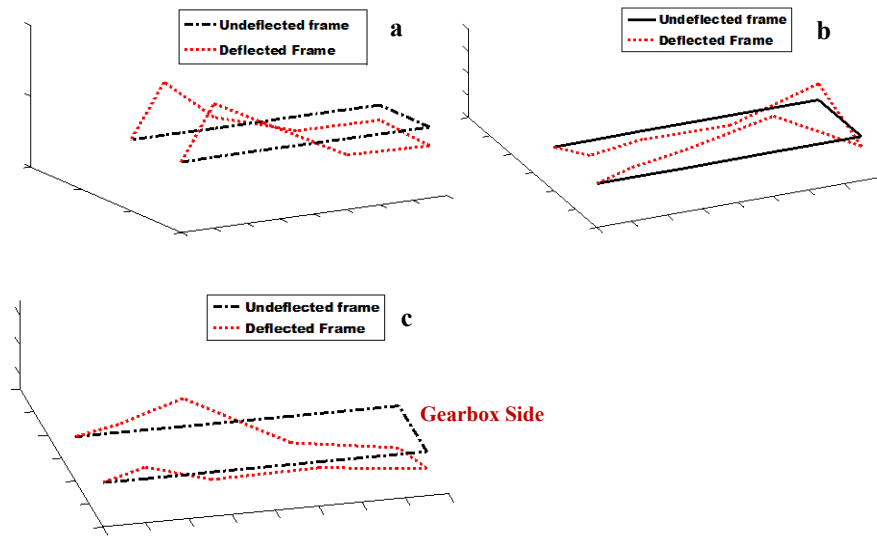


Figure 6 Steel frame ODS at: (a) 24.75Hz; (b) LGMF 93Hz and (c) HGMF 346Hz

3.0 Modal Tests

The modal test was conducted on the support steel frame using the impulse-response method [3], where the frame was excited using instrumented hammer, when the entire tower was under static condition (zero speed) and the vibration response was collected at the 16 locations on the steel frame shown in Figure 3.

Figure 7 shows typical FRF plot for the vibration data collected at location 1V1, it is very clear that two identified natural frequencies at 97.5Hz and 345Hz are close to the LGMF (92.4Hz) and HGMF (346.5). This confirms that both gear mesh frequencies are always in resonance during fan operation.

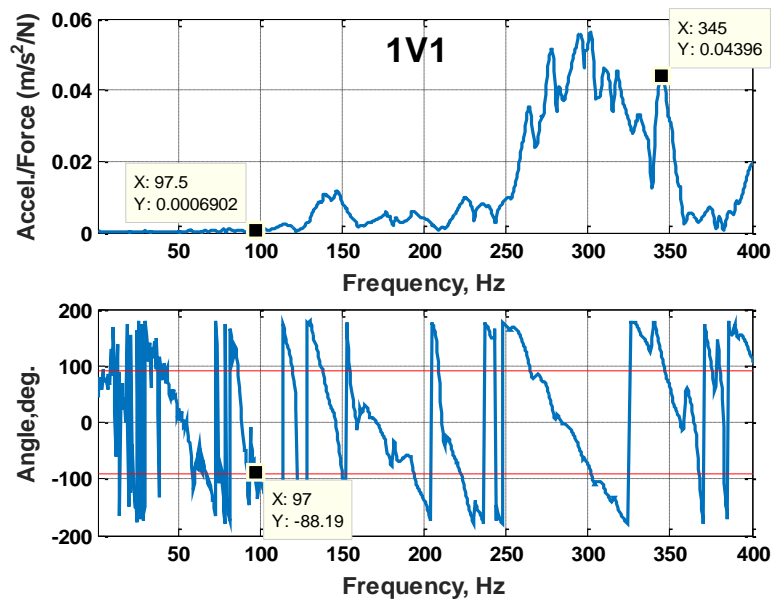


Figure 7 Typical FRF plot

4.0 Possible Solutions & Plant Implementation

This problem can be sorted by changing the structure's natural frequencies, in order to avoid any resonance in the system or replacing the existing gearboxes with different gear ratio to shift the gear mesh frequencies away from the structures' natural frequencies.

In 2015, the gearboxes were replaced with new gearbox with significantly different gear ratios as shown in Figure 8. Table 1 shows comparison between the old and new gearboxes.

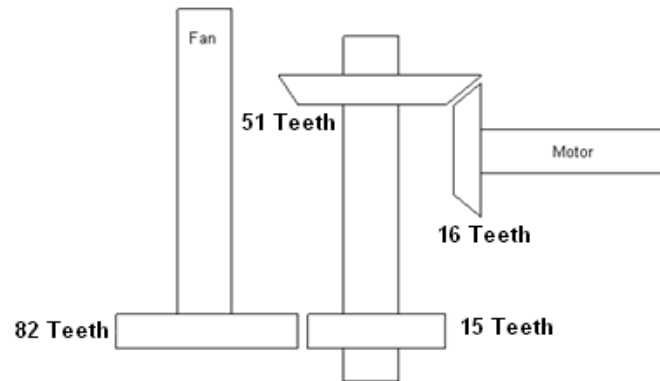


Figure 8 Schematic diagram of the new gearbox

Table 1. Old and new gearboxes configurations

Running speeds/frequencies	Old Gear Box	New Gear Box
Motor speed	1485 RPM, 4.75Hz	1485 RPM, 24.75Hz
Fan speed	84.38 RPM, 1.4Hz	85.22RPM, 1.42Hz
Intermediate shaft speed	371.2 RPM, 6.18Hz	465.88RPM, 7.76Hz
Low GMF (between fan and intermediate gear shaft)	92.4Hz	116.44Hz
High GMF (between motor and intermediate gear shaft)	346.5Hz	396.8Hz
Number of fan blades	6	6
Fan Blade Passing Frequency	8.43Hz	8.52Hz

Modal tests were again conducted on the support steel frame with the new gearbox in both vertical and horizontal directions. The modal tests confirm that none of its natural frequencies coincide with the gear mesh frequencies. Figure 9 shows FRF plot for the new gearbox.

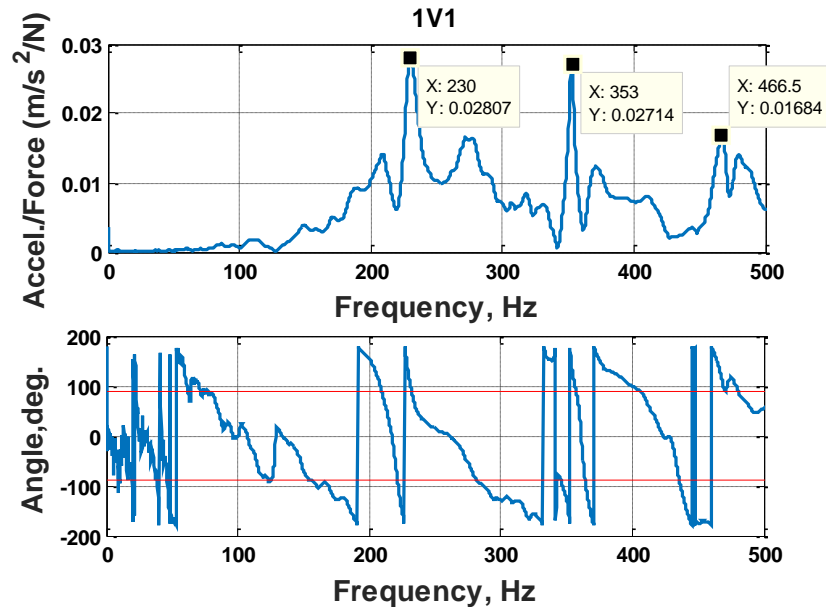


Figure 9. Typical FRF plot for the new gearbox structure

It is clear that none of the new structures' natural frequencies coincides with the gear mesh frequencies. Since the gearboxes were replaced, no more vibration issues have been observed on the cooling towers.

5.0 Conclusion

A Combined Cycle Gas Turbine with 3 identical units with total power of 1135MW has 3 cooling towers. Upon the observation of the repeated frequent failures in 27 out of the 30 cooling fans, vibration measurements (under static and rotational conditions) were conducted to ascertain the root cause(s) of the failure. Data analysis show high possibility of resonance phenomena. Also, the ODS analysis clearly indicate that both frame legs are moving out of phase at the LGMF and in phase but different vibration amplitudes at the HGMF which cause stress on to the motor as well as the intermediate shafts and hence the meshing teeth. The old gearboxes were replaced with new ones with different gear ratios in order to shift the gear mesh frequencies away from the earlier values. There were no natural frequencies were found close to the gear mesh frequencies and hence no failure since then.


6.0 Acknowledgment

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Shortcomings of applying standalone Conventional Reliability Method for Rolling Stock Risk Assessment

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Abstract Reliability and risk analysis methods can allow for systematic evaluations of these uncertainties supporting effective decision making associated with reducing the consequences in case of unexpected results. However, it has become a common practice in the rolling stock industry that standalone conventional methods are used for the evaluation of performance and risk. This approach often leads to inconclusive decision-making process regarding risk and reliability management. This paper focuses on a systematic literature review of the limitations by adopting single conventional tools and techniques for reliability and risk management. Traditional methods including Failure Mode Effects Analysis, Fault Tree Analysis, Reliability Block Diagram, Event Tree Analysis are reviewed and limitations assessed using a pneumatic brake unit as a case study. Finally, an integrated approach using these traditional standalone methods is proposed to address the shortcomings of each technique for effective assessment of reliability and risk.

Key words Reliability, Quantitative, Qualitative, Failure Mode Effect Analysis, Fault Tree Analysis

1.0 Introduction

Unforeseen failures and incidences of rolling stock operated in major cities could result in severe delays affecting the daily commute of passengers leading to high financial losses. This drives the point of focus towards exclusive reliability and risk assessment of rolling stock. Risk is defined as the effect of uncertainty on objectives and risk management is the coordinated activities to direct and control an organisation about risk [1]. Risk management can be managed through the influence of factors such as reliability. Reliability is commonly perceived as the ability of a product to give long periods of satisfactory performance without

failure in use [2]. And it is widely defined as the ability of an item to perform a required function under given conditions for a given time interval [3].

Traditional methods mainly Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Failure Mode Effects Analysis (FMEA) and Reliability Block Diagram (RBD) have been the focus tools in systems modelling in risk, reliability, and safety applications [4]. An integrated approach using more than one of the conventional reliability methods for risk management providing a robust assessment of risk is proposed. Also, a case study using Pneumatic Brake Unit PBU of a rolling stock system is used as a demonstration throughout this paper.

2.0 A simple overview of the Pneumatic Brake Unit PBU

The primary purpose of the PBU is to provide the necessary brake effort to stop the train using friction, emergency and parking braking methods as shown in Figure 1.

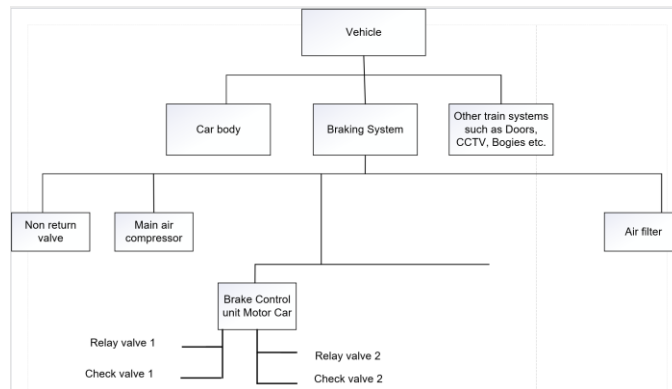


Figure 1 Illustration of the PBU as part of an overall rolling stock vehicle

Table 1 PBU subsystem functions and failure rates

List	Subsystem	Failure rates	Functional description
01	Non-return valve (NRV)	4.68×10^{-8}	To prevent air backflow into the dryer. It is part of the BCU
02	Main air compressor (MAC)	3.033×10^{-7}	To provide and maintain a supply of compressed air
04	Air filter (AF)	6.814×10^{-7}	To protect air supply from filter impurities
05	Relay Valve (RV)	3.75×10^{-8}	To maintain brake cylinder pressure and it is a subsystem of the BCU
06	Check Valve (CV)	2.925×10^{-7}	To ensure the protection of Brake supply reservoir BSR in the event of a mainline leak also part of the BCU

3.0 Failure Mode Effects Analysis FMEA

FMEA is a bottom-up method to prevent the happening of undesirable situations. The method estimates the magnitude of the effects upon the system by the potential failure modes of the lowest level components of a system. It also analyses the detection method of a failure mode [5]. FMEA analysis is successfully performed preferably early in the development cycle so that the removal or mitigation of the failure mode is most cost-effective [6]. The traditional FMEA uses three factors, i.e. likelihood of Occurrence (O), Severity of potential effect (S), and difficulty for Detection (D), to determine the Risk Priority Number (RPN), which can address and priorities the potential failures rapidly. This criticality is then translated into risk, which can decide whether or not the corrective action will be taken [7]. FMECA and FMEA can be considered as quantitative and qualitative reliability methods respectively. For example, a simple overview of the FMECA for non-return valve (NRV) subsystem of the PBU is shown in Table 2; The risk priority number (RPN) is the product of the occurrence, severity and detection ratings as shown in Equation 1 [8]. Table 2 shows that the RPN values for the two failure modes associated with the NRV have the same value of 8, where the severity, occurrence and detection have the same rating. Thus, failure mode prioritisation between “the leaks to the atmosphere” and “valve fails to close” become complicated and challenging to address adequately.

Therefore, RPN is unable to assess the weighting to the three factors, which may exist during the analysis process and needed by the participants to effectively allocate required resources to the failure modes [9–12]. Other limitations of the FMECA include the following [13]; (i) Interdependencies of failure modes and effects on the same and different levels are not considered. Consequently, the risk of a failure can be underestimated when it has multiple impacts on others [10,12]; (ii) Different sets of the three factors can produce the same value for RPN as shown in Table 2. However, the hidden implications may be entirely different [9,14]; (iii) High intensiveness of resources or the allocation of sufficient resources for the implementation of FMEA (material, facilitator support, sponsor support etc.) is required. Thus, FMEA is time-consuming and tedious to trace failure through FMEA charts [15]. Due to these limitations associated with FMEA/FMECA as a standalone method, other tools should be considered.

$$RPN = S \times O \times D \quad (1)$$

Table 2 FMECA for non-return valve NRV

Function	Failure Mode	Causes of Failure Mode	Effects on system	Effects on vehicle	Part Quantity in Entire System	[1/OH]	Part Failure Rate (failures per 10 ⁶ hours)	Seriousness (S)	Detection (O)	Occurrence (O)	RPN (S·D·O)	Fault Detection Method	Failure Management
To prevent air backflow into the dryer	Leaks to atmosphere	Seat failure	Reduced air pressure output from Air Supply	Built-in redundancy with the 2nd compressor	2	4.68 E-08	0.00468	2	2	2	8	Audible venting during six monthly maintenance check	Replace Non-Return Valve
To prevent air backflow into the dryer	Fails to close.	Wear or contamination.	Reverse air flow is causing reduced pressure in the Main Reservoir.	Built-in redundancy with the 2nd compressor	2	4.68 E-08	0.03042	2	2	2	8	During blow down of Air Supply for maintenance work	Replace Non-Return Valve

4.0 Fault Tree Analysis FTA

FTA is a top-down approach to analyse failures and risks, and it is used to define a failure mode and to identify potential root causes for the failure mode. Those potential causes are logically added to the fault tree using logic gate symbols, such as OR, AND, NOT, etc. It is vital to obtain Cut Sets and Minimal Cut Sets (MCS) for an FTA [7]. A quantitative FTA can be used when the probabilities of primary events are known [16]. The probability of an unfavourable outcome of an OR and AND gate (“system”) consisting of n independent input gates or events are shown in Equations 2 and 3[16]:

$$F_s(t) = 1 - (1 - F_1(t)) \cdot (1 - F_2(t)) \cdot \dots \cdot (1 - F_i(t)) \cdot \dots \cdot (1 - F_n(t)) \quad (2)$$

$$F_s(t) = \prod_{i=1}^n (F_i(t)) \quad (3)$$

Now considering the PBU with top event failure as “Failure of train braking system” with information from Figure 1 and Table 1, overall failure rate and the MCS can be estimated as shown in the FTA diagram in Figure 2 with an assumed mean time to repair (MTTR = 2 hours) during the annual operating regime of 6,400 hours.

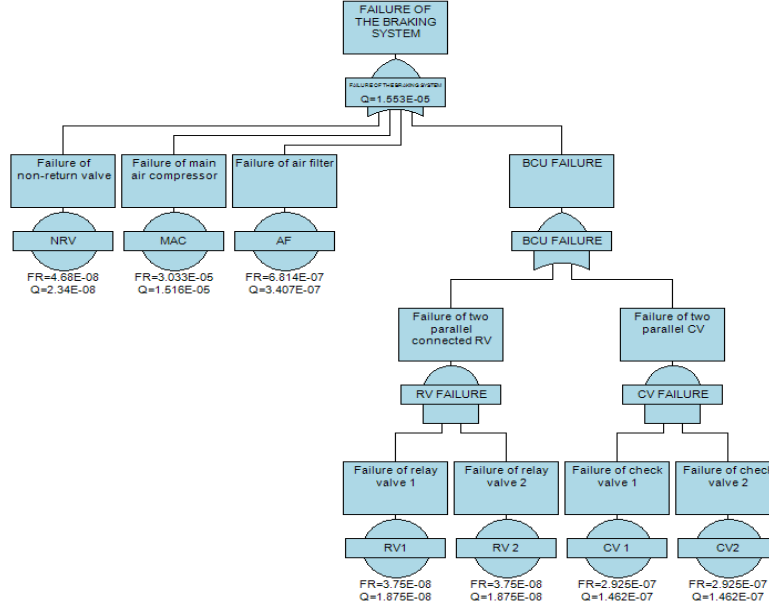


Figure 2 FTA diagram for failure of the brake system

Using Equations 2 and 3, the overall failure rate of the top event “Failure of train braking system”, F_T , is estimated as ($F_T = 3.106 \times 10^{-5}$) and the qualitative Minimal cut sets MCS; $RV1 \cdot RV2$, $CV1 \cdot CV2$, NRV , MAC and AF are determined. That means the occurrence of any of these would fail the brake system. The limitations of the FTA include the following; (i) the usual quantification methods for classical fault trees do not consider uncertainty in failure data[17]; (ii) FTA can only evaluate the safety and reliability of static systems and it becomes a challenge for large complex systems [17]; (iii) FTAs are not suitable for analysing redundant failures, common cause failures, or mutually exclusive primary events [18]; (iv) Events in an FTA are assumed independent, which is not usually a valid assumption [19–21]

5.0 Reliability Block Diagram RBD

The RBD Method is based on the representation of a system into blocks linked together (configurations serial, parallel, etc.) in terms of influence on the reliability of the overall system [22]. The modelling techniques described are intended to be applied primarily to systems without repair and where the order in which failures occur does not matter [23]. In general, RBDs can be classified into the following two categories: Series-Parallel RBDS and Non-series-parallel RBDs [24]. RBD

can be used as a standalone reliability tool which shows clear areas of vulnerability when nodes are arranged in a series structure, whereas relatively safe areas are noticed when nodes are in parallel [25].

PBU data shown in Figure 1 and data contained in Table 1, the unavailability of the PBU for the annual operating time of 6400 hours is 0.001553 per cent equivalent to the availability of 99.998447 per cent using Equation 4 as shown in Figure 3(a), 3(b) and 3(c). Similarly, the PBU's reliability is $R(t) = 0.8197$.

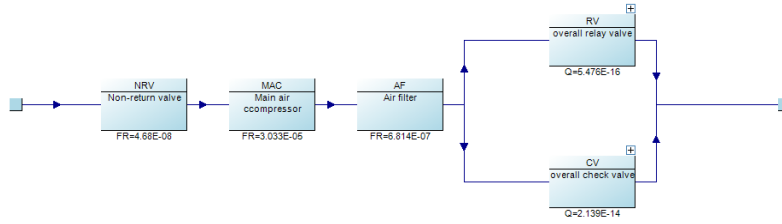


Figure 3(a) Overall RBD for PBU

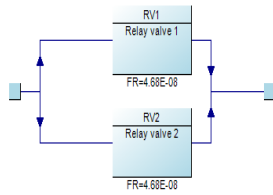


Figure 3(b) Parallel Relay Valve

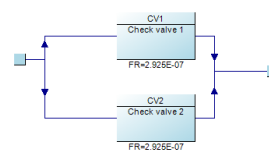


Figure 3(c) Parallel Check Valve

However, RBD as a standalone method for reliability and risk management has its limitations such as [25]; (i) Failure probabilities of components are statistically independent; (ii) The interconnections within the RBD do not necessarily show how the basic events/ component failures are physically connected; (iii) The complexity of component inter-dependence should be low. These limitations inhibit RBD to be implemented as a standalone technique.

6.0 Events Tree Analysis ETA

Event tree analysis (ETA) is an inductive procedure to model the possible outcomes that could ensue from an initiating event and the status of the mitigating factors as well as to identify and assess the frequency or probability of the various possible outcomes of a given initiating event [26]. The Event Tree Analysis (ETA) shows the sequences of events related to the success or failure of the system [27]. Event tree analysis (ETA) is a rather straightforward method for modelling of impact pathways (impact scenarios) and consequences [28].

The application of ETA to the PBU in Figure 1 using the unavailability values from the FTA in Figure 2, for the initiating event of “total loss of train braking system” with consequences is shown in Figure 4. Note for this paper the consequences have been restricted to impact on safety and operation only.

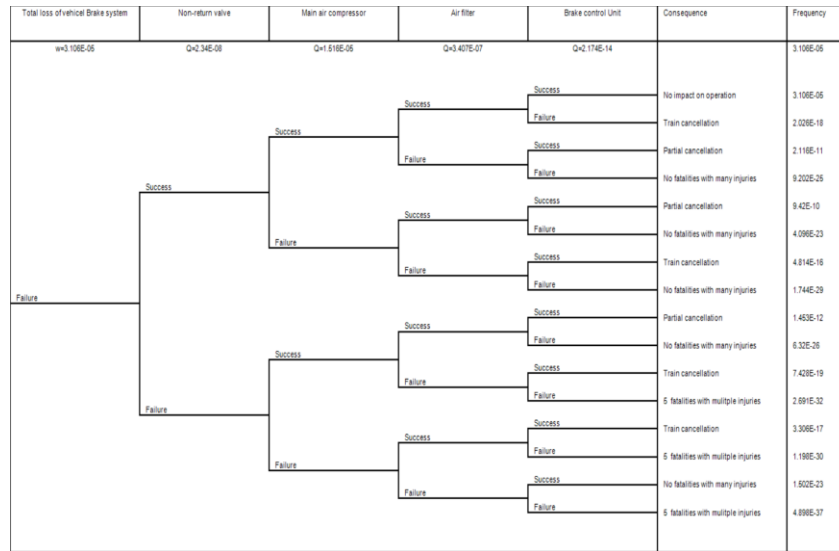


Figure 4 ETA for loss of train braking system

It can be realised from the analysis of the ETA that most of the data information for basic and gate events is obtained from analysis of the FTA. Other limitations exhibited by ETAs include the following [29]; (i) It is not applicable to transient systems if the probabilities of the considered events are dependent on time, in case of which, Markov models could be more appropriate; (ii) Event trees can be difficult to construct for large and complex systems.

7.0 Discussions and the review of the proposed integrated approach using conventional methods

Figure 5 illustrates an integrated model using two or more of the conventional reliability and risk assessment tools to address the limitations posed by each traditional method. The model allows a bottom-up approach starting with the application of FMEA/FMECA where the outputs from this model feed directly into the FTA and proceeding models. The yellow line indicates this in Figure 5. Similarly, the top-down approach can be carried out depending on the availability of data relating to the system under investigation. The black line in the model indicates the top-down approach method.

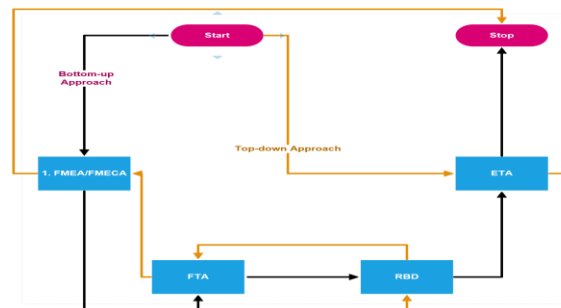


Figure 5 Integrated conventional reliability and risk model

8.0 Conclusion

This paper provided a systematic literature review of the limitations posed by standalone conventional reliability and risk methods used for risk assessments within the rolling stock industry. The constraints posed by traditional methods; FMEA/FMECA, FTA, RBD and ETA were investigated to ascertain the impact of these limitations and effects on the output of the assessment. An integrated model was proposed that addresses the shortcomings of each of the standalone method. The singular utilisation of the conventional method does not effectively address reliability and risk assessments for a rolling stock system.


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ME2018_1115

Hybrid model for maintenance frequency extension using Weibull and wear analysis

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Abstract Maintenance optimisation has become a common endeavour among rolling stock organisations via the qualitative risk assessment techniques. Furthermore, it is a common practice where the inability to apply the quantitative statistical approach to support risk management is replaced by experience and knowledge of personnel who are oblivious to imminent risk. Thus, maintenance extension for safety-critical systems such as collector shoe, brake disc etc. dictates for both qualitative and quantitative evaluations of potential risk. Therefore, this paper proposes a unique quantitative hybrid model utilising Weibull analysis to estimate the failure rate via historical data and wear analysis by cumulative density function of degradation data to evaluate wear levels. Outputs from both quantitative techniques provide the basis for a recommendation regarding maintenance periodicity extensions. A case study using a collector shoe component of a rolling stock vehicle is demonstrated using the hybrid model.

Key words Maintenance frequency, Weibull Analysis, wear analysis, Rolling stock

1.0 Introduction

Risk assessments via identification and proposed mitigation actions of potential hazards are undertaken to inform and address any unexpected risk. However, in the rolling stock industry, most risk assessments for maintenance extension is carried out qualitatively often without any quantitative analysis. Mostly RCM and total productive maintenance (TPM) can play an essential role in maintenance optimisation projects. However, they are more qualitatively driven nature. Also, data analysis and statistical modelling techniques that are valuable tools that engineers can implement to optimise the maintenance frequency of assets are not readily available [1,2]. Also, the qualitative approaches of RCM miss the what-if-analysis options which are so needed robust risk assessment [1]. They can be implemented via a previous case study, strategic decision support system and

operational decision support system [1]. Based on the selected option, it is imperative the underlying quantitative analysis based on the historical and performance data of the assets is considered where the impact on reliability and cost can be obtained effectively [3]. Quantitative models are relatively complex, and maintenance analysts have been slow to apply them since the data are scarce [1,2]. It is vital that the right quantitative approach is selected for optimisation data such as Bayesian parametric model for bathtub failure rates [4]. Quantitative risk assessment requires a great deal of data both in the evaluation of probabilities and assessment of consequences [5].

2.0 Weibull statistical methods

There are different forms of Weibull distribution; however, in this paper, only the 2-parameter is considered. Failure rate for Weibull demonstration is as shown below;

$$\lambda(t) = \frac{\alpha}{\beta} \cdot \left(\frac{t}{\beta} \right)^{\alpha-1} \quad \alpha > 1, \beta > 0 \quad (4)$$

Where $\lambda(t)$ denotes the failure rate at time t , α is the shape parameter and β the scale parameter [6]. Suppose the survival time T has Weibull distribution with probability density function (pdf) and the corresponding hazard rate function is given as follows[7];

$$f_T(t; \eta, \beta) = \frac{\beta}{\eta} \left(\frac{t}{\eta} \right)^{\beta-1} \exp \left[- \left(\frac{t}{\eta} \right)^\beta \right], t > 0 \quad (5)$$

Hazard function,

$$H(t; \eta, \beta) = \frac{\beta t^{\beta-1}}{\eta^\beta} \quad (6)$$

The failure probability at a given time t can be determined from the cumulative distribution probability and the mean time between failure (MTBF) as shown in Equations (4) and (5) below;

$$F(t) = 1 - \exp \left[- \left(\frac{t}{\beta} \right)^\alpha \right] \quad (4)$$

$$MTBF = \beta \cdot \Gamma \left(1 + \frac{1}{\alpha} \right) \quad (5)$$

where $\Gamma(x)$ is the gamma function. The values of the two parameters α and β can be obtained from failure and maintenance records using maximum likelihood estimations [6]. The reliability function is as shown in Equation (6);

$$R(t) = \exp \left[- \left(\frac{t}{\eta} \right)^\beta \right] \quad (6)$$

where η is the characteristic life [8]. The times between failures of a non-repairable system are independent and identically distributed (iid), and this is the most common assumption made when analysing time-to-failure data, but in some situations, it might be unrealistic [9,10]. The Weibull parameters are determined in the Least-squares Regression method by minimising the sum of squared residuals of the x values as shown [11];

$$\beta = \frac{n \sum_{i=1}^n [\ln(\sigma_i) \cdot y_i] - \sum_{i=1}^n (\ln \sigma_i) \cdot \sum_{i=1}^n (y_i)}{n \cdot \sum_{i=1}^n [(\ln \sigma_i)^2] - \left[\sum_{i=1}^n (\ln \sigma_i) \right]^2} \quad (7)$$

$$-\beta \cdot \ln \theta = \frac{\sum_{i=1}^n (y_i) - \beta \times \sum_{i=1}^n (\ln \sigma_i)}{n} \quad (8)$$

where β is the shape parameter, θ is the scale parameter and σ is the location parameter but with 2-parameter Weibull $\sigma = 0$.

3.0 Wear Analysis

Degradation is the reduction in performance, reliability, and lifespan of assets. Degradation could be modelled in several approaches such as random process model, general degradation model, linear regression model, mixture degradation model and many more [12]. The random process model fits degradation measurements at each observation time by a specific distribution with time-dependent parameters [13]. In this method, multiple degradation data at a particular time have to be collected and treated as scattered points without orientation [14]. Linear regression is then used to find the equation for $\mu(t)$ and $\sigma(t)$. For Weibull distribution, one has to use the following equations to find μ and σ from the fitted distribution [15].

$$\mu(t) = \eta \cdot \Gamma\left(1 + \frac{1}{\beta}\right) \quad (9)$$

$$\sigma^2 = \eta^2 \cdot \left[\Gamma\left(1 + \frac{2}{\beta}\right) - \Gamma^2\left(1 + \frac{1}{\beta}\right) \right] \quad (10)$$

The wear data analysis can fit other distributions such as Gamma and standard normal distributions. Suppose that the wear data y at any time t_i follows the Weibull distribution, the cumulative density function CDF of degradation level is given by [15];

$$F(y) = 1 - \exp\left[-\left(\frac{y}{\eta}\right)^\beta\right] \quad (11)$$

Similarly, other CDFs degradation levels can be evaluated depending on the selected distributions such as normal, exponential etc. A natural representation for this degradation process is to draw z vs t in $t-z$ the plane. As such a curve: $z = z(t)$ will be obtained which is referred to as the path or history. Suppose that there are paths and path includes observation points: $\{tij, zij, i = 1, 2, \dots, n, j = 1, 2, \dots, m_i\}$. A linear interpolation relationship is given by [16]:

$$z_i(t) = z_{ij} + (t - t_{ij}) \frac{z_{i(j+1)} - z_{ij}}{t_{i(j+1)} - t_{ij}}, t_{ij} < t < t_{i(j+1)} \quad (12)$$

Without loss of generality, let T be the time when the degradation level reaches a critical threshold D and assuming Weibull distribution is used for this illustration. T is assumed to follow the Weibull distribution as a linear model as shown [15]:

$$R(t) = \exp(-\alpha_y \cdot t^{\beta_y}) \quad (13)$$

α_y, β_y are functions of $y = D$ and must be determined based on the degradation data. For the n observations, all time points are arranged in ascending order as: $t_1 \leq t_2 \leq \dots \leq t_j \leq \dots \leq t_n$. The corresponding degradation data observed at these ordered points are: $y_1, y_2, \dots, y_j, \dots, y_n$.

4.0 Hybrid model for maintenance frequency extension using Weibull and Wear

The hybrid model considers two outcomes from the Weibull and wears data analysis.

- Step 1: Condition using Weibull analysis
Assuming a 2-parameter Weibull analysis, the condition for meeting the proposed frequency is dependent on the probabilistic results of the survival and hazard rate as shown below in Equation 14:

$$R(t)_{proposed} \geq m_{proposed} < H(t)_{proposed}$$

$$\exp\left[-\left(\frac{t}{\eta}\right)^\beta\right] \geq m < \frac{\beta t^{\beta-1}}{\eta^\beta} \quad (14)$$

- Step 2: Condition for wear analysis
The wear analysis uses a combination or mixture from random process, linear and general path degradation models. Considering the wear values at specified times t_1, t_2, \dots, t_n at the degradation values y_1, y_2, \dots, y_n can be estimated based on Equation 12 as;

$$w_{12} = \frac{y_2 - y_1}{t_1 + t_2} \quad (15)$$

where w_{12} is the wear value between times t_1 and t_2 degradation values y_1 and y_2 . Subsequent wear values can be estimated based on the specified time and degradation data as. $w_{12}, w_{23}, \dots, w_{n-1}$. The CDF for an equivalent standard normal distribution based on Equation 11 is as shown below;

$$f(w, \mu, \sigma) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\left(\frac{(w-\mu)^2}{2\sigma^2}\right)} \quad (16)$$

where μ is the mean of the normal time-to-failures also noted by \hat{T} , and σ is the standard deviation of time-to-failure for the normalised CDF wear value w . The maximum allowable degradation value at the degradation level w for a defined manufacturing tolerance level or theoretical threshold level D_0 is given by:

$$p(\hat{T} \geq w) = \hat{T} \cdot z < D_0 \quad (17)$$

Where z is the proposed maintenance frequency extension value in distance, time or cycles. Overall the hybrid model for a system or task can be extended based on the conditions that the requirement of Equations 14 and 17 as shown below,

$$R(t)_{proposed} \geq m_{proposed} < H(t)_{proposed} \text{ and } m_{wear} < D_0, \text{ and } m_{wear} = \hat{T} \cdot z$$

5.0 A case study using a collector shoe/gear of rolling stock

The case study illustrates quantitative analysis using the hybrid model to arrive at recommendations for extending the maintenance frequency of a collector shoe from 14,000 Km to 20,000 Km with no more than 5% of failures (i.e. “B-life “ of 5%) expected at the proposed frequency. Five-year historical data for the shoe/gear was analysed using Isograph software as shown in Figure 1 and Figure 2 for the survival probability and Hazard rate respectively;

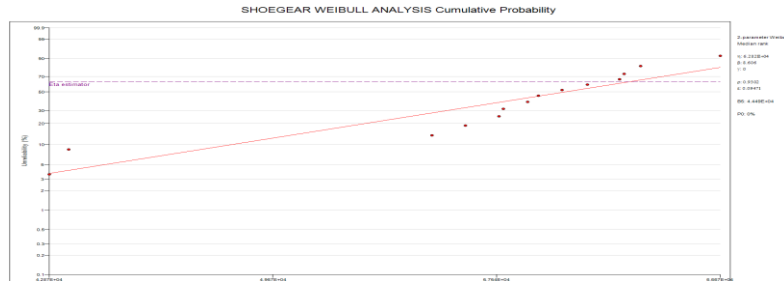


Figure 1 Cumulative frequency probability of shoe gear

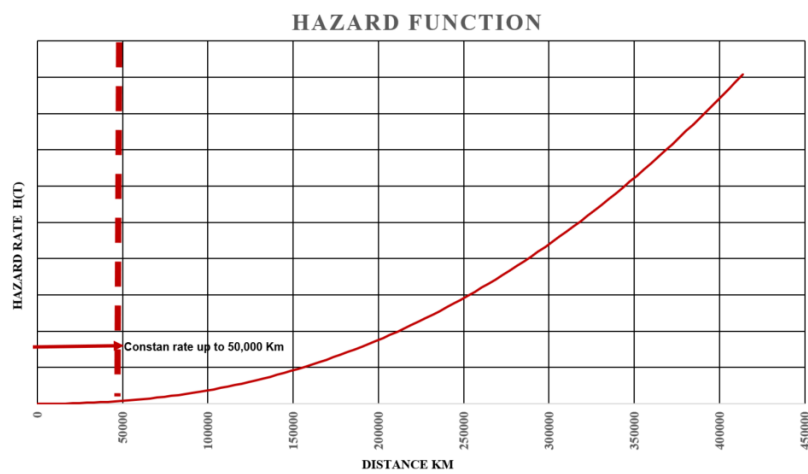


Figure 2 Hazard rate of the collector shoe gear

The average wear value w for the normalised CDF for the shoe gear was estimated, and it could last up to the fourth inspection with the critical threshold value D_0 at 5 mm as Figure 3 and 4 respectively.

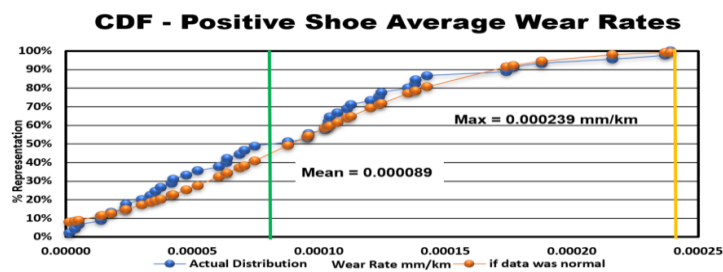


Figure 3 CDF for positive collector shoe showing mean wear rate

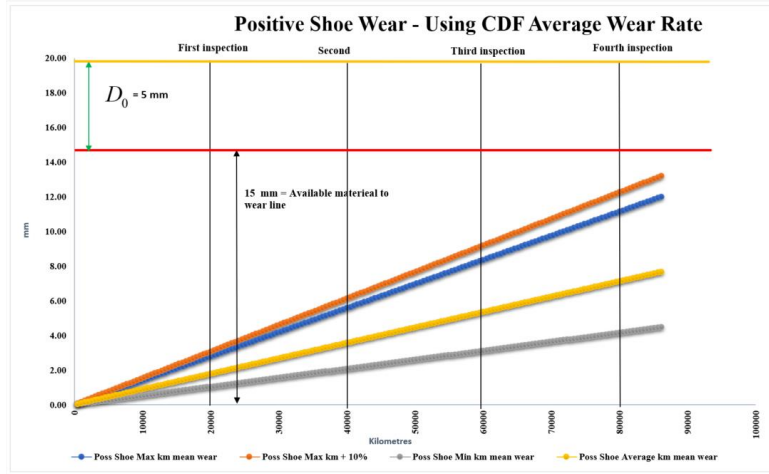


Figure 4 Collector shoe gear wear rate against inspection intervals

6.0 Analysis of results

Weibull analysis of the collector shoe gear with a “B” life of five per cent (5%) was estimated as 44,490 Km with correlation coefficient and goodness of fit parameters at 0.9302 and 0.09471 respectively demonstrating a proper distribution fit for the failure data and far exceeded the proposed periodicity extension (i.e. 20,000Km). Similarly, the hazard rate is constant up to the 40,000 Km where it begins to increase. Also, the average wear rate value was estimated as 0.00089 Km/mm. The total wear value over the proposed maintenance frequency of 20,000 Km was

determined as 1.78 mm (i.e. $m_{wear} = \bar{T} \cdot z$). Thus, provided the shoe gear is new, the next replacement will occur on the fourth inspection (at 80,000 Km), and this means the critical wear threshold D_0 , ($D_0 = 5mm$) will be reached at the fourth inspection. In summary, the quantitative analysis showed $R(t) = 44,490Km$, $H(t) = 40,000Km$ and $m_{wear} = 1.78mm$ showed the collector shoe gear met the conditions set for the hybrid mode.

7.0 Conclusion

This study has systematically investigated the hybrid model using Weibull and wear degradation analysis for maintenance frequency extension using a

quantitative approach. The hybrid model allows the survival and the hazard rate probabilities of the system to be estimated using the Weibull distribution together with establishing the wear rate value at the proposed extended periodicity for the same system using a combination of degradation models. The degradation analysis uses a mixture of models including; random process, general path and linear models to arrive at the final hypothesis for hybrid wear model. The normal distribution technique was adopted to establish the CDF for the hybrid model. Further, the hybrid model was applied to a case study for maintenance frequency extension of a collector shoe gear where the technique was used to extend the maintenance frequency from 14,000Km to 20,000Km. In summary, the hybrid model is a versatile model combining Weibull and wear degradation analysis for robust extension of maintenance frequency using quantitative techniques.

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Authors' Biography

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ME2018_1120**The Importance of Reliability and Maintenance for the Circular Economy****Luís Ferreira¹, José Sobral²**

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Abstract The Circular Economy is today considered a factor of extreme importance for the organisations that inevitably are inserted in a context of competitiveness and innovation. It is a strategic concept based on the reduction, reuse, recovery and recycling of materials and energy, replacing the concept of end-of-life normally used in a linear economy. The Circular Economy aims at promoting an economic model where the production and consumption systems articulated in an organized way. It is a dynamic process, where the economic and social aspects are combined with the technical requirements and the engineering activities to reach the proposed objectives. This concept goes beyond the simple actions of waste management and recycling, being broader and more comprehensive, and based largely on an optimisation and use of all available resources, taking maximum efficiency of their technical cycles. Maintenance thus assumes a preponderant role in achieving most of the objectives of a Circular Economy, being fundamental in the physical assets exploration phase, but also taking an active part in other stages, such as during the decommissioning or dismantling phase where the circle is not closed, turning waste into resources. Keywords used in the explanation and definition of Circular Economy, such as "repair", "reuse", "maintain" or "extend", show how the Maintenance function plays an active role in this strategic concept. This paper aims to present the concept of Circular Economy and its current relevance, and within this context to show how the Reliability of systems and equipment, as well as their Maintenance throughout their life cycle, play a decisive role for their success. The demonstration goes on to show how the inherent reliability of systems and equipment, according to the objectives defined in the design phase, allows its use according to its specifications and with controlled risks for the user, and how the correct maintenance of systems and equipment allows less consumption of materials and energy, thus allowing it to normally extend its useful life at controlled costs (lower OPEX). The application of maintenance techniques such as CBM (Condition Based Maintenance), as a support for TPM (Total Productive Maintenance) and RCM (Reliability Centred Maintenance) policies, always per-

formed in a Lean perspective, have allowed improving equipment performance and its circularity, through greater availability, avoiding failures with serious consequences. Its application allows the use of other resources, such as Predictive Analytics, thus also fitting in recent developments in the industrial sector, as it is the concept of "Industry 4.0". All these concepts have led to new forms of business, with consequences for Maintenance, on which a brief reference will be made in this paper.

Key words Circular Economy, Maintenance, Reliability.

1.0 Introduction

Sustainable development is a type of society development in which we live where we try to meet the needs of the present without compromising the ability of future generations to meet their own needs. Contains two key concepts [1, 2]:

- The concept of "needs", in particular the essential needs of the world's most deprived, to which priority must be given priority; and
- The idea of limitations imposed by the state of technology and social organization on the ability of the environment to meet current and future needs.

In essence, sustainable development is a process of change in which resource exploitation, investment direction, technological development orientation and institutional change should all be in harmony and enhance the current and future development potential to meet the needs and human aspirations. Within this concept of sustainable development, organisations must take into account not only the economic objectives, but also have environmental and social objectives in carrying out their activities, whether commercial or otherwise. It is within the scope of this concept of sustainable development that the concept of circular economy originates.

2.0 The concept of the Circular Economy and its current importance

According to the Ellen MacArthur Foundation [1], "A circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials,

products, systems, and, within this, business models.”. Also, “As predicted by its creators, a circular economy is a continuous cycle of positive development that preserves and enhances natural capital, optimizes the yields of the resources used, and minimizes system risks through the management of finite stocks and renewable flows. It works effectively on all scales. ”

As can be seen in Figure 1, this contrasts with a so-called linear economy which is a resource utilisation model of "raw materials, production, distribution, consumption and disposal". Circular Economy can be defined as a regenerative system in which the inflow of resources and the loss of waste, emissions and energy are minimized by the slowing, closing and reduction of circles of use of raw materials and energy. This can be achieved through design, maintenance, repair, reuse, remanufacturing, renovation and long-term recycling.

This economy concept is based on some simple principles [1]. First, at its core, a circular economy aims to "project" useful products without waste. Waste "does not exist", the products are designed and optimized for a cycle of disassembly and reuse. These improved component and product cycles define the circular economy and differentiate from disposal and even recycling, where large amounts of built-in energy and labor are lost. Secondly, circularity introduces a rigorous differentiation between consumable and durable components of a product.

Contrary to what is happening today, consumables in the circular economy are largely made up of biological ingredients or "nutrients" that are at least non-toxic and possibly even beneficial and can be safely returned to the biosphere either directly or in cascades of consecutive uses. Goods, such as engines or computers, on the other hand, are made of technical "nutrients" unsuitable for the biosphere, such as metals and most plastics. In a Circular Economy these are designed from the beginning for reuse. Third, the energy needed to power this cycle must be renewed by nature, again to lessen dependence on resources and increase the resilience of the system (for example, to withstand oil shocks).

For technical nutrients, circular economy largely replaces the concept of consumer with that of user.

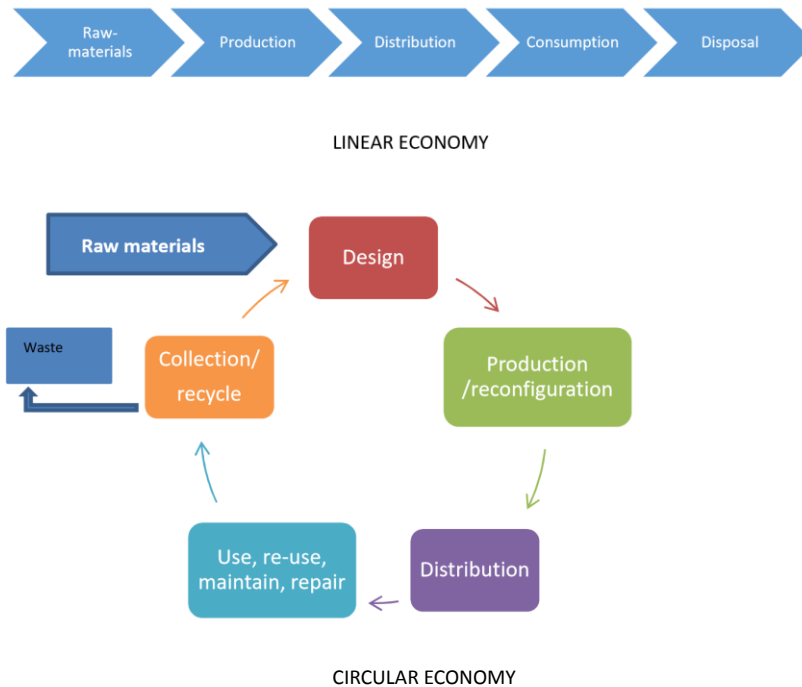


Figure 1: Generic concepts of Linear Economics and Circular Economics

3.0 The relevance of Maintenance in the Circular Economy

The principles of circular economy allow not only a description of how the economy should function as a whole, but also outlines specific sources of economic potential value creation [3].

The economy and the comparative proposal of different circular configurations (eg, reuse versus remanufacturing versus recycling) may differ significantly for different products, components or types of material in any particular segment of the supply chain. However, there are some simple principles of circular value creation that are easy to understand.

Thus we have the power of the inner circle: in general, the tighter the circles, the greater the cost savings in terms of material, labor, energy, capital and other costs associated with externalities such as emissions, water, etc. Tighter circles will also benefit from a comparatively higher substitution effect of new raw materials (less use of new materials, considering process inefficiencies along the linear chain).

This possibility that is emphasized when comparing linear and circular configuration is the core of its relative value creation potential. Whenever the cost of collecting, reprocessing and returning the product, component or material for the economy is lower than the linear alternative (including the prevention of end-of-life treatment costs), the creation of circular systems becomes economically meaningful. With rising resource prices and higher end-of-life treatment costs, this option becomes more attractive, especially at in the early stages of design, when economies of scale and the benefit from higher productivity gains can be achieved (because of the low starting base).

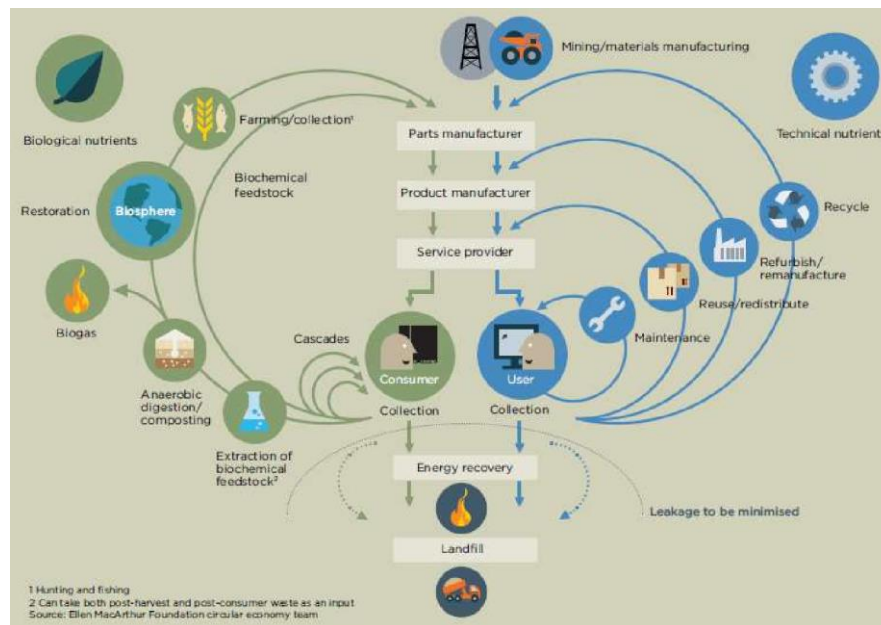


Figure 2: Circular economy - an industrial system that is restorative by design
[adapted from [1]]

We also have what is designated by the power of circulation for a longer time: a second potential of value creation stems from the maintenance of products, components and materials in use for longer periods in the circular economy. This can be done through more consecutive cycles (for example, not just a remodeling of one subset of the equipment, but several) or by spending more time within a cycle (for example, extending the usage time of an equipment through a more robust design). This extension of use will replace virgin material intakes to combat the inevitable loss of materials. Here, too, rising resource prices make this lever of value creation more attractive.

However, a possible increase in operating and maintenance costs or efficiency gains due to rapid product innovation can lead to this longer circulating power losing its competitive advantage.

This power of circulation, with the optimum use of resources, fits into a perspective of "Lean Thinking", whose main objective is to eliminate the wastes in the productive processes. The most common causes of waste in process industries can be described as [4]:

- Condition of the equipment: Equipment that is not in its proper functional condition has low availability, produces products of insufficient quality and in less than necessary quantities. Also, they operate inefficiently (usually with high energy costs and poor use of raw materials). To avoid this happening, there is a need to apply maintenance systems that have a Kaizen effect (continuous improvement) in the long term, such as the RCM and the TPM.
- Non-optimized operation: Typically, a manufacturing process involves a combination of several physical parameters: temperature, pressure, density, flow rate, vapor level, chemical concentration, ..., which are programmed into the equipment to process the material. If these parameters are not optimized (often due to equipment failures), the process will lose efficiency and quality.
- Project and technology: Often the equipment is obsolete or not technologically adapted to the products requested by the customers. Sometimes they are degraded and it becomes necessary to do a revamping of the installation.
- Availability of equipment: Availability may be affected by loss of equipment reliability, a complex set-up to change the product type, or long maintenance interventions. Equipment starting may be difficult and long after maintenance interventions. TPM or RCM actions and SMED (Single Minute Exchange of Die) techniques can lead to significant improvements.

The Kaizen philosophy is of Japanese origin and means continuous improvement. Continuous improvement involves the participation of all employees and has as main objective to improve the processes and performances of the organisation, implementing improvements that involve low investments. To obtain a Kaizen effect in maintenance with an impact on the circular economy the application of the principles of TPM - Total Productive Maintenance appears as immediate. It is a process of continuous improvement, which aims to maximize equipment performance, establish a rational system of Preventive Maintenance throughout the life of the equipment, is implemented by various sectors of the company (engineering, production and maintenance) and involves all personnel from the company. It is based on the promotion of Preventive Maintenance for the motivation and management of small autonomous groups. Its indicator is OEE - Overall Equipment Effectiveness, which is the product of availability, quality achieved and speed of production.

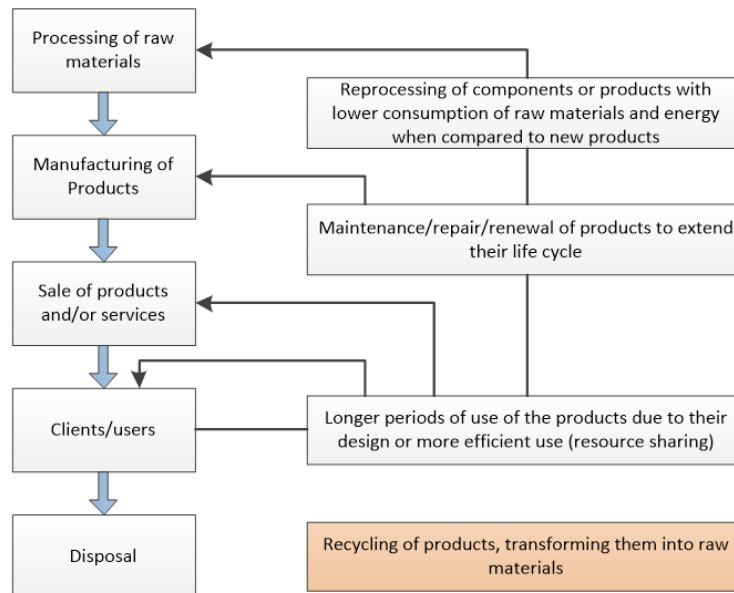


Figure 3: Potential economic gains of the circular economy

In turn, the RCM also appears as a privileged partner for the implementation of the Lean Thinking philosophy, as described by the Toyota Way [4], Figure 4, and within a perspective of circular economy.

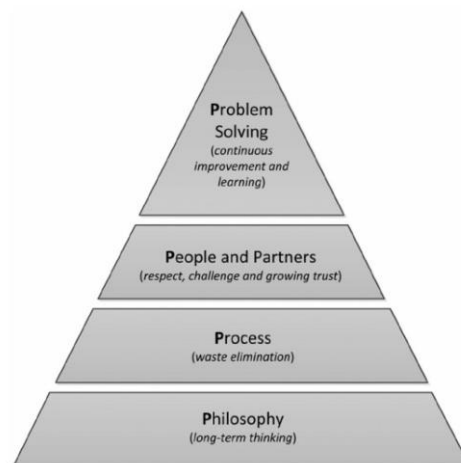


Figure 4: TOYOTA Way - Lean Thinking [4].

The Reliability-centred Maintenance (RCM) methodology is a structured approach that has been applied in a wide variety of industries, with emphasis on its application in the process industries. The RCM is a methodology used to determine the maintenance requirements of a system or equipment in its operational context to ensure that it will continue to achieve the specified operational performance objectives [5]. Its objective will be to allocate the means of maintenance where they are really needed, with a minimum use of human and material resources, which is in line with the objectives of the circular economy. Both TPM and RCM, applied separately or in a complementary manner as maintenance methodologies, result in better resource utilisation and equipment longevity, allowing a greater number of "inner circles" as described in Figure 2.

4.0 The Circular Economy in a context of Big Data and Internet of Things

The combination of circular economics principles with the exponential increase we have witnessed of the so-called "smart" and interconnected devices can drastically increase resource efficiency and lead to significant social and economic benefits [6]. As we have already seen, there is a very important evolution in the design of systems and equipment, which with the possibility of using all the available knowledge and the sensitisation / monitoring of the equipment allowed the development of systems in the concept of Digital Twin Factory [7].

Within this concept, the design of the equipment or product / machine is conceived as a mechatronic system that can be digitally tested, developed and validated. This allows the concepts to be tested and developed before actual manufacturing starts. The "real machine" data is preloaded into the model during the design phase. This gives rise to a digital twin that allows the simulation of production operations and product flow throughout the "machine" life cycle.

Thus, digitization allows to increase efficiency in all phases of the "machine" life cycle. It is possible to pre-validate projects and test the configuration of the control system of equipment and digital systems scanned from real equipment installed in real environments. Configuration analyzes, manufacturing process and checks take place before the actual engineering process is started, which reduces the risk of failures and errors in critical life cycle phases, such as during installation and commissioning, which previously only could be eliminated with great effort and under time pressure. If machine information is available on an integrated data platform, later modifications can be tested and verified in exactly the same way, thus accelerating the introduction of technological changes or a new product. In addition, with the help of models, the machine's operational data can also be used to optimize the feature parameters for its redesign and production - from power consumption to operating error rates and maintenance cycles.

The use of these twin digital systems also allows for interactive testing of maintenance cycles, optimizing the CBM - Condition Based Maintenance processes and giving rise to what is now called intelligent maintenance or CBM +, which can be defined as [8]: the application and integration of appropriate processes, technologies, and knowledge-based resources to improve the reliability and maintenance effectiveness of systems and components. At its core, CBM + is the maintenance performed from the evidence of need provided by the RCM analysis and other knowledge processes of the equipment. CBM + uses a systems engineering approach to collect data, enable analysis, and support decision-making processes for procurement, maintenance, and system operations. Thus, monitoring sensor devices can transmit performance data to the manufacturer, enabling the development of predictive maintenance programs and, at the same time, twin digital software upgrades.

As can be seen, these concepts take advantage of all the knowledge developed with the application of methodologies such as the RCM and TPM, in which regularly scheduled maintenance intervals, whenever possible supported by the knowledge of the condition state of the equipment or component, have ensured less downtime and a more disciplined approach to the use of human resources and maintenance materials.

However, inefficiencies continue to exist, since in the process of controlling the traditional condition we have the application of the so-called "instantaneous" maintenance concept, in which whenever an evaluation parameter of the condition state is exceeded an intervention process is triggered. Today, the wide availability of sensors and monitoring platforms, integrated in IIoT systems – Industrial Internet of Things and Big Data Analytics, allows to evolve technologically into maintenance for condition based maintenance plus (CBM +) or proactive maintenance. Under the concept of CBM +, the maintenance data obtained in real time are permanently analyzed and standardized to give rise to indicators of degradation of the condition, allowing better knowledge of the development of an incipient fault that later would lead to the loss of function of an equipment. As CBM + improves the knowledge of the P - F interval (P - Initial point of detection of functional failure, F - Point in which functional failure occurs), this results in a more efficient use of human and material resources and decreases the time of asset inactivity, which allows better maintenance with a more rational use of the "products" and leads to a greater longevity of the "products" taking in consideration the length of service actually provided, allowing to improve its management and its circularity.

5.0 The evolution of business characteristics in a Circular Economy

The concepts of circular economy with the application of the concept of user instead of consumer, has led to the development of new concepts of business organisation and new types of business, namely new business models. In these new business models, we can highlight [9, 10]:

- Establishment of so-called "inverse" logistics networks:

The potential total value of the circular economy goes far beyond the simple recycling of used materials. This value results from the reuse, maintenance, renewal and reprocessing of components and products, from materials considered by users as being at the end of life. That is why it is equally important to strengthen the so-called "inverse" logistics networks, just as global product production and distribution networks have been developed.

- Extended product life:

The extended product lifecycle, achieved through a more robust design or through actions during its use life cycle, allows organisations to extend the product and asset lifecycle. Values that would otherwise be lost through wasted materials are instead maintained or even improved through maintenance, repair, upgrade, reprocessing, or remarketing actions. With this practice, a company can help ensure that products are economically useful for the longest possible time and that product updates are more targeted (for example, an out-of-date component is replaced rather than the entire product).

Looking from a commercial point of view, selling less may seem disadvantageous. But when looking at the business set of longer term, it turns out that the final balance is positive. Thus, one can improve customer loyalty and maintain a relationship with the customer called "circular" through the maintenance work, which is much more about a partnership relationship than a linear and unique transaction. It also allows the customer to lower costs, which easily transforms existing customers into marketing products and services and ambassadors on behalf of the company. This illustrates how the circular design of systems / equipment usually involves changes to the business model as well as technical product innovations.

- Sharing Platforms:

The business model of the sharing platforms promotes the existence of a collaboration platform between the users of the products, be they individuals or organisations. This facilitates sharing unused resource capabilities, avoiding underutilisation, increasing productivity, and creating value for users. This model,

which helps maximize utilisation, can benefit companies whose assets have a low utilisation rate by sharing ownership.

- Products as services:

The product business model as a service provides an alternative to the traditional "buy and own" model. Products are used by one or more customers through a lease or pay-per-use agreement. This business model encourages durability and lifecycle upgrading of products by changing their design from "volume" to "performance." With a business model of the product as a service, product longevity, reuse and sharing are no longer viewed as risks of cannibalisation, but rather drivers of revenue and reduced costs. This model is particularly attractive to companies whose shared operating costs are high and have a qualification advantage over their customers in product maintenance management (giving them an advantage in the sale of services and recovery of residual value at the end of life).

By prioritizing access to ownership, these models drive change from consumers to users. On the other hand, by adopting a product-as-a-service model, companies are encouraged to develop products of longer duration. And by getting used products back, companies are motivated to ensure through material design and selection that they can be reprocessed as raw materials for the manufacture of similar new products or something completely different. Also, maintainability is usually improved.

All of these models imply new customer relationships, long-term relationships that will be vital to facilitate maintenance processes, product upgrades, and other product-related services, and driving customers to return products at the end of each cycle of use.

6.0 Conclusions

The circular economy in a more or less evident way has been developing, above all with the evolution of the social conscience of the need to preserve raw materials, which are known to be finite and not always easy to obtain. Its advantages, through existing examples, are the evidence of more sustained economic growth, substantial saving of raw material and energy costs, creation of employment opportunities and increased innovation.



The total potential value of the circular economy goes far beyond the simple recycling of materials used. This value is incorporated into the reuse, maintenance, renewal and reprocessing of components and products. With the use of new technological means and through a more efficient maintenance, it becomes possible to better monetize the use of systems / components.

This is achieved through new business models, with which we are currently confronted and in which maintenance appears as an essential factor.

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Maintenance Management and Design of Experiments

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Abstract The design and analysis of experiments is an effective tool that must be integrated in the tools portfolio of maintenance management. To support this sentence, a diversity of case studies published in the literature are presented as examples. To foster the Design of Experiments (DoE) usage, the most common mistakes and what researchers and practitioners should consider for a successful application of this tool in process / equipment's and product's quality (reliability, availability, performance, robustness, productivity, etc.) improvement are highlighted.

Key words: ANOVA, Errors, Quality, Randomization, Reliability, Replication.

1.0 Introduction

Maintenance management policies and practices impacts on organizations performance significantly. Low quality of products or services, high manufacturing costs, low process / equipment capability and productivity, short times between failures or low availability, and accidents or health problems are common reasons by which maintenance management has to be efficient and not just effective. This requires a permanent valorization (education and training) of human resources, availability of suitable technologies, and use of appropriate methodologies and tools to achieve the best performance. The design and analysis of experiments (hereafter termed DoE) is one of the most widely used tools to design and improve processes/equipment's and product's quality (reliability, availability, performance, robustness, productivity, etc.). There are many case studies showing the vast field of application and benefits resulting from the application of DoE in various types of industry, including aeronautics, chemistry, pharmaceuticals, automotive and biomedical industries. However, national and international studies show that DoE is far from being pervasive in industry (and academy) [1-3]. In fact, the trial-and-error approach is often used in industry and

academy. This unstructured (empirical) practice is more expensive in terms of time and cost, besides the desired or expected results are achieved only under very special conditions [4]. DoE is a much more effective tool and cannot be ignored by maintenance managers. To encourage and help them design experiments and achieve the desired process / equipment's and product's quality, bad practices and common mistakes on DoE usage are revisited, and guidelines for avoiding them are highlighted.

2.0 DoE in Maintenance Management

The Statistical design and analysis of experiments is a technique widely tested and validated in various settings. It can be adjusted to several characteristics of the phenomena and variables under study, as well as to the type of information that is intended to be collected from an experimental study. Thus, DoE can be integrated in the set of tools that can be used within the scope of maintenance management. According to [5], DoE has been increasingly used for improving the reliability of products and processes / equipment, and it is neither limited to single response improvement nor process / equipment's and product's lifetime maximization [6-7]. The set of works referred to in this section is only a very small part of what could be presented and would result from a further search in the main academic databases (WoS and Scopus). This work is underway, but it is already possible to highlight various distinctive works as examples, namely: a) robustness and performance maximization of projectiles used in grenade launchers [8]; b) reliability improvement of integrated circuits [9]; c) Capacitors lifetime maximization [10]; d) rupture faults minimization of pipes subjected to external hydrostatic pressure [11]; e) asphalt fatigue resistance maximization [12]; f) breakage faults minimization of couplers for railway carriages [13]; g) reliability improvement of aircraft landing gears door lock mechanism [14]; h) maximization of pulley's lifetime in automotive air-conditioning compressors [15]; i) reliability improvement of aluminum packaging equipment for the beverage industry [16]; j) redefinition of the preventive maintenance strategy for locomotive wheels [17]; k) simultaneous optimization of the volume and lifetime of mechanical devices [18]; l) lifetime maximization of diamond-tipped drills [19]; m) simultaneous optimization of the mean and the variance of fatigue life of a lorry cab [20].

Regardless of the scope or areas of activity in which DoE is employed, this tool is particularly appropriate and highly recommendable in the initial phase of experimental studies, the so-called screening phase, where many variables exist and the objective is to identify those with significant effect on the response with a minimum number of experiments and involving the lowest number of resources. DoE is also useful for understanding the relationship between the variables and the response, as well as for optimization purposes. However, several arguments are used to justify the non-use of DoE. The most common are the following: i) human and technological resources are scarce or nonexistent; ii) run experiments is not

feasible due to technical and / or economic reasons; iii) its application is useless or unnecessary; iv) there are no resources with competence to design experiments and analyze their results. These arguments and others listed in [21] show a lack of strategic clairvoyance and a clear ignorance of what the DoE is, so they will be explored in a future work.

3.0 Errors in DoE Usage

It is often said, with some irony, that the best time to draw experiences is after they have been performed. In fact, this sentence means that any experimental study must be both iterative and sequential: a hypothesis is formulated, experiments are run, and from the collected information and/or the achieved conclusions the hypothesis is reformulated, restarting the cycle. Bad practices in the planning and execution phases of DoE are a rich source of learning and an effective way to get confidence and successfully use this tool. Among the most common bad practices are the following:

- Wanting to solve (extremely) complicated problems. In fact, the minimization of the particles deposition inside the heat exchangers of a black liquor recovery boiler is an example of what should not be a priority problem, because most likely this will be a less successful or impossible task to perform in an industrial context for technical and economic reasons associated with the operation of this equipment and its implications in the production process. It is preferable to start with simple problems so that the team involved gains and conveys the necessary confidence to apply DoE in other problems. Nevertheless, complex or more difficult problems, like that of the boiler problem, can be minimized or solved through the so-called Computer Experiments (simulation), as shown by Costa et al. [22].

Solving problems misaligned with the objectives and priorities of an organization or for which it is not possible to estimate the financial return it is also a non-recommended practice. Moreover, to ensure the engagement and availability of resources by management, the estimate financial return that can be obtained from the DoE usage cannot be omitted.

- Poorly defined objective and response. To increase the time interval between preventive maintenance actions on a given equipment by 15% is not necessarily the best way to express the expected result with an experimental study. To achieve this objective could be time consuming and difficult to validate. So this is an unappealing objective. Reducing the mass of accumulated particles on the heat transfer panels of a black liquor combustion boiler would also not be a good response because it would be very difficult to quantify, if not impracticable. The mass of particles entrained by the flowing gases would be an easier response to measure and would even be in line with the above-mentioned hypothetical objective, as the minimization of the mass of particles will increase the time interval between cleaning operations of the boiler heat exchangers may increase and the associated

costs will decrease. Note that popular business drivers are money, timeliness, quality (reliability, safety, ...), and productivity so study objective and expected results must be set in “this language”. The overlap between the objective and the response (process or product quality characteristic / output variable that must be measured) in an experimental study is not uncommon. Study objectives must be clear, succinct, achievable, realistic, relevant, and measurable. Response variable must capture, as much as possible, a quantity or quality of interest for the experimental unit while providing guidelines for measurement accuracy and precision.

- Measurement devices are uncalibrated or inoperative. This issue is (very) usual and invalidates all measurements obtained with the devices. Its correctness is decisive before the experiments are performed.

- Omitting variables and / or assigning less favorable values to variable levels. No problem will be solved if all the variables impacting the response are not considered and their values properly set. To gather a multidisciplinary team to address the problem is fundamental, including the identification and assignment of values to the variables levels, which must be duly substantiated. Testing a variable with an excessively large values range may bias the variable effect and the effect of its interaction with other variables on the response. This problem also occurs when variables range is too small. No less usual is the impossibility of running some experiments. Therefore, a critical analysis of the values assigned to the variables and running test experiments are advisable.

- The number of designed experiments is low. When a too small fraction of the total number of variable levels combination is run, one cannot expect that analysis method yield reliable solutions. This will happen because the effect of some variables and / or their interactions is masked or skewed by the effect of other variables or interactions. To (statistically) design a set of additional experiments is always possible to unmask effects and achieve reliable solutions.

- Randomization and Blocking are ignored. To run the designed experiments under the standard order is violating a DoE’s principle. The randomization of experiments helps to minimize the effect of unknown variables, which can be appropriately estimated and taken into account in the analysis of the results if replicates of each experimental run (treatment or combination of variable levels) are performed. Replications should not be confused with repeated reads of the result of an experiment at a given time. Replicating experiments (doing the same experiment at different time under similar conditions) is another DoE’s principle. The replicas allow us to obtain an estimate of the experimental error and an estimate of the effect of the variables (and their interactions) on the location and the dispersion of the response, the latter being directly related to what is known as system (product / equipment / process) robustness.

Restrictions on randomization due to inability to perform all experiments under homogeneous conditions (without being subject to disturbances introduced by known and controllable variables, like batches of raw material, people, machines, factories, etc.) or because it is convenient due to technical and economic conditions to keep the value of one or more variables fixed are very common occur-

rences in industrial contexts. For example, to randomly perform a set of experiments designed in which the value of one of the variables (the temperature of a furnace) does not change because it is time consuming and / or costly to change its value (the temperature of that furnace) from experiment to experiment, it is translated into what will be called a Split-plot experiment. This is different from the case where, for example, it is not possible to perform all designed experiments with the same lot of raw material, whose effect on the response is not in the interest of the researcher but is known to be a bias factor of the experimental results. In this case it is said that the experiments must be performed in blocks, and the analysis method is different from that of split-plot experiments.

Violation of any of the DoE's principles (Randomization, Blocking and Replication) will bias the experimental results and, most likely, the study conclusions. Therefore, in contrast of what often happens in practice, none of these principles must be ignored or overlooked.

-Analysis methods assumptions are not validated. Statistical techniques are used in the belief that analysis methods assumptions are irrelevant, so their checking is sometimes omitted or ignored [3]. However, all formal statistical analyses require certain assumptions to hold in order to be valid. As examples, most analysis methods of unreplicated two-level factorial designs used in the screening phase of experimentation assume that data follow a normal distribution and do not include outliers; results of the Analysis of Variance (ANOVA) method, which is used in characterization and optimization phases of experimentation, are sound if the following assumptions are validated: i) each sample (observations of a treatment or combination of factor levels) approximate a normally distributed population (or dependent variable approximates a multivariate normal distribution); ii) all samples have a common variance (or error variances of all data points of the dependent variable are equal or homogenous throughout the sample); iii) All samples are drawn independently of each other; iv) Within each sample, the observations are sampled randomly and independently of each other. Residual analysis is recommended for this purpose (see [23], as example).

- Incorrect choice of response modelling methods. The relation between the variables and the response should not always be established with the Ordinary Least Squares (OLS) method nor must the adequacy of the model fitted to response be assessed only with the popular Pearson Coefficient (R^2). It is advisable to consider the adjusted R^2 and the predicted R^2 as well, though other metrics and the analysis of residuals must be used. Operating times up to the occurrence of a failure (life or use) of a product, equipment or component is an example of a response that should not be modeled with the OLS method. For this kind of responses, or any others in which the statistical distribution that best fits the results of the experiments is not Normal, but Weibull, Exponential, lognormal or Gamma, the identification of variables with a significant effect on the response cannot be done with ANOVA and the response modeling has to be performed with an alternative method to OLS method. For example, the Generalized Least Squares method must be used when the residuals variance is not constant and / or the residuals are not in-

dependent. The Weighed Least Squares method is another alternative when the residuals variance is not constant. Either of these two methods can be used when response values are censored. For this type of data, the ML (Maximum Likelihood) method can also be an alternative, especially when the amount of data (sample) is large [24]. When there are restrictions on randomization of experiments, the Generalized Linear Mixed Model is the most appropriate response modeling method [25].

- Properties of optimal solutions are ignored. For problems with multiple responses there is not a unique (optimal) solution. So solutions reproducibility cannot be ignored in the solution selection procedure in order to assure that product or process will perform as expected when theoretical results are implemented in productive environments. As alternative to the current practice of identifying an optimal solution based on the value of optimization criterion used, usually a desirability-based criterion, metrics and graphical tools for qualitative and quantitative assessment of optimal or Pareto solutions are available and recommended [26].

- Undesired or unplanned events are omitted. A detailed planning is crucial to obtain reliable conclusions from experimental studies so no statistical and non-statistical issues can be omitted in the experimental plan. Nevertheless, undesired or unplanned events may occur during the experiment, such as changes in the environmental and/or technical conditions under which the experiments should be performed, namely changes in the runs order, in the factor settings, and the replacement of machines or people. All the unplanned events have to be recorded because they can help to find solutions for avoiding them in future experiments and need to be taken into consideration in the data analysis. In any case, efforts (training and checking practices) should be undertaken to avoid any kind of changes in both the planned activities and procedures for running, collecting and recording data.

4.0 Conclusion

The design and analysis of experiments is useful for designing and improving products and processes / equipment. It allows the generation of data in a structured way to understand the phenomena and achieve solutions to problems with a minimum use of resources and in the shortest time period. Bad practices (common errors or bad practices) at the planning and execution stages of DoE are also revisited and recommendations to avoid them are provided. This way, criticisms or depreciation of DoE usefulness as consequence of disappointing study results become meaningless.

This work intends to foster the DoE usage in problems faced by maintenance managers as well as researchers and practitioners in industry and academy. Various case studies validate the applicability and usefulness of this tool in the

maintenance field, without assuming that DoE is a magic wand that applies and solves all problems, namely those of product and process /equipment quality (reliability, availability, performance, robustness, productivity, etc.) improvement. It is also important to highlight that existing software considerably facilitates calculation tasks, but it does not exempt the user from having theoretical knowledge on DoE and subject matter to support their options and to be critical about the results achieved. Today it is widely accepted that many of the studies where DoE is employed fail due to lack of planning. It is therefore necessary to ensure that DoE users will be sensitized to criticality of non-statistical activities to be considered before, during, and after running the experiments, especially those activities highlighted in the previous section of this article.

For future work the authors leave as suggestions a further review on the literature and illustration of some (easy-to-use) analysis methods to solve problems that are found in the scope of maintenance management. We also notice that although many researchers are using computer experiments (simulation) to solve many types of problem, DoE will keep a key role in this approach, both in identifying the variables with significant effect on the response(s) and building metamodels for (multi)response optimization purposes in a structured and faster way.


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ME2018_1123**Pipeline inspection and maintenance via acoustic methods and tools****Kassandra A. Papadopoulou¹, Saeed Abdullah Alzahrani², Jyoti Sinha²**

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Abstract There is a wide variety of pipeline inspection tools and each one has its advantages and limitations. This paper presents a study used for the development of a novel pipeline inspection tool for the oil and gas industry using acoustic reflectometry. A review of inspection techniques is presented with a focus on acoustic techniques as reliable and accurate inspection methods. A set of experiments is carried out to investigate acoustic reflectometry as a pipeline inspection tool. Inspection of a single leakage, a fault 1.5 mm in diameter, in a 30 m straight pipeline is carried out in order to detect and locate it as accurately as possible with the acoustic wave being injected from one side of the pipeline. Then a relation between the reflected leakage signal amplitude and the leakage size is established and described so that the leakage size can be estimated if the signal amplitude for the particular pipeline setting is known. In order to obtain a high amplitude reflected signal to maximise energy input, an injected signal frequency needs to be properly chosen. This helps to read the fault signal easily and precisely. This experiment was repeated each time on a single leakage (1.5 mm in diameter) for five different distances from the signal injected. This was then repeated for the same distances from the acoustic wave injected with additional sized leakages: 1.5 mm, 2 mm, 2.5 mm and 3 mm in diameter. Hence, the fault signal amplitude which resulted from various injected signals is analysed and presented with respect to the injected acoustic signal injected.

Key words acoustics, pipeline, maintenance, inspection tool, acoustic reflectometry, leakage detection.

1.0 Introduction

Over the years, pipelines have been subjected to various forms of failure due to internal or external factors. In other words, in some cases, pipelines might be affected by unusual working conditions which result in leakages, blockages or even damage. Besides, corrosion affecting pipelines, could also be a result of environmental influence. As a consequence, the pipeline deteriorates and then fails. Furthermore, poor manufacturing processes may sometimes, result in defects which in turn develop into failures. For example, non-uniformity in pipeline wall thickness may lead to a breakage or crack.

In the case of oil and gas industry, deterioration and failure of pipelines is of critical importance mainly due to the fatalities, injuries and costs [1]. Data from [1] indicates that material, weld or equipment failure has the highest percentage of repeated failure causes, which would include various types of leaks in the pipeline. The EGIG conducts a failure frequencies analyses for gas pipelines and describes the failures in relation to type and size of leak. The highest percentage of detection of incidents is a combination of pinhole/crack and hole type leaks at approximately 85% [2]. The industry is open to methods including detection and inspections techniques that can improve the reliability of the systems [3]. The need for accurate and quick inspection tools becomes necessary, especially when pipelines extend for long distances.

Pipelines are susceptible to breakdowns, for this reason, different studies are carried out to locate the pipe fault like Acoustic Ranger tool (AR) [4], Impact Echo Technique [5], EMAT technique [6] and Acoustic Reflectometry Technique [7], but even more focus is required to study the relation between fault signal properties and fault size and location.

Visual image inspection technique is the traditional tool [8] which depends mainly on monitoring the pipeline and provides an image illustrating the location of the defect. This technique is not applicable for some pipelines that are installed in water depths, buried under soil and extended for hundreds of miles. In these cases, it is difficult to visually decide where failures occur, and in order to monitor them it is not feasible and economical to mount sensors along the whole length of the pipeline. For these reasons, there is a need for advanced and effective inspection tools like acoustic inspection techniques [7, 9-13].

Pipeline length, material and configuration play an important role when choosing the inspection method. For this reason, a set of experiments have been carried out to investigate the appropriate inspection tools for such pipelines [6, 14]. Analysis of a reflected signal is used to identify the defect mode and location [5, 15]. The detailed theory and methodology of the acoustic reflectometry used is described in [7, 15-17]. There is a strong relationship between acoustic waves, pipe size and working conditions. According to different experiments that have been carried out, it was found that the transmitted wave's properties, such as velocity, wave length and signal strength, can be used to identify the type of material from which the pipe was made [18].

The current study again investigates the acoustics as pipeline inspection tools to find a better method so that the size of the leakage and blockage can be estimated based on the associated frequency peak and its amplitude in the reflected leakage acoustic signal. The short time Fourier transformation (STFT) is applied to the track the different frequencies presence in the signal with respect to time.

2.0 Experimental set-up

Experiments were carried out based on acoustic signal generation and then observation is made on its propagation, reflection and behaviour along a pipe. This was done using the apparatus arrangement shown in Figure 1 [16] and pipeline arrangement as in Figure 2. The rig consists of a PVC pipe, with an internal diameter of 42 mm and 4 mm wall thickness filled with stagnant air at 17.2 °C (for the multi leaks at 16 °C). The pipe is an open-ended pipe at 30.14 m, which is verified using the reflectometry technique as well. The experiments were carried out by introducing a number of circular holes with different hole diameters and the reflected leakage acoustic signals generated for all cases were recorded for the further analysis.

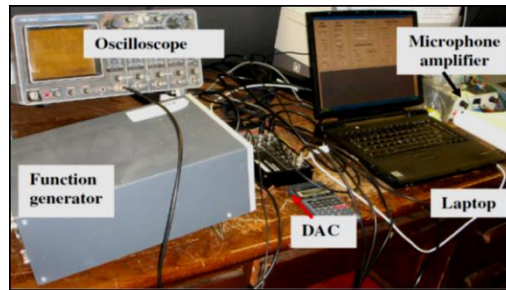


Figure 1 Experiment's apparatus including function generator, oscilloscope, data acquisition card, laptop and microphone amplifier [16]

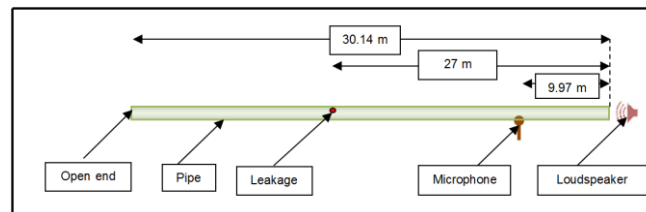


Figure 2 The pipeline arrangement for the simulated leakage at 27 m

3.0 Observations and results

The measured signals are analysed in time domain analysis initially and then in frequency domain for both a single leakage and multiple leakages.

3.1 Time domain analysis

Time domain illustrates the relation between the signal amplitude and the time it needs to reach the pipe defect and reflect back. The first task is to establish a signature signal. This is to inject the initial signal inside the healthy pipe in the absence of defects and then repeat the same process and send the same signal in presence of defects. The interrupted signal will be reflected back from the fault and appears in the leakage signal recorded. This is typically shown in Figure 3 for the different injected frequencies ranging from 55 Hz to 20,000 Hz. Hereafter the only 4 injected frequencies 880 Hz, 1000 Hz, 3000 Hz, 7000 Hz are discussed further in the frequency domain analysis.

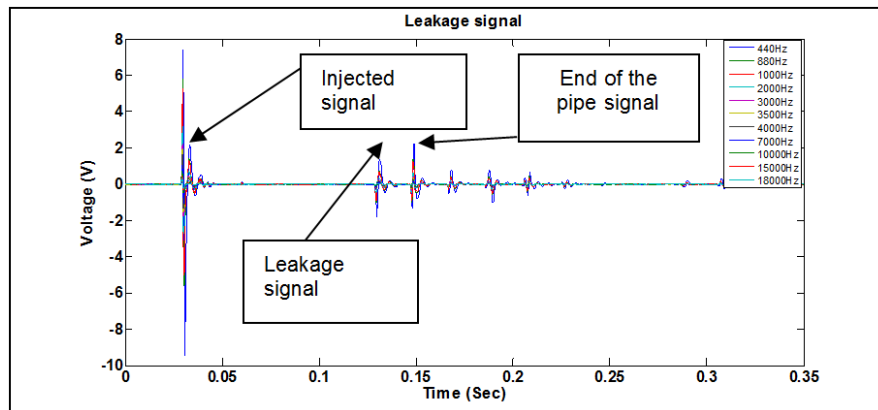


Figure 3 Leakage signal illustrated on time and voltage coordinates

3.2 Frequency domain analysis

Having determined the leakage location, the following step is to find the frequency associated with the leakage signal. The aim of this step evaluates if there is a relation between the hole size and the leakage signal frequency so that the leakage size can be estimated. Both spectrum and the short time Fourier transformations (STFT) analyses were carried out.

Two types of experiments are carried out on the same pipeline, one with a single leakage hole and other with a single leaking hole but at 5 different locations in the pipe and of 4 different hole sizes. The observations and results are discussed here.

3.2.1 Single leakage location

The signal is sent using a loudspeaker that is fixed on the pipe inlet and the leakage signal is picked by a microphone located at a distance of 9.97 m from the loudspeaker (pipe inlet). Figure 4 shows the spectrum of the reflected leakage signal for an injected signal of 880 Hz and the leakage hole of 1.5 mm.

As observed, the frequency around the leakage location is at the region of 200 Hz which is assumed to be the frequency of the leakage signal. The STFT analysis was also carried to further understand that whether this 200 Hz is appearing at the pulse location or not. The spectrogram contour plot of the STFT analysis is shown in Figure 5 which clearly shows the frequency peak at around 200 Hz at the pulse location in the leakage signal. Therefore, it can be assumed that the frequency of 200 Hz represents the defect size of 1.5 mm in the pipe.

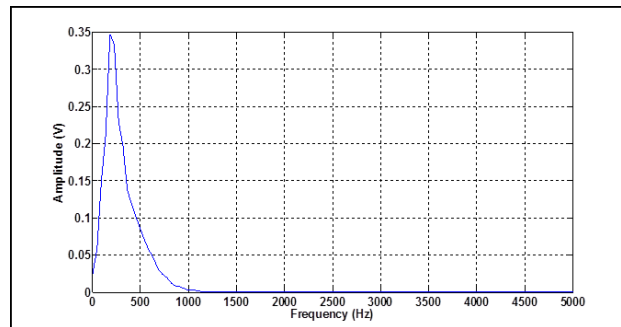


Figure 4 Spectrum of the reflected leakage signal for the input injected signal at 880 Hz and leakage hole size 1.5 mm

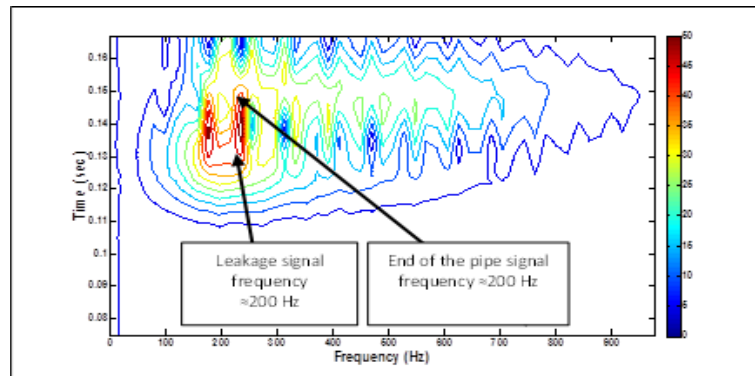


Figure 5 Spectrogram contour plot of the reflected leakage signal for the input injected signal at 880 Hz and leakage hole size 1.5 mm

In further strengthening this observation, the reflected leakage signals for the injected signals at 1000 Hz, 3000 Hz, and 7000 Hz were also analysed. The spectrogram contour plots are shown in Figure 6 that again indicates the presence of 200 Hz irrespective of the injected signal frequencies. Hence the frequency at around 200 Hz can be considered as the indicator of 1.5 mm leakage hole for the pipe used in the experiment.

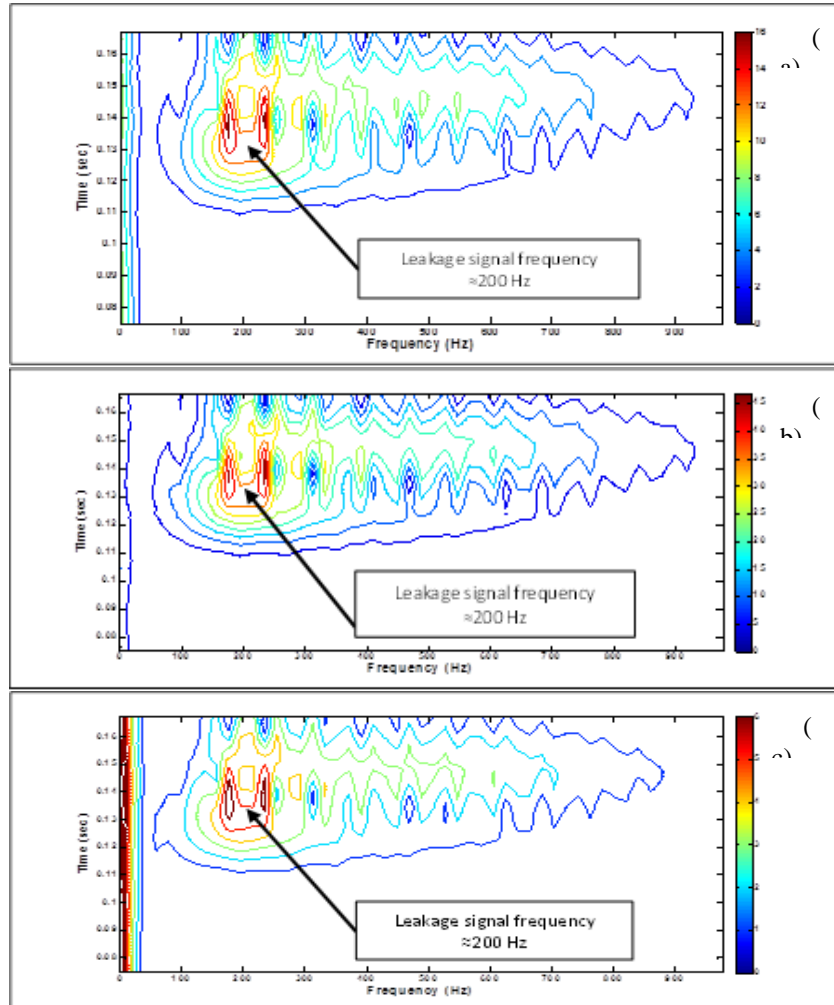


Figure 6 Spectrogram contour plots for of the reflected leakage signals for the leakage hole size 1.5mm in the pipe but the input injected signals of frequencies (a) 1000 Hz, (b) 3000 Hz and (c) 7000 Hz

3.2.2 A single leakage hole at different locations and of different sizes

The experimental setup shown in Figure 2 was then modified pipes having a single hole at different locations and different sizes, as shown in Figure 7. In this part of the experiments, the different hole sizes of 1.5 mm, 2 mm, 2.5 mm, 3 mm and different locations noted as L1, L2, L3, L4, L5 (at 13 m, 16 m, 19 m, 22 m and 25 m from the loud speaker location) were used.

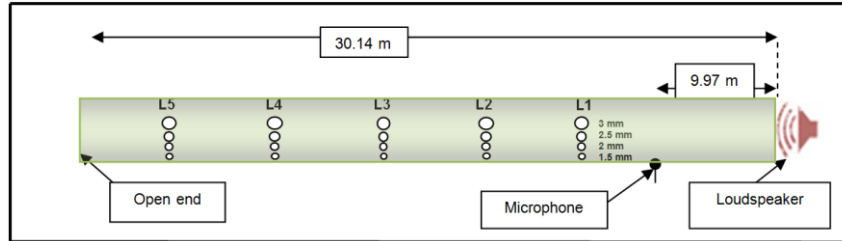


Figure 7 Experiment set up showing different hole locations and their sizes

Figure 8 provides the spectrogram contour plots for a single hole at the location L3 (19 m) the hole sizes used were 1.5 mm, 2 mm, 2.5 mm and 3 mm and the input injection signal of 110 Hz was used for all cases. As seen in Figure 8, the frequency at around 180 Hz is appearing for all cases irrespective of the hole sizes. The variation in the frequency is due to the change of the fluid properties where in the single leak inspection, the temperature was 17.2 °C for the first set of experiments (as in sections 3.1 and 3.2.1), and 16 °C for the second set of experiments.

Exactly similar observations were also made for a single hole of different sizes but at the different locations in the pipe. This indicates the presence of frequency around 180-200 Hz which is the leakage frequency. However the amplitudes of the leakage frequency peak around 180-200 Hz were different for the different sizes holes which highlights the possibility of estimating hole sizes.

4.0 Concluding remarks

The study clearly indicates the appearance of frequency peak at around 180-200 Hz (depending upon the fluid properties) if there is a leakage hole in the pipe. This observation was consistent irrespective of the hole sizes, hole locations and the input injected signal frequencies. The amplitude of the frequency peak may provide the information for the determination of hole size which is underway.

It is likely that the poor resolution in the STFT analysis for such transient signals was not able to show the shift in the frequency depending upon the size of the holes so different signal processing techniques such as the wavelet analysis should be looked into.

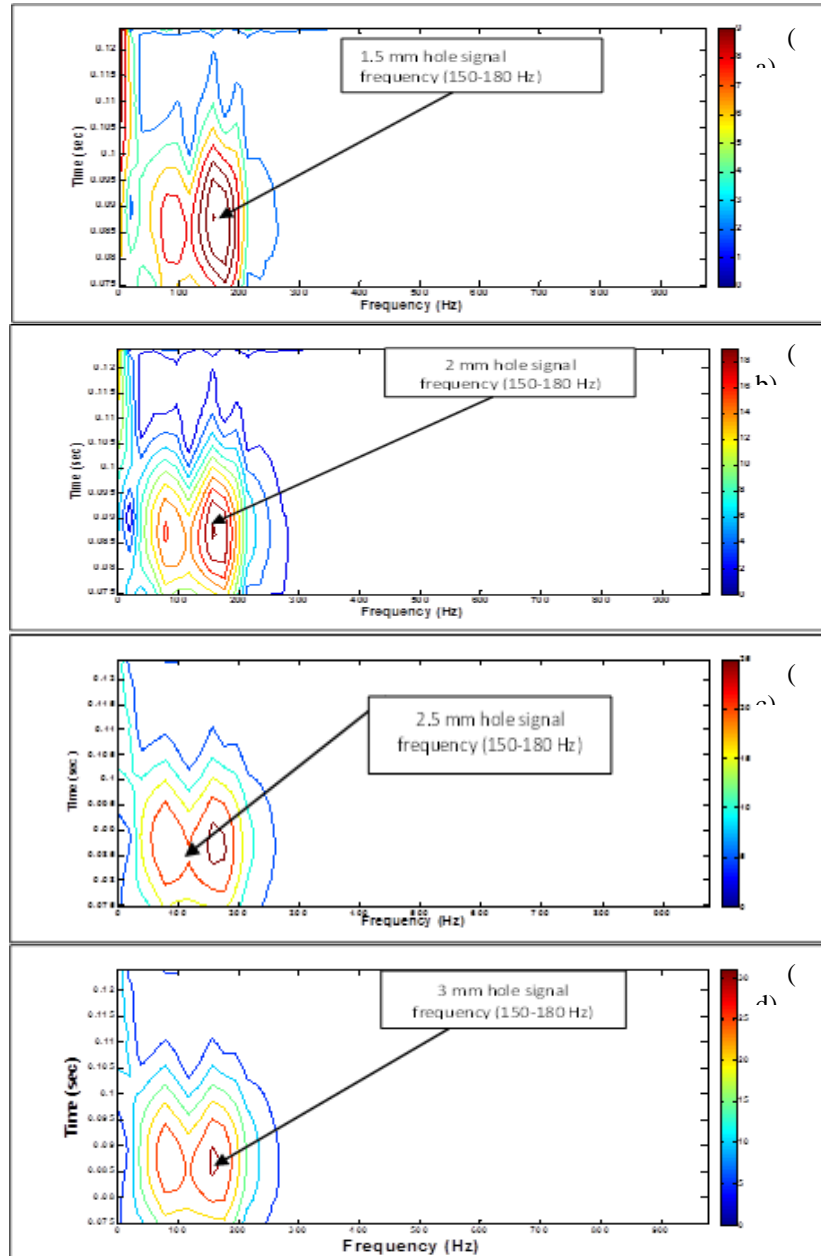


Figure 8 Spectrogram contour plots for of the reflected leakage signals for a leakage hole in the pipe and the input injected signals of frequency 110 Hz for different hole sizes (a) 1.5 mm, (b) 2 mm, (c) 2.5 mm, (d) 3 mm



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A Decision Support Framework for Human Reliability Analysis

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Abstract Human behaviour is often a root or significant contributing cause of a system failure. This observation has been known for more than 30 years and it has been recognised that the role of human operations is critical in risk assessment of plant operations. This has led to the development of more than 70 methods which are known as human reliability analysis (HRA). HRA accounts for the effects of human error in risk and reliability analysis. This paper reviews and discusses HRA methodologies, suggesting that there is a need for considerable further research and development before they meet the needs of modern risk and reliability analyses. In addition, there is a need that HRA methods are able to provide decision-makers with the guidance they need to manage complex systems effectively. Therefore, the aim of this study is to propose a Decision Support Framework for Human Reliability Analysis which helps analysts and decision-makers to consider and manage risk in a complex system more effectively.

Key words Human Reliability Analysis; Decision Support System; Risk Assessment.

1.0 Introduction

Human error is a major contributor to the risk in industry. For example, 37.64% of the US railways accidents are caused by human errors [1]. Additionally, 80% of marine fatalities and shipping accidents are caused by human errors [2, 3]. This has led to catastrophic consequences which urge the need to study, understand, analyse and evaluate human errors in order to help designers and engineers to eliminate or reduce risk.

Traditionally, human reliability is not considered in the design and risk analysis processes. This could be due the lack of data in a particular industry. During the

design stage a thorough assessment of human factors is key for optimising the design and ensuring high levels of reliability and safety during operation. The consideration of human factors; however, can be a challenge during the design stage especially where there is a high level of innovation, very little applicable historical data and a high level of uncertainty. One of the ways in which human factors can be considered is by including the end users and all other key stakeholders within the design process. There are several design methodologies that integrate human factors within the design process [4]. However, the collection and assessment of the necessary data remains a challenge [5]. Despite the current issues with data collection, consistency of analysis and accuracy, such issues can be slowly addressed as industry moves into the big data era. This opens a bigger scope for the integration of human factors within the design development process at an early stage. There is a need for defining the data requirements in terms of human factors as well as the analytical process. There are many areas where HRA can be used. First, in the design of a system when human is involved and their behaviour can affect the overall system. Second, during the licencing discussion in order to show that a system can meet safety or legislations requirements. Third, HRA can be used during the modification of a system [6]. It can be concluded from this that HRA can be a powerful assessment in any stages of a plant life-cycle.

The aim of this study is to propose a decision support framework for human reliability analysis which helps analysts and decision-makers to consider and manage risk in a complex system more effectively.

This paper is structured as follows. **Section 1** introduces the problem statement and objective of this study. **Section 2** reviews briefly common HRA methods, human error classification, and some of the decision – making methods that can be used later in the study. **Section 3** illustrates the general steps which are required to conduct a HRA, and proposes the decision support framework for human reliability analysis. **Section 4** discusses some of the attributes, strengths and weaknesses which are considered in selecting and evaluating a HRA method. **Section 5** concludes this study and highlight some of the future research directions.

2.0 Literature Review

Human Reliability Analysis (HRA) is a section of the reliability discipline where an overall human performance is studied [7]. There are more than 70 HRA methods have been developed in the past 50 years. Some of these methods are not publicly available which make them difficult to review. It is estimated that 35 of these HRA methods are used in various industries [6]. Initially, most of these

methods are developed for the use in the nuclear power industry [8 - 11]. Later, these methods are utilised in pharmaceutical industry [12], aviation industry, railway [1], and maritime industry [3, 8, 13]. HRA were developed differently because of the fact that a particular method can differ in terms of the purpose, scope, level of task decomposition, human errors, quantification of human error opposability (HEP), and how to represent the results. This has led to a lack of consistency which has led to different results and different HEPs [6]. Human reliability analysis can be defined as *the probability of a person to correctly perform an activity, and perform no extraneous activity (with no connection with the task) that can degrade the system* [10]. This human error probability (HEP) can be calculated by **Equation 1**. Human performance can be represented as Performance shaping Factors (PSF), Performing Influence Factors (PIF), and Error Producing Conditions (EPC).

$$HEP = \frac{\text{Number of errors}}{\text{Number of opportunities for error}} \quad \text{Equation 1}$$

In literature, researchers classify HRA methods into two generations. The HRA first generation is developed based on the study of human error probability and does not consider the cause of behaviour [14]. Some of these methods are: Technique for Human Error Rate Prediction (THERP) [10], Accident Sequence Evaluation Program (ASEP) [15], Human Error Assessment and Reduction Technique (HEART) [16], and Simplified Plant Analysis Risk Human Reliability Assessment (SPAR-H) [17]. These methods break a task into component parts to calculate the HEPs and later consider potential impact of modifying factors such as pressure and stress [7]. The model of the human behaviour in the HRA first generation is shown in **Figure. 1**.

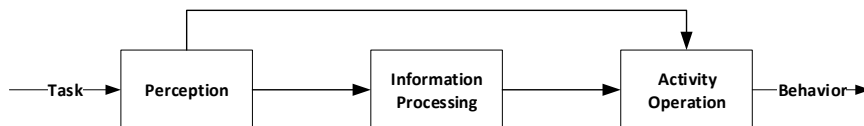


Figure. 3 A model of human behaviour in HRA first generation [7]

The second generation methods consider the context as a factor affecting human performance failure and later evaluate the relationship between the context and HEPs [2]. Some of these methods are: A Technique for Human Event Analysis (ATHEANA) [18], and Cognitive Reliability and Error Analysis Method (CREAM) [19]. These methods consider cognitive behaviour of the human. The activities of the human are assumed as performed for specific purpose, which is illustrated in **Figure. 2**.

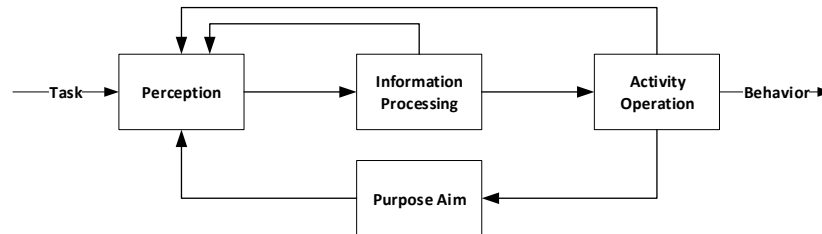


Figure 4 A model of human behaviour in HRA second generation [7]

Some researchers have added a third generation in HRA methods, which considers dynamic simulation system with a virtual representation of human to determine challenging human performance situations [14]. The following subsection review some of the most used HRA methods in the 1st and 2nd generations.

2.1 Human Reliability Analysis (HRA) Methods

Firstly, the following methods are considered as 1st generation HRA. **A) Technique for Human Error Rate Prediction (THERP)** which was developed in the Sandia Laboratories for the US Nuclear Regulatory Commission [10]. It is a very well-known and structured tool based on event-tree approach for evaluating the probability of a human error. This method builds a tree of events and it quantifies the associating scenarios to each outcome a nominal error probability. The method can be developed in the form of procedures and may be applied in several areas. **B) Success Likelihood Index Method (SLIM)** which assesses the likelihood of error, based on indicators defined by the experts, with a computerized procedure [14]. **C) Human error assessment and reduction technique (HEART)** was developed by Williams in 1986 for use in overall engineering systems [16]. HEART considers all of the factors that adversely affect the performance and the execution of an activity, each independently, in order to obtain a total error probability. There are 9 Generic Task Types (GTTs) described in HEART, each with an associated nominal human error potential (HEP), and 38 Error Producing Conditions (EPCs) that may affect task reliability, each with a maximum amount by which the nominal HEP can be multiplied. **D) Standardized Plant Analysis Risk – Human RA (SPAR-H)** was developed for the US Nuclear Research Commission, Office of Regulatory Research [17]. This method divides causes of error into *diagnosis* and *action*. The model considers the context through the use of 8 PSFs namely: Available time, Stress and stressors, Experience and training, Complexity, Ergonomics and Human Machine Interface, Procedures,

Fitness for duty, Work processes. The model is simple, quick and easy to use. It can be extended to other sectors.

Secondly, the following methods are considered as 2nd generation HRA. **A) Cognitive Reliability and Error Analysis Method (CREAM)** was first proposed by Hollnagel in 1998, which was originally developed for nuclear power plant applications [19]. This method evaluates the effect of the context of risk of error and pays great attention to the control of the scenario in which the operator works. The method integrates individual factors, technological and organisational. CREAM encompasses the influence of human reliability into 9 factors which are called Common Performance Conditions (CPCs) namely: *1. Adequacy of organisation. 2. Working conditions. 3. Adequacy of the man-machine interface and operational support. 4. Availability of procedures/plans. 5. Number of simultaneous goals. 6. Available time. 7. Time of day. 8. Adequacy of training and experience. 9. Quality of crew collaboration* [19]. According to human cognition and action, there are four characteristic control modes which are determined by the CPCs, namely: “Scrambled”, “Opportunistic”, “Tactical” and “Strategic” [19]. The control modes are linked to different failure probability intervals representing human action failure probabilities. **B) A Technique for Human Event Analysis (ATHEANA)** was developed for the US NRC [18]. This method identifies faults and their causes. The method considers human errors can be occurred as a result of “error-forcing contexts” (EFCs). It does not decompose actions under activities, but it describes the basic process of the operators [14]. These methods will be more analysed and reviewed in a greater depth in the future; **Section 4** shows strengths and weaknesses of some selected HRA methods.

2.2 Human Error Classification

A human error can be defined as an *action that goes beyond the acceptable limits, those being defined by the system* [10]. Human error can be categorised as skilled – based, rule – based, and knowledge – based. First, skilled – based behaviour requires little or no mental effort such as cycling or switching gears when driving. The error probability in this type can be estimated from $1/200$ – $1/20,000$. Second, rule – based behaviour is when performing an activity needs to follow a specific procedure or guidelines. For example, when an operator conducts an infrequent test. The error probability in this type can be estimated from $1/20$ – $1/2,000$. Third, knowledge – based behaviour (*i.e. cognitive behaviour*) requires significant mental activity to process and solve a problem or take a decision. The error probability in this type can be estimated from $1/2$ – $1/200$ [6]. Alternatively, human error can be classified as *omission* and *commission* errors, which can be seen in **Figure. 3** [10]. An omission error is when a person does not perform a

task at all or not on time. A commission error is when a person perform a task incorrectly, poorly, or with wrong parameters.

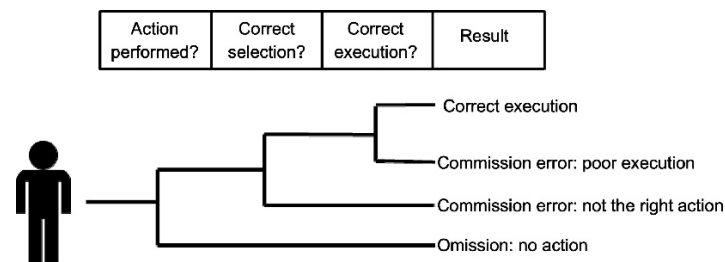


Figure. 5 Representation of the classification via an event tree [10].

2.3 Decision – Making Methods

Engineering problems can be solved by decision – making methods which include three main groups: Multi – Criteria Decision – Making (MCDM) methods [20], Problem Structuring Methods (PSMs) [21], and Decision – Making Problem – Solving (DMPS) methods [22]. Each of these group has its characteristics, applications, strengths and weaknesses. The MCDM can be further divided into: *Multi-Attribute decision-making (MADM)* methods which deal with a finite number of alternatives and a discrete solution space; and *Multi-Objective decision-making (MODM)* methods searches within an infinite (and unknown) set of solutions in a continuous space [22]. Methods of MADM are the Multi-Attribute Utility Theory (MAUT), the Analytic Hierarchy Process (AHP) [23], the Analytic Network Process (ANP) [24], the VIKOR method [25], Goal Programming (GP) [26], and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [27]. On this stage of this study, the focus will be only on the first group which is MCDM. Later, there will be further review and analysis to select which MCDM will be chosen and why.

3.0 Methodology

Different HRA methods have different approaches in order to complete both the quantitative and qualitative phase of the analysis and then calculate the HEPs for a task and later perform a human error management. Generally, most HRA methods follow the following 10 steps which include: 1) Examining the system in detail, 2) Reviewing existing risks, 3) brainstorming human activities that could lead to a

potential failure in performing a task, 4) detailing activities that could lead to commission or omission errors, 5) assigning a HEP for each activity, 6) modifying the HEP by applying PSFs, 7), assessing probabilistic dependences between human activities, 8) calculating the overall HEP_{system} for the task, 9) considering recovery actions to eliminate, mitigate, or reduce risks, 10) conducting sensitivity analyses [28].

The proposed framework in this paper, which can be seen in **Figure. 4**, is conceptual model that can meet the objective of this study. The framework consists of seven main processes which will help analysts and engineers to conduct a HRA more efficiently and effectively. First, the initial scope of this study is to consider generic maintenance tasks which can be performed in various industries. Therefore, the first step is define the problem and determine the scope of the analysis in order to formulate a maintenance task. Second, a maintenance task is broken down into steps and human activities. These activities could include physical activity or cognitive activity. This step is also known as task decompositions. Third, since there are a number of GTTs, EPCs, PSFs, and different maintenance scenarios, a MCDM method will be used in order to calculate the importance weight of the criteria and to obtain relative performance measures of the alternatives, i.e. a maintenance task will be assigned and analysed by the optimum method. The framework considers THERP, HEART, CREAM, and ATHEANA on its analysis. These selected methods are based on a number of attributes which will be mentioned on **Section 4**. Fourth, human errors will be identified in this process. It is important to identify both commission and omission errors in this step. Fifth, human errors will be represented and modelled in order to help the analysts to understand the relationships of all factors that could generate risk. Sixth, each human error will be quantified by assigning a probability of failure. This will help to determine which human errors are the significant contributors to the overall HEP. This step heavily depends on the availability of data and the used method. Seven, if the overall HEP value is acceptable and does not generate risk, a maintenance task can be performed. If the overall HEP value is not acceptable, a human error management should be conducted. This step is the most important process in the whole HRA. In this process, a recovery actions can be taken in order to eliminate, reduce or mitigate risk. This can be done by including barriers to prevent errors, or provide means to perform a task correctly. Finally, the result of this analysis will be reported back in order to update the original maintenance procedure. This will help to continuously improve the system.

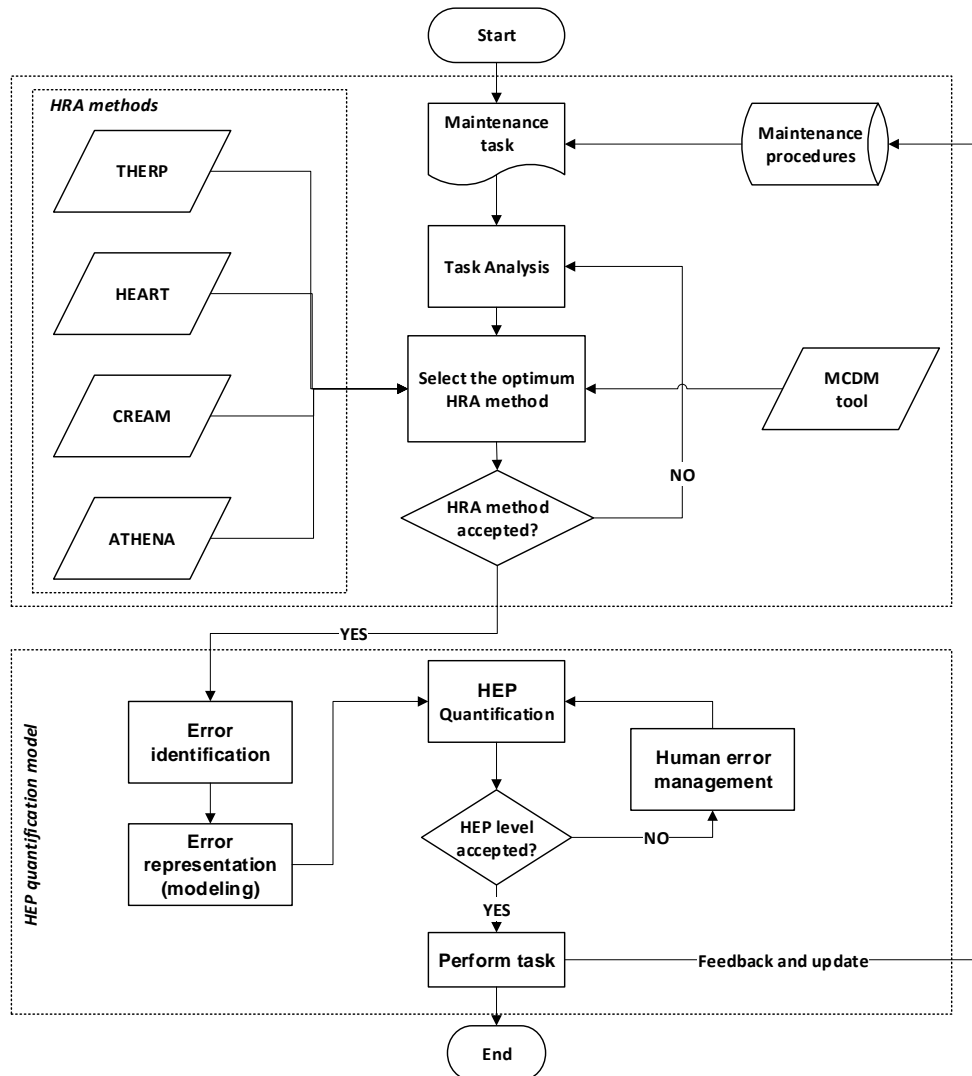


Figure. 6 The proposed Decision Support Framework for Human Reliability Analysis

4.0 Discussion

Since there is no a single HRA method that can solve most engineering problems, there is a need to understand the capabilities, strengths and weaknesses of each method. This has motivated the author to provide this decision support framework in order to carefully choose a method that not only to simplify the selection process, but also to use the selected HRA method effectively.

This study considers four HRA methods including: 1st generation (THERP and HEART), and 2nd generation (CREAM and ATHEANA). These methods are selected based on the following attributes: 1.purpose of the method, 2.screening 3.capability, 4.task decomposition, 5.list of PSFs, 6.errors coverage (i.e. data availability), 7.HEP calculation procedure, 8.task dependency and recovery, 9.HEP uncertainty bounds, 10.level of knowledge required, 11.validation, 12.reproducibility, 13.sensitivity, and 14.availability of the method in the public domain.

There are many challenges in performing a HRA [29]. First, there is still a lack of empirical data to model and validate a method. Second, there is a large variability in implementation. This is one of the motivated reasons to develop this proposed framework. Third, there is a great reliance on expert opinions in selecting PSFs. This could be limited when performing an unfamiliar task. Fourth, some of the HRA methods does not specify how to complete a task analysis or quantify an error [30]. This is why the proposed framework will guide the user on how to conduct the analysis. Last, **Table.1** and **Table.2** briefly highlights the strengths and weaknesses of the selected HRA methods.

Table.6 Strengths and weaknesses of the selected HRA methods [9]

Human Reliability Analysis method		Strength	Weaknesses
1 st Gen.	THERP	<ul style="list-style-type: none"> • Used in design stages. • It can be audited. • It is well-used in practice. 	<ul style="list-style-type: none"> • It is a time consuming. • Level of detail can be extensive. • Modelling a scenario is not guided.
	HEART	<ul style="list-style-type: none"> • It is easy and quick to perform. • It uses limited resources. • It suggests how to reduce errors. 	<ul style="list-style-type: none"> • Error dependency modelling is not included. • It needs more clarification to help the user to distinguish between GTTs and EPCs.

Table.7 Strengths and weaknesses of the selected HRA methods [9] (Cont.)

Human Reliability Analysis method		Strength	Weaknesses
2 nd Gen.	CREAM	<ul style="list-style-type: none"> • It is well structured. • It follows a well laid out procedure. • It allows for a direct quantification of HEP. • It uses principles of predictive analyses. 	<ul style="list-style-type: none"> • It is time consuming. • It needs high level of resources. • It potentially fails to provide means to reduce errors.
	ATHEANA	<ul style="list-style-type: none"> • Key risks are likely to be identified. • It helps to identify of human factor(s) is a cause of an accident. • It considers a wider range of PSFs. • HEPs can be estimated in this method by a variety of factors and combinations. 	<ul style="list-style-type: none"> • It does not prioritise human factors that contributed to an accident. • The quantification is weak in this method. • The guidance in this method is complex.

5.0 Conclusion

It has been found that human behaviour is a significant contributing cause of a system failure. 80% of marine accidents are caused by human factors. This paper has introduced the concept of HRA and presented why there is a great need to perform such an analysis. Currently, there are more than 70 HRA methods that have different characteristics and different procedures. As a result of the discussed limitations and challenges in **Section 4**, the aim of this study was to propose a decision support framework for human reliability analysis which helps analysts and decision-makers to consider and manage risk in a complex system more effectively. The proposed framework has a systematic processes which can be easily followed. This framework has considered four HRA methods including: THERP, HEART, CREAM, and ATHEANA. The reasons of this selection was based on the number of attributes mentioned on the discussion section. Since this is still a conceptual framework, the study will identify which MCDM method can be used, formulate a number of maintenance scenarios, conduct and validate the proposed framework.

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A Structural Model of the Impact of Organisational Culture on Participation of Autonomous Maintenance in the Power Industry

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Abstract The implementation of modern maintenance strategies has a positive impact on improving industrial assets. There are examples of asset high performance, quality, and reliability being achieved through successful maintenance approaches. Total Productive Maintenance (TPM) is an ideal approach to support the development and implementation of operation performance improvement. It systematically aims to understand the function of equipment, service quality relationship with equipment and probable critical equipment failure conditions. Implementation of TPM programme need strategic planning and there has been little research applied in this area within Middle-East power plants. Employee Empowerment is one of the main criteria in TPM implementation. TPM programme will not work without empowering the operators or the production workers to carry out the autonomous maintenance. However, there is a clear lack of literature that explores the influence of employee empowerment on autonomous maintenance participation and therefore, this research aims to examine the impact of organisation culture on the participation of autonomous maintenance within power plants using a structural equation modeling approach. Hofstede's (1980) dimensions of culture (power distance, collectivism/individualism, masculinity/femininity, and uncertainty avoidance) were used to inform the theoretical framework. Data were collected from 124 professionals in the Abu Dhabi power industry using a postal questionnaire. Structural equation modelling, using partial least squares path analysis (SmartPLS software version 3.0), was performed to test the hypothesised model. Participants in the study were requested to answer three main questionnaires: Hofstede's cultural dimensions questionnaire, structural employee empowerment questionnaire, and participation of autonomous maintenance questionnaire. Findings indicated that power distance and masculinity/femininity dimensions had a direct negative and meaningful effect on employee empowerment. On the other hand, collectivism had a direct positive effect on employee empowerment. Furthermore, structural empowerment had a direct positive impact on autonomous

maintenance participation in the power industry. Besides, the effect of uncertainty avoidance on structural empowerment was not statistically significant. In short, the findings confirmed the role of organisational culture and structural employee empowerment in participation of autonomous maintenance. This research will contribute to bridge the current gap in knowledge.

Key words Total Productive Maintenance (TPM); Participation of Autonomous Maintenance; Structural Employee Empowerment; Structural Equation Modelling

1.0 Introduction

The implementation of modern maintenance strategies has a positive impact on improving industrial assets. There are examples of asset high performance, quality, and reliability being achieved through successful maintenance approaches. Total Productive Maintenance (TPM) is an ideal approach to support the development and implementation of operation performance improvement. Principally, TPM empowers employees by giving them mutual responsibilities and a sense of ownership and only companies that have been able to recognise this fact have managed to succeed in TPM adoption [1]. For accelerating this success, teams should have the authority to determine their individual tasks without the interference of management. Hence, it ensures more active involvement in taking decisions and accepting responsibilities. However, at times, the meaning of the word ‘employee empowerment’ is misinterpreted. The assumption that it signifies that all decisions must be taken by employees can result in complete chaos. This is why rules and policies play an integral part in preventing or eliminating the confusion. Furthermore, what is most difficult is ascertaining decisions that must be taken by management and the ones that must be taken by employees, alongside the ones that must be mutually considered. Similarly, this misinterpretation can also lead to the incorrect decision of not giving adequate responsibilities to workers [2].

Several authors have acknowledged the significance of TPM implementation in the power industry Aljanabi et al. [3]; Wai Foon and Terziovski [4]; Reiman and Oedewald [5] and in the service sector Mad Lazim and Ramayah [6]. Correspondingly, Nasurdin et al. [7] opined that empowerment remains one of the most important philosophies entrenched in TPM which is expected to enhance employees’ sense of autonomy. For example, in autonomous maintenance, operators are not merely permitted to oversee the efficacy of the machines/equipment within their care, but are also given the opportunity of deciding and initiating corrective actions in order to prevent unscheduled breakdowns [8]. In the same context, operators or shop floor workers are likely to enjoy greater autonomy. Therefore, Nasurdin et al. [7] advocated the concept of empowerment amongst employees in organisations performing TPM programmes.

Under such circumstances, employees' flexibility and autonomy will be increased. Furthermore, as noted by Nakajima [9], operators are required to participate in giving suggestions to improve the production line in the form of small group activities, which in turn, guide them to experience greater autonomy. Thus, it can be concluded that involvement in TPM activities paves the way for heightened autonomy amongst employees. This evidences the importance of participation of autonomous maintenance for successful implementation of TPM programmes within power plants, and empowerment can be a significant to the development of such programmes. Employee Empowerment is one of the main criteria in TPM implementation. TPM programme will not work without empowering operators or production workers to carry out the autonomous maintenance. However, there is a clear lack of literature that explores the influence of employee empowerment on the autonomous maintenance participation and therefore, this research aims to examine the impact of organisation culture on the participation of autonomous maintenance within power plants.

2.0 TPM

Innovative TPM maintenance strategies are utilised for affecting an increase in overall equipment effectiveness. This is achieved by setting up inclusive productive maintenance schemes that cater for the complete life-cycle of equipment [10]. Correspondingly, for the entire lifespan of equipment, TPM allows the establishment of thorough PM systems [9]. It motivates maintenance staff and operators to collectively design high standard good working procedures, focused on improvement and teamwork, which in turn augment equipment and process effectiveness [11] – [12]. Nakajima [9], the chairman of the Japanese Institute of Plant Maintenance (JIPM) in 1971 introduced TPM in Japan and today this system exhibits wide scale adoption, particularly in the manufacturing sectors. Directed towards increased performance, availability, and quality, TPM aims to ensure zero defects, zero accidents, and zero equipment failures. TPM is underpinned by principle practices known as 'pillars', specifically: autonomous maintenance; education and training; focused improvement; development management; office TPM; planned maintenance; quality maintenance; and safety, health, and the environment. Correspondingly, an explanation about TPM processes can be found in Nakajima [9], and Reiman and Oedewald [5]. To support the achievement of a TPM philosophy, maintenance staff and operators need to exhibit high knowledge levels, which subsequently allows for job function sharing between colleagues, and new skill development [12]. Implementation of TPM is not easy and faces many obstacles; details about its barriers are articulated by Ahuja and Khamba [13]. However, according to Waeyenbergh and Pintelon [14], there is a lack of clarity in standard maintenance rules and utilisation of simple maintenance policies, and TPM can be limited in providing complete maintenance concepts. Therefore in the power industry, whether participation of autonomous maintenance can result in robust TPM strategies needs to be further explored. In maintenance, the TPM approach aims at

continuous performance improvement through increased efficiency and effectiveness of certain industrial activities. This is evaluated through the Overall Equipment Effectiveness (OEE), which is computed through the product of quality, performance, and availability. In its calculation, “six big losses” [quality losses (1) process defects, (2) reduced yield; performance losses (3) minor stoppages, (4) slow cycles or speed; availability losses (5) plant failure, (6) set-up and adjustments] are measured to systematically reduce 100% theoretical availability to achieve maximum equipment effectiveness. However, according to Waeyenbergh and Pintelon [14], this calculation does not provide a complete analysis as it neglects the component of profits and cost, thus limiting its applicability in comparison of competitive systems or machines. This further evidences the incomplete nature of TPM as a maintenance concept in the power industry. It could be argued that a wider classification of losses is necessary for OEE to help improved machine utilisation understanding. Also, diverse industries and business domains are affected by different OEE measurement levels and factors. Correspondingly, the first country that utilised the 5S approach was Japan in the mid-1950s in manufacturing sector organisations [15]. As corroborated by Gupta and Jain [16], 5S implementation in organisations ensures continuous improvement. The 5S approach signifies, Shitsuke (sustain), Seiketsu (standardize), Seiso (sweep), Seiton (set in order), and Seiri (sorting) [16]. This 5S system is oriented towards productivity and quality optimisation and waste reduction that is achieved by orderly workplace maintenance and ensuring consistency in operational outcomes through visual cues. This evidences TPM implementation promotion, by forming a fundamental base for 5S in the TPM pillars. Furthermore, autonomous maintenance is one of the most critical barriers that could affect the successful implementation of TPM [7].

2.1 Autonomous Maintenance

The contributions of autonomous maintenance and planned maintenance pillars enable production operators to run equipment effectively, thus also preventing deterioration [6-9]. Prickett [17] argued that it must be recognised in developing fully autonomous maintenance systems that all relevant data pertaining to the state and performance of machine systems should be recorded. This can then be analysed and results used to support more effective maintenance. This process will rely on skilled operators who have the ability to increase machine performance. Mad Lazim and Ramayah [6] discussed that all activities related to cleaning, inspections, lubrications, adjusting of equipment and so forth should be recorded and maintained for regular analysis. Through regular analysis, the results can be shared among all employees and performance can be observed accordingly for further improvements. Wai Foon and Terziovski [4] discovered that maintenance practices of keeping records, total preventive maintenance, and collection and analysis of information, have significant impact on power plant performance. Moreover, Ben Daya [10] argues that in TPM implementation, the active involve-

ment of operators results in permanent improvement in the overall effectiveness of equipment. Thus, employee empowerment and equipment management are two fundamental features of TPM. It is pertinent for mechanics and operators to cooperate and work in teams towards the same goals, since there is high significance placed upon the involvement of operators in successful TPM implementation. This can be pragmatically achieved through a systematic approach of learning by properly trained and certified operators and vice-versa skill training to enable operators to perform mechanical tasks. There are several benefits of these operation and maintenance partnerships:

- ❖ Multi-skilling of mechanics and operators results in improved worker flexibility and job enrichment;
- ❖ A sense of ownership, pride, and responsibility is inculcated as operators are involved in routine maintenance tasks;
- ❖ Results in an increase in productivity and reduction in delay times;
- ❖ Operations and maintenance staff develop improved teamwork qualities.

To achieve this, participation of autonomous maintenance need to be performed effectively to ensure optimal overall equipment effectiveness and hence enable operators to perform their tasks easily. Empowerment of operators can play a significant part in driving successful participation.

2.2 Organisation Culture and Employee Empowerment

In this study, the authors propose a shift away from the direct and narrow concept of environment (like the workplace) to a broader framework as well as a concept of the indirect environment (like organisational culture). The reason behind this proposal is that culture is one of the most significant, stable and long-lasting factors that impacts upon behaviour and well as cognition. Furthermore, cultural issues also serve as barriers towards successful implementation of TPM. Thus, the current research takes an essential step in the development of proactively integrating culture into the realm and constructs of employee empowerment. Hofstede's theory [22] also assumes that cultural values and dimensions impact on employee empowerment. Moreover, employee empowerment are intrinsic needs for operators to participate in maintenance activities [23]. The element of empowerment is closely related to the emphasis to acquire organisational efficacy through effective and discerning human resource utilisation. Furthermore, empowerment techniques play a key role in improving group development as well as maintenance [18]. Kanter [19] was one of the oldest proponents of the concept of empowerment. She discussed that the organisation characteristics and structures determine the element of empowerment. More specifically formal job characteristics as well as informal partnerships affect the employees' ability to complete their work successfully. Based on the structural empowerment framework of Kanter [19], the researchers evaluated the effect of access to

support, power, resources, opportunities and information on the autonomous maintenance (operators) participation in power plants. Kanter [19] defined that power is the ability to organise and secure resources in order to let the workforce complete their job in appropriate way. Employees get empowered (power is 'on') when they are able to access support, resources, information, as well as other opportunities to grow and learn. In case these lines become unavailable (power is 'off'), employees' ability to work effectively reduces drastically. The power lines are 'structural' empowerment sources in the concerned organisation. Kanter points out that these lines emanate from formal as well as informal systems within organisations. According to Orgambidez-Ramos and Yolanda Borrego-Alés [18], formal power can be obtained from job characteristics such as flexibility, adaptability, making discretionary decisions, visibility, as well as alignment with overarching organisational goals and purpose. Furthermore, informal power can be sourced from social links, information communication channels with sponsors, friends, bosses, subordinates, and other assistive groups. Accessing these structures result in heightened levels of structural empowerment [18-19]:

1. Opportunity access implies that there is possibility of growth within the company as well as the opportunity of growth through obtaining wider skills/knowledge.
2. Resource access means the ability to source pertinent materials, financial support and other necessary supplies need to execute a function.
3. Information access implies the necessary informal and formal knowledge that helps the one to remain efficacious in the workplace.
4. Support access entails obtaining guidance and feedback from peers, superiors and subordinates.

2.3 Development of Conceptual Framework

This research paper is concerned with examining the impact of organisational culture and employee empowerment on the participation of autonomous maintenance. Organisation culture that has bad practices may affect the empowerment of employees. Furthermore, workplaces in the UAE have not widely considered organisational culture [20]. According to Al-Khalifa and Aspinwall [21], the quality implementations in organisations are impacted by national cultures, which affects organisational culture, as it is representative of commonly shared society/country values. Correspondingly, the culture differences amongst clustered cultures and nations have four dimensions [22]; and are categorised as (1) "Masculinity-Femininity"; (2) "Power-distance"; (3) "Individualism-collectivism"; and (4) "Uncertainty avoidance" on high or low level positioning of these dimensions.

- ❖ Masculinity – Femininity: According to Hofstede in Masculine cultures men and women display discernibly different social roles and correspondingly, in feminine cultures, there is an obvious significant overlap in social roles where women are considered as supporters.
- ❖ Power-distance: This culture represents the acceptance of power distance based on high or low power. In high power societies, the members show high respect to senior management, while in low power societies, there is an equality in distribution of authority and hence establish a democracy culture as social control.
- ❖ Individualism-collectivism: In individualist cultures, an individual assumes the role of responsibility to his/her immediate family as a natural course of action; alternatively in collectivist cultures, an individual belongs to a group by birth permanently.
- ❖ Uncertainty avoidance: As the name indicates, in this cultural scenario, the people introduce and establish strict behaviour codes with absolute truths belief to avoid situations deemed unclear, and unstructured.

On the other hand, employees are of the opinion that any work environment enabling access to these points is on their way to empowerment. Kanter's theory [19] pertains to the perception of employees concerning the real working conditions, as opposed to the manner in which they psychologically interpret this information. Thus, the authors took into consideration, the concept of 'structural' empowerment to forecast the participation of operators in the power plants' maintenance activities. Meanwhile they employed these dimensions: (senior management commitment, management style and empowerment, communication and coordination, rewards and motivation, and knowledge sharing) in the research model that was premised on Kanter's structural empowerment framework.

❖ Senior Management Commitment

According to Hooi and Leong [24], senior management roles are critical in the early phases in order determine the master plan whilst commencing the entire program's for TPM implementation. Senior leadership's involvement provides direction for their power plants and ensure that operators are empowered, which in turn leads to continuous improvement and enhances the participation of operators in maintenance activities [6].

❖ Management Style and Empowerment

TPM is a technology-driven concept; the justification for any event of failure is often denoted as organisational matters, and is a reflection of the style of management [25]. Wai Foon and Terziovski [4] reported that management style has an impact on employee empowerment in power plants.

❖ **Communication and Coordination**

According to Park and Han [26], a frequent process that involves effective coordination and communication across organisations may pave the way for great commitment, involvement, as well as cooperation from all employees. Without doubt, this fosters a strong association amongst participants and creates a motivating environment.

❖ **Rewards and Motivation**

According to Poduval et al. [27], rewards and motivation became an effective factor for successful TPM implementation. They specified that senior management should be able to prevent attrition by offering world-class remuneration as well as employee benefits. Positive attention from senior managers is arguably the most important reward at the workplace. However, individual perspectives concerning the punishments as well as rewards may vary; managers also need to recognise what is it that suits their requirements [28]. On the other hand, positive employee motivation is a key intangible consequence as TPM builds a sense of ownership through autonomous maintenance operators [24].

❖ **Knowledge Sharing**

According to Poduval et al. [27], lack of knowledge sharing is one the major causes of TPM failure since the staff is not well aware of TPM and consequently, is not adequately motivated to implement it. Moreover, a continuous sharing/learning program promotes a knowledge-based organisation wherein employees are well equipped with the knowledge to undertake maintenance tasks with greater efficiency [24]. Refaiy and Labib [29] elaborated that knowledge sharing has a positive effect on the performance level of maintenance activities based on three measures of maintenance performance: mean waiting time (MWT), mean time to repair (MTTR), and mean time between failures (MTBF). However, they found the impact of knowledge sharing is stronger in the UK compared to Arabic countries.

❖ **Hofstede's Cultural Dimensions Model**

By introducing dimensions of cultural (power distance, masculinity/femininity, collectivism/individualism, and ambiguity avoidance), Hofstede [22] posited that the degree to which the culture of organisations curtails members' freedom through initiation and action plays a key role in preventing employee empowerment. Excessive organisational regulations, high power distance and avoidance of ambiguity have been known to curtail individual freedom [30]. In a similar manner, insufficient focus on individual viewpoints in collective organisations has also been known to affect freedom of action [31]. Likewise, an overbearing focus of competition in masculine organisations results in heightened pressure and curtailed productivity in individuals, which then results in external motivation and the destruction of internal satisfaction [32]. Considering all these points aforementioned, the present research plans to investigate the relationship between cultural organisation based on Hofstede's cultural dimensions as well as employee empowerment.

Furthermore, there is no research which has tackled the issue of how culture affects the employee empowerment with autonomous maintenance (operators) participation in the power industry. Carrying out such a study will make a contribution towards building upon the existing body of knowledge and hence understanding of the way culture affects the employee empowerment with autonomous maintenance (operators) participation. Based on the aforementioned theoretical framework (Figure 1), the following hypotheses can be postulated:

H1: Employee empowerment has a direct impact on participation of autonomous maintenance (operators) in the power plants.

H2: Power distance has a direct impact on employee empowerment.

H3: Collectivism versus individualism has a direct impact on employee empowerment.

H4: Masculinity versus femininity has a direct impact on employee empowerment.

H5: Avoidance of uncertainty has a direct impact on employee empowerment.

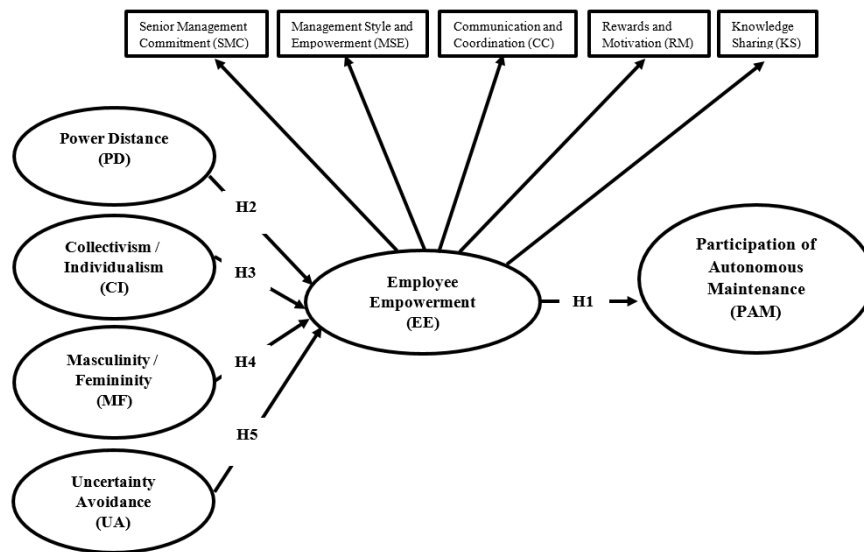


Figure 1 Theoretical Model of the Research

3.0 Research Methodology

Many industries have shown an understanding of the needs and significance of TPM. However, participation of autonomous maintenance is one of the most critical barriers for implementing TPM due to organisational culture issues. Conversely, within Abu Dhabi power plants, there is little literature to evidence research application in this specific area. Thus, this research paper aims to examine the impact of organisation culture on the participation of autonomous maintenance within Abu Dhabi power plants using a structural equation modeling approach.

3.1 Procedure and Design of Data Collection Tool

Data were collected from 124 professionals in the Abu Dhabi power plants using a postal questionnaire. A sample comprising of three participant organisations was selected based on their experience in operations and maintenance of power plants, particularly in the power sector and included power generation, transmission as well as distribution organisations. A response rate of 82.67% was achieved with the receipt of 124 out of 150 responses. Snowball sampling was used for this study; it is a famous methodology of survey sample selection frequently used to trace hidden populations. The authors used this strategy to recruit people who are often difficult to identify due to critical issues shown in the questionnaire that asked them about current maintenance practices and organisation culture. Structural equation modelling, using partial least squares path analysis (SmartPLS software version 3.0), was performed to test the hypothesised model. Participants in the study were requested to answer three main questionnaires: Hofstede's cultural dimensions questionnaire, structural employee empowerment questionnaire, and participation of autonomous maintenance questionnaire. The authors included multiple items for each construct in addition to a seven Likert scale by deploying declarative statements along with a list of response categories. These statements were rated on a Likert-scale with the range being from 1 (which means strongly disagree) to 7 (which means strongly agree). Participation of autonomous maintenance construct was measured using 3 items, each adapted from previous studies [6 and 33]. Hofstede's cultural dimensions construct was measured using 17 items adapted from Sadeghi et al. [31]. Employee empowerment construct was measured using 20 items, each adapted from previous studies [33, 34, and 35]. In order to measure this construct, the authors used Kanter's theory [19] for structural employee empowerment. This construct is made of 20 statements measuring five types of empowerments: senior management commitment (4 items), management style and empowerment (4 items), communication and coordination (4 items), rewards and motivation (3 items), and knowledge sharing (5 items). Furthermore, in this study, modifications followed an articulate process to check the grammar, spelling of statements and the content validity through the feedback of consultees, which included an academic professional as well as an experienced professional

practitioner who was experienced in the power industry. Based on their suggestions, a few grammatical and structural modifications were made to some of the statements.

3.2 Analytical Methods

This research used statistical techniques to undertake the analysis of data sourced from the questionnaires in order to interpret and analyse the research's results. Statistical and numerical analysis was undertaken through SmartPLS (version 3.2.4) software that employs the concept of partial least squares-structural equation modelling (PLS-SEM) was utilised for examining the relationship between independent variables (signified by organisation culture factors) and the sole dependent variable (participation of autonomous maintenance in power plants). This analysis is based on a correlational design, employing a structural equation modelling (SEM) approach. SEM refers to second-generation multivariate data analysis method and it has gained popularity in engineering management researches owing to its ability to theoretically test linear as well as additive causal model. PLS-SEM is mainly utilised to develop theories in the context of an exploratory research with an emphasis on explaining the variance (R square) in dependent variables whilst examining the model. PLS-SEM also handles all data types, ranging from nonmetric to metric by making minimal assumptions about the data characteristics [37]. Furthermore, PLS-SEM has high flexibility compared to the multiple regression (older method) and it primarily focuses on variances explanation (instead of covariances), thus implying that it entails prediction-oriented approach [38]. It has also the capability of examining the complex relationship with multiple independent and dependent variables.

In this study, the authors considered PLS-SEM due to exploratory nature of the present study [37]. Also they used this approach to test new theory since there is no literature that examines the casual relationship between cultural dimensions, structural employee empowerment and participation of autonomous maintenance in the power industry. The second reason for considering PLS-SEM is focus on prediction [40]. Furthermore, the authors adopted a two-step approach related to PLS-SEM, based on the findings of Anderson and Gerbing [39]. The first step is an evaluation of measurement model that is used to check the reliability and validity of research constructs and measuring instruments within the research model. The second step is an evaluation of structural model that is utilised to examine path coefficients (hypotheses) between the model's constructs thereby highlighting the path significance of the research model. This research used the SmartPLS 3.0 software to perform the analysis using the bootstrapping technique (with 1000 sub-samples) [31]. This bootstrapping technique is also used to enhance the measurement and structural research's model.

4.0 Results and Analysis

The authors analysed the research model into two stages. In the first part, the measurement model is studied in order to determine the reliability (internal consistency) and validity (discriminant validity) of the constructs and research instruments. In the second stage, the structural model is analysed in order to test the hypotheses of the research model.

4.1 Results of Measurement Model

Firstly, the measurement model was assessed in order to underpin and meet the convergent validity. This was examined through the average variance extracted (AVE), composite reliability (CR), and factor loadings [40]. In concurrence with Hair et al. [40] the Composite Reliability (CR) was used to measure the constructs' internal consistency. A threshold criterion of 0.70 has been reported for CR [38] and in this study all the included latent variables were found to exceed this threshold criterion. In addition, the assessment of both the parameters of Factor Loadings, and Average Variance Extracted (AVE) were used to assess the constructs' convergent validity. It has been reported by Hair et al. that for social science studies the acceptable factor loadings are between 0.6-0.7 [40]. Similarly, an adequate convergent validity is suggested for cases with AVE value above 0.5 [37, 38, 40]. In this study all the involved latent variables demonstrated AVEs and factor loadings, which were above the recommended levels. Correspondingly, for all the constructs, the results of CR, Cronbach's alpha, and AVE as well as the factor loadings are presented in Table 1.

Table 1 Assessment of Factor Loadings, Cronbach's Alpha, CR, and AVE

Constructs	Items	Factor Loadings	Cronbach's Alpha	Composite Reliability	Average Variance Extracted (AVE)
Power Distance	PD1	0.77	0.87	0.90	0.65
	PD2	0.82			
	PD3	0.85			
	PD4	0.79			
	PD5	0.81			
Uncertainty Avoidance	UA1	0.66	0.82	0.86	0.55
	UA2	0.80			
	UA3	0.81			
	UA4	0.69			
	UA5	0.74			
Collectivism	HC1	0.74	0.71	0.82	0.60
	HC2	0.76			
	HC3	0.83			
Masculinity	MAS1	0.64	0.76	0.84	0.58

	MAS2	0.86			
	MAS3	0.86			
	MAS4	0.64			
Senior Management Commitment	SMC1	0.72	0.70	0.83	0.55
	SMC2	0.74			
	SMC3	0.74			
	SMC4	0.78			
Management Style and Empowerment	MSE1	0.76	0.70	0.84	0.58
	MSE2	0.74			
	MSE3	0.80			
	MSE4	0.73			
Communication and Coordination	CC1	0.80	0.75	0.83	0.56
	CC2	0.72			
	CC3	0.82			
	CC4	0.63			
Rewards and Motivation	RM1	0.77	0.72	0.82	0.60
	RM2	0.78			
	RM3	0.70			
Knowledge Sharing	KS1	0.82	0.80	0.88	0.63
	KS2	0.84			
	KS3	0.74			
	KS4	0.80			
	KS5	0.83			
Participation of Autonomous Maintenance	PAM1	0.88	0.81	0.89	0.73
	PAM2	0.83			
	PAM3	0.84			

Fornier-Lacker criterion was used to assess the discriminant validity as suggested by Hair et al. [40]. According to this criterion each latent variables' square root of AVE is supposed to be more than its correlation with other latent variable. The authors in the current paper, as such, inferred a higher correlation with other latent variable of each latent variables' square root of AVE with the application of this approach. The correlation matrix and square root of AVE is presented in Table 2.

Table 2 Correlation Matrix and Square Root of AVE (Fornell-Larcker Criterion)

VARIABLE	1	2	3	4	5	6	7	8	9	10
1. PD	0.81									
2. UA	0.68**	0.74								
3. HC	0.39**	0.41**	0.77							
4. MAS	0.24**	0.25**	0.39**	0.76						
5. SMC	-0.35**	-0.26**	0.28**	-0.23**	0.74					
6. MSE	-0.30**	-0.15*	0.31**	-0.29**	0.57**	0.76				
7. CC	-0.16*	-0.18*	0.28**	-0.27**	0.47**	0.54**	0.75			
8. RM	-0.14	-0.12	0.18*	-0.22**	0.37**	0.44**	0.51**	0.77		
9. KS	-0.12	-0.09	0.13	-0.20**	0.31**	0.37**	0.41**	0.48**	0.79	
10. PAM	-0.10	-0.04	0.07	-0.17*	0.30**	0.33**	0.35**	0.43**	0.38**	0.85

The values on the matrix diameter show the correlation for the square root of AVE

* $p < 0.01$; ** $p < 0.05$

4.2 Results of Structural Model

The relative importance is highlighted through the significance of each indicator's weight. Also through boot-straping process, one can examine the absolute importance, which is represented by the loading. The bootstrapping procedure needs at least equivalent cases as original samples' observation [40]. In the current study, the boot-strap technique with 1000 sub-samples was utilised to estimate T statistic and hence indicate the path coefficients' significance [38]. Furthermore, for the determination of each predictor variable's share in deriving an explanation of the variable variance the criteria of path coefficients are applied as per Hair et al. [40]. Also, using predictor variables the explained variance of criterion variable is indicated by the R² amount [38]. The authors in this study were used SmartPLS 3 software for modeling and examining the significance of indicators' weights and relevance. The tested model is illustrated in Figure 2.

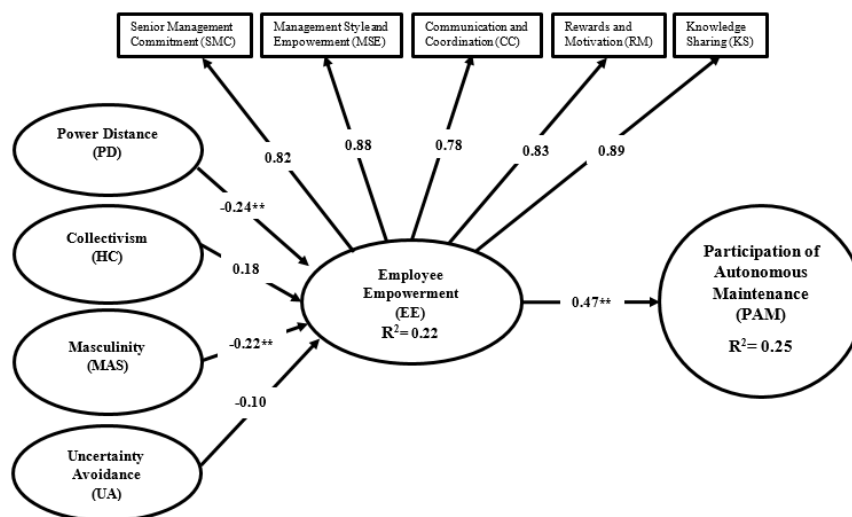


Figure 2 Tested Model of the Research (* $p < 0.01$; ** $p < 0.001$)

As Figure 2 specifies, the impact of employee empowerment on participation of autonomous maintenance in the power industry is positive and significant at 0.001 (0.47). The impact of power distance (-0.24) and masculinity (-0.22) on employee empowerment is negative and significant at 0.01. However, the impact of collectivism (0.18) on employee empowerment is positive and significant at 0.01. On the other hand, the impact of uncertainty avoidance on structural empowerment was not statistically significant. Furthermore, employee empowerment explains 25% of changes in participation of autonomous maintenance; and cultural dimen-

sions in general explain 22% of changes in employee empowerment. Table 3 shows the results of testing the research hypotheses. According to the Table 3, hypotheses 1, 2, 3, and 4 are supported but hypothesis 5 is rejected.

Table 3 Testing of Research Hypotheses

5.0 Discussion and Conclusion

The aim of this study is to examine in-depth the impact of organisation culture on the participation of autonomous maintenance within power plants based on the context of Kanter's structural empowerment framework and cultural dimensions of

Hypothesis	Path Coefficient	T Value	Significance	Result
Employee Empowerment >> Participation of Autonomous Maintenance	0.47	8.20	0.001	Supported
Power Distance >> Employee Empowerment	-0.24	-3.14	0.01	Supported
Collectivism >> Employee Empowerment	0.18	2.88	0.01	Supported
Masculinity >> Employee Empowerment	-0.22	-3.02	0.01	Supported
Uncertainty >> Employee Empowerment	-0.10	-1.08	-	Not Supported

Hofstede's model. To achieve this purpose, the study proposed a conceptual model, which was underpinned by a cohesive theory and practice review and further structural equation modelling was used on it for a thorough examination. According to study results, in autonomous maintenance participation 25% of the changes were attributed to ensuring employee empowerment. Moreover, in employee empowerment with the use of Hofstede's cultural dimension 22% of the changes were predicted. In addition, it was inferred that employee empowerment had a direct effect on participation of autonomous maintenance, which in turn, signified that empowerment is achieved through: senior management support, association with maintenance team, inter-departmental communication and coordination, rewards and motivation, information sharing and analysing. This furthermore affects positive organisational behaviour with high self-esteem. In addition, employees as regards their day-to-day equipment operation presented higher inclination towards developing a sense of ownership. Herein, for the assurance of TPM success an ownership towards this equipment constitutes a crucial factor. This can be attributed to individual attention and focus of every operator to maintain the equipment through cleaning, tightening, and lubrication in order to keep equipment in good condition and hence achieve the target of as good as new condition. These study inferences are in alignment with the proposed research's theoretical model, which envisages the significant positive effect of meeting employee empowerment on autonomous maintenance participation in the power industry. Another impera-

tive study finding reveals that power distance negatively impacts employee empowerment. These findings demonstrate the resultant effect of forced compliance to supervisors' directives, authorities taking technical decisions and authorities' perception of restraint on operators for expression of their maintenance issues views. It was found that under these conditions, operators will get less opportunity for growth and they are challenged with limited materials and resources in order to contribute within maintenance activities, limited sharing and analysing of power plants' failure data with the lack of support in form of superiors, peers and subordinate oriented feedback and guidance. This observation can be attributed to the restriction and limitation of freedom of action amongst personnel. As a matter of fact, power companies having higher power distance levels provide limited opportunities to their operators for demonstrating their freedom of action, initiation, and competence. In addition, Ramayah et al. [41] state that with concerns of avoiding damage to expensive equipment, managers in some organisations do not trust on the operators' capability and restrict operators from engaging in machine adjustments and repairs. This has been evident in organisations not prepared or inclined towards TPM programme implementation. Moreover, a decrease in trust, confidence, and sense of ownership is seen in power plants, which have hierarchical systems, in combination with managers/supervisors having more power in power utilities. This can be explained by the fact that subordinated relationships lead to more power and associated increase in control, which further deteriorate relationships between members. This finding is in line with Kanter's theory "structural empowerment framework" that highlights the negative effect of a controlling environment on employee empowerment [19]. The study also significantly highlights that employee empowerment is negatively impacted by masculinity/femininity. Progress and competition are over-emphasised with the external motivation promoted through higher masculinity levels in power utilities. According to Sadeghi et al. [31], external motivation is directly related to restrictions in the environment that impacts employee empowerment negatively [19]. Conversely, it is observed that power companies demonstrating lower masculinity levels offer increased opportunities towards employee empowerment. This is attributed to supportive and friendly peer relationships. Also, higher autonomy and augmented sense of ownership in power companies is evidenced amongst operators who support each other as per Nasuridin et al. [42].

On the other hand, the study significantly highlighted that employee empowerment is positively impacted by collectivism. It is inferred that employees in power utilities with higher levels of collectivism have: high loyalty for organisations to achieve their goals, high sense of interdependence, and joint responsibility to systems. This kind of loyalty results in patterns of cooperation between groups and increasing the work productivity. Moreover, high collectivism fosters more informal coordination and communication mechanisms between operators and maintenance staff [43]. According to Kirkman and Shapiro [44], collectivism leads to team empowerment and hence improves work performance through reducing resistance to team participation. Mad Lazim and Ramayah [6] highlighted that communication and coordination between operators and other departments is the

critical success factor that may empower autonomous maintenance participation positively.

The current study takes into consideration the correlation matrix, which highlights a negative relationship of Hofstede's cultural dimensions (excluding collectivism dimension) with employee empowerment. This is manifested through senior management commitment, management style and empowerment, communication and coordination, rewards and motivation, and knowledge sharing. This means that the higher the ambiguity avoidance, power distance and masculinity in power organisations, the less the staff will feel autonomous and skilled. Furthermore, power organisations with high profiles for power distance, ambiguity avoidance, and masculinity have the distinctive characteristic of limiting individual freedom of action, which in turn affects operator's autonomy adversely. In addition, the efficacy feeling is negatively impacted in such organisations due to the power gap between members. The use of initiative also prevents high ambiguity avoidance rates. This is primarily observed in power organisations displaying an adherence to traditional characteristics that impact competence and efficacy of members negatively. Operator competence similarly is adversely influenced from gaps in focus on innovative activities by individuals, as well as the emphasis on collectivism. Likewise, in masculine societies efficacy feelings can be negatively affected with competition overemphasis resulting in increased pressure on operators' participation within maintenance activities.

According to Hofstede [22] in organisations, change is often resisted due to the cultural values that represent organisation most stable aspects. Also, resistance to change is further augmented due to individual organisational values presented as a subculture in the form of social values. Hofstede also defines the improbability of organisations undergoing direct change in their values as these are in fact, a semblance of a hidden mental software that regulates the behaviour of members. Correspondingly, at a power utility the organisational culture displaying a controlling characteristic and employee empowerment confinement will encounter a challenge in changing such values and regulating the environment's controlling power. According to Hofstede [22] a change in explicit behaviours is the ideal mechanism to affect a change in values. For example, introducing changes in rules and regulations of power companies, with the purpose of impacting a reduction in the environment's controlling power. Such changes, moreover can lead to provision of increased initiation and freedom of action to operators, self-esteem promotion in operators' maintenance participation and also active decision-making as regards maintenance activities. It also validates: (i) system regulations and control; (ii) augmented cooperation within operators; (iii) emphasised freedom of action; (iv) initiative use; and (v) de-emphasis of progress and competition. Notably, in the Abu Dhabi power sector, the centralisation system imposes a reduction in managers' extent of power and assets performance planners. Within the company TPM ideally should be directed and managed by full-time employees with qualities of expertise and enthusiasm according to Park and Han [26]. These coordinators should be equipped to implement TPM methodology with adequate educational

qualifications, motivational and persevering temperament, and necessary skills for seamless change process management.

Findings from this study reveal an inversely proportional relationship between power distance and masculinity in an organisation with fulfilment experience of organisation members as regards basic employee empowerment. This will lead to a lower level of operators participation within maintenance activities, which can be a serious threat to the success of implementing a TPM programme within power industry. These findings thus recommend an inculcation of cooperativeness and support amongst members in the power sector by managers and authorities to drive progress and competitiveness with a singular focus on individual needs. Moreover, rather than focusing on the end products of action, it is recommended to encourage members to address the process. With this process oriented focus, members experience a higher internal motivation with satisfactory workplace. Thus, it is recommended that in organisations to lower the power distance the organisations should adopt moderate hierarchical structure, motivate direct work associations between managers and their staff members. Also, concurrently bureaucracy should be avoided. Moreover, transparent, real-time and sharing of relevant information has been observed to be critical to employee empowerment, as such information sharing is directly proportional to organisational performance. The main deterrents to information sharing are lack of trust and power distance. Thus, organisations should encourage staff and managers to foster workplace relationships which are control-free, direct and more friendly. For employee empowerment support, a two-way communication which is well-structured and developed is crucial. Improved involvement and commitment results in frequent and open communication. This communication can be achieved via formal and/or informal modes and the following personnel should be included in this communication at a power utility: employees, supervisors, shop floor executives, engineers and managers. Such open communication stimulates an augmented understanding of the motives underpinning TPM implementation. Furthermore, operators within maintenance activities participation can be propelled with adoption of various mechanisms of employee empowerment like: rewards and incentive, recognition of the efforts, training for skill improvement, promotion of knowledge and cross functionality. Thus, it can be inferred that empowering operators constitutes a significant criteria in successful implementation of a TPM strategy and their empowerment is necessary to foster a high sense of power plant ownership.

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The Impact of Effective Model of Maintenance Optimisation (Predicting Remaining Useful Life) on Successful Participation of Autonomous Maintenance in the Power Industry

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Abstract The power industry has recognised the impact of implementing Total Productive Maintenance (TPM) as a maintenance strategy to enhance its proactive techniques and improve power asset reliability. The needs and significance of prognostic techniques (predictive maintenance strategy) within TPM implementation is well understood in many different industries. However, there has been almost no research applied in this area within Middle-East power plants. Intelligent techniques within power plants are being used to integrate and interpret data from multiple sensors to predict wear and life of equipment. Thus, successful power utilities have sufficient failure data that predicts accurate times to failure of their power assets, based on condition monitoring techniques. Power transformers are the most expensive elements and their faults are particularly costly. Therefore, detection of power transformer failures at an early stage is important to assure reliable and efficient operation. The aim of this research is to investigate the critical role of prognostic techniques based on maintenance optimisation models and how they can drive successful participation of autonomous maintenance (operators) in the maintenance activities through a planned maintenance pillar. The research presents an innovative technique that enables operators to detect and diagnose early faults in power transformers based on paper degradation analysis. This method uses measurements obtained from the Abu Dhabi power distribution network of the degradation factor of power transformer paper insulation (degree of polymerisation - DP values) over time, from condition monitoring data that is obtained through dissolved-gas analysis (DGA). The mathematical exponential model uses degradation measurements DP values of paper insulation for multiple power transformers to extrapolate these measurements over time, and hence predicts potential failure times before they occur. This is based on a prognostic technique that utilises ReliaSoft's Weibull++ software. The results of this research show that successful implementation of TPM in the power industry can be achieved through appro-

appropriate techniques of predictive maintenance within the planned maintenance pillar of TPM, thus increasing availability, performance, quality and reliability rates by preventing sudden failure of power transformers. The major result achieved in this study is the development of a conceptual framework that integrates a maintenance optimisation model (predicting remaining useful life) with autonomous maintenance participation, for early fault detection of paper insulation of power transformers.

Key words Total Productive Maintenance (TPM); Participation of Autonomous Maintenance; Condition Monitoring (CM); Predictive Maintenance (PdM); Dissolved-Gas Analysis (DGA); Degradation Analysis; Remaining Useful Life (RUL)

1.0 Introduction

Maintenance has a significant impact on the business strategy of power organisations. Maintenance of power plants aims to promote safe, cost effective, and reliable electricity supplies. This kind of maintenance has complex activities and requires highly skilled maintenance staff; therefore, proper utilisation of technology is critical to achieve both plant safety and availability [1]. Power companies have recognised the importance of implementing Total Productive Maintenance (TPM) as a maintenance strategy to optimise their proactive techniques and improve power asset reliability. Further, successful power utilities need to have robust data management procedures such as computerised maintenance management systems (CMMSs), that include sufficient failure data. Otherwise, utilities cannot predict accurate times to failure of their power assets through condition monitoring (CM) techniques. CM systems lead the power industry to better maintenance management performance and higher reliability. CM can monitor the critical parts of power plants such as transformers, and determine the optimal period for particular maintenance [2]. Preventive maintenance involves the systematic scheduling of inspection, detection, and prevention of incipient faults before they occur as major or actual failures. Predictive maintenance (PdM) is a distinctive type of preventive maintenance that can be performed at intervals or continuously, based on the requirements to diagnose the condition of equipment. PdM plays an essential role to generate improvement in safety, availability, performance, quality of equipment and reduced maintenance costs. Implementation of PdM becomes significant where security of power plants is critical. Thus, it has been utilised as a strategic decision-making technique that consists of predictive tools as well cost-effective methods (e.g. dissolved-gas analysis, vibration monitoring, and thermography) to obtain real time data and hence measure the physical condition of equipment during its operation. According to this, all activities of maintenance are organised and scheduled, based on priority and criticality analysis of equipment [3]. The aim

of this paper is to investigate the critical role of prognostic techniques based on maintenance optimisation models and determine how they can drive successful participation of autonomous maintenance (operators) in the maintenance activities through a planned maintenance pillar. With high demands on quality, productivity, and availability, power plants become more complex and costly. Developing a maintenance programme is not an easy process, and it faces many obstacles during its implementation; it often lacks a systematic and reliable methodology. The authors intend to integrate the participation of autonomous maintenance with using optimisation a mathematical model that employs the concept of planned maintenance pillar on critical power plant; e.g. power transformers in order to drive successful implementation of TPM within power industry. The finding in this paper is that there is a need to apply effective prognostic techniques to drive successful implementation of TPM in the power industry, through enabling autonomous maintenance (operators) to carry out planned maintenance pillar effectively.

2.0 Literature Review

In this section, there is a review of the literature pertaining to TPM, followed by a review of literature on multiple concepts that may influence the integration of TPM strategies, particularly autonomous maintenance within the application of maintenance optimisation models in the power industry.

2.1 Total Productive Maintenance (TPM)

TPM is an innovative maintenance strategy employed to increase overall equipment effectiveness by establishing an inclusive productive maintenance scheme covering the entire life-cycle of equipment [4]. It brings operators and maintenance staff together through creating a combination of good working procedures with high standards, team working, and focused improvement, thus increasing the effectiveness of processes and equipment [5] – [6]. It was introduced in Japan 1971 by Nakajima [4] who was the chairman of the Japanese Institute of Plant Maintenance (JIPM) and is extensively adopted in manufacturing sectors today. TPM aims to achieve zero equipment failures, zero accidents, and zero defects in order to have high availability, performance, and quality. The principle TPM practices are named the pillars of TPM, specifically: planned maintenance; focused improvement; autonomous maintenance; development management; office TPM; education and training; quality maintenance; and safety, health and environment. An explanation about TPM process can be found in Nakajima [4] - Reiman and Oedewald [1]. Operators and maintenance staff need to have high levels of knowledge, be able to share each other's job and sometimes

develop new skills to achieve the TPM philosophy [6]. Its implementation is not easy and faces many obstacles; details about its barriers are articulated by Ahuja and Khamba [7]. Waeyenbergh and Pintelon [8] argued that TPM does not reflect a maintenance concept because it has no clear maintenance rules and policies to decide which simple maintenance policy will be utilised. Thus, building a robust planned maintenance pillar in the power industry needs to be investigated to promote TPM implementation through predictive maintenance tools. Introducing the TPM methodology in power industry is considered a major challenge due to cultural issues [1]. One of the most critical barriers of TPM implementation is participation of autonomous maintenance [6] that may affect also successful implementation of this maintenance strategy within power industry. According to Nakajima [4] successful participation of autonomous maintenance needs expert operators who have wider technical knowledge about their equipment and hence they can carry out the light maintenance activities such as inspection and condition monitoring techniques besides operating machines. On the other hand, planned maintenance is one of the eight pillars of TPM programme [7] and its effective utilisation by operators may drive impact on optimising the industrial assets through detecting the potential failures signs and hence preventing the catastrophic failures. Planned maintenance pillar aims to achieve zero breakdowns through preventing unpredicted failures and equipment deterioration. It involves activities related to predictive maintenance in order to predict equipment lifespan [4].

2.2 Predictive Maintenance (PdM)

Predictive maintenance techniques have become the foundation for most modern maintenance methods. Predictive maintenance programs involve different methods of problem diagnosis in order to predict equipment faults before they occur. This diagnosis involves several types of equipment testing to deliver results that can be compared with standard results, and based on results, correct maintenance action can be taken [9]. Condition monitoring techniques are: vibration analysis, acoustic analysis, thermography-infra-red radiation, oil analysis and human senses among others. Further, the Dissolved-Gas Analysis (DGA) technique examines the oil and its chemical composition in order to predict failure modes. The results of this test will determine the following: high content of silicon thus indicating contamination of grit; and high levels of iron indicating a wearing of components, and iron or aluminium presence indicating worn piston rings. Right fault classification is significant in power transformers to minimise power quality (PQ) disturbances. Partial discharge (PD), corona, arcing and thermal heating cause PQ disturbances and hence may lead to catastrophic failures (e.g. interruption of power supply, damaged equipment, increase maintenance costs, and high safety risks to operators and technicians). Gases generate when faults get dissolved in the oil of power transformers. DGA is widely utilised by power utilities as an effective tool for fault diagnosis of transformers. Since the late 1970s, DGA interpretation has used standards such as IEC 60599, IEEE C57.104-1991, etc [10]. In addition, a number

of new methods have also been designed and have been described in the literature - Ghoneim and Taha [11] – Li et al. [12] – Mansour [13].

2.3 Degradation Model in Reliability Analysis

Failures have different causes which can be categorized either as external or internal. Internal failures happen due to internal system faults (e.g. ageing of materials). External failures are caused by environmental conditions (e.g. pollution, vibrations, and humidity). In general, failures can be divided into two groups: degradation failures and sudden failures. Degradation failures can be predicted by a single condition monitoring indicator or by several indicators. Furthermore, the degradation process effects and reduces the reliability of assets. Sudden failure cannot be predicted through condition monitoring techniques or the measurement of asset age. Figure 1 shows how assets reach the degradation level (failure threshold) and hence fail. Degradation has two types: natural degradation and forced degradation. Natural degradation occurs due to age, or is time-dependent. Forced degradation occurs due to external causes to the system (e.g. due to high demand of power, the load of power transformers increases significantly and reaches the failure threshold level and hence the transformer can no longer safely take the load) [14].

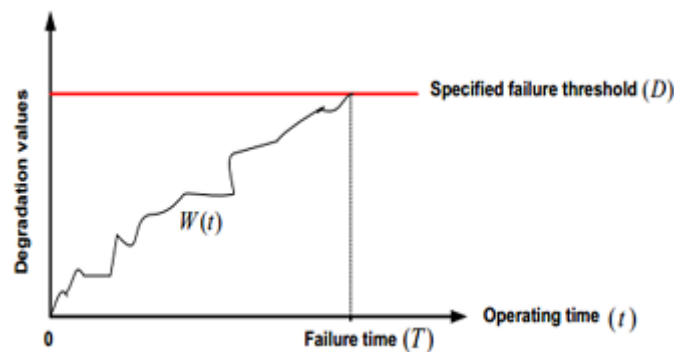


Figure 1 Degradation Process. Source: [14]

2.4 Paper Degradation of Power Transformer

Power systems have many different elements; the power transformer is the most expensive element and its faults can be very costly [11]. Power transformers are responsible for power transmission and distribution. The main function of

transformers is to step-up or step-down voltage levels of substations. Negative economic impacts in electrical networks are often caused by unplanned outage of power transformers. It is important to determine any problems from an early stage, before disastrous failure occurs. Accurate identification of problems supports reliable power transformer operation. Alongside predictive and corrective maintenance, preventive maintenance may be considered more important, and it should be implemented to guarantee as far as possible the highest performance and reliability of power transformers. Condition monitoring in electrical networks provides useful data to maintenance staff to support activities such as: the planning of operation and maintenance activities; assessments of condition of equipment; predicting the remaining life of electrical assets, and discovering areas of further development and improvement. Power transformers have two windings: high voltage winding and low voltage winding, shown in Figure 2. The material used in the insulation system of these copper windings is Kraft paper immersed in mineral oil. The aging transformer under load can lead to oil and paper insulation degrades. The result of this situation will lead to catastrophic failure in electrical networks.

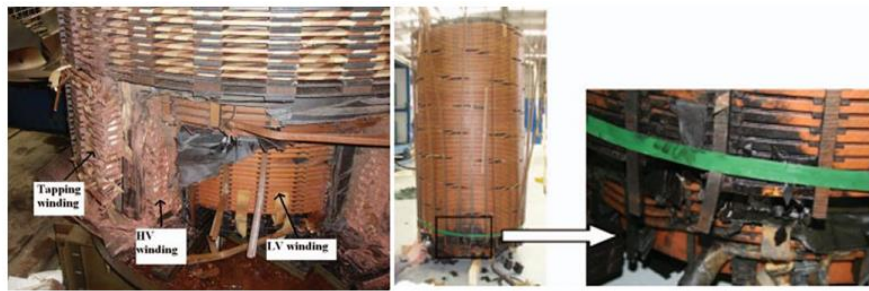


Figure 2 Failure of Paper Insulation of Power Transformer, Source [15]

The power transformer tank contains paper, and its function is to insulate the two windings (high and low). This paper is made from a cellulosic material such as wood pulp. Over a period of time, high temperatures, water, and oil acids could potentially degrade the paper and hence the windings of the transformer could eventually fail. This paper has polymer chains and glucose rings which are linked together and repeated. Moreover, monomer is shaped from the repeating unit of glucose and has an average number of glucose per chain; this is known as the degree of polymerisation (DP). Figure 3 shows how the paper is produced from long-chain molecules.

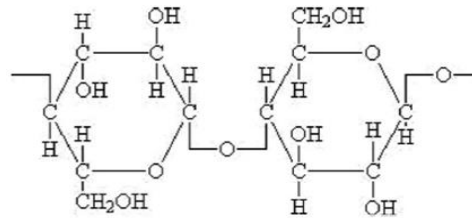


Figure 3 Cellulose Chain, Source [15]

The state of paper insulation is very strong (electrical and mechanical strength) when the DP value of the power transformer is 1000 and above. On other hand, when the DP value is around 200 or less, it reflects the weak condition of paper insulation and the paper is unable to perform its required functions; therefore the power transformer could fail within a short period of time. Furthermore, there are many factors that can affect paper insulation age: high temperatures (pyrolysis), moisture around the paper (hydrolysis), and acid and oxygen (oxidation) within the transformer oil [15]. Over many decades, oil-paper insulation has been used inside transformer tanks due to its good reliability and performance. However, over a long period of operation, transformer paper could degrade as a result of many factors (its ageing, rising energy consumption, electrical and thermal stresses). These factors therefore could result in a reduction in the DP value as well as a reduction in electrical and mechanical strength of power transformers [16]. Paper insulation is therefore an important element in power transformers and its DP value gives an indication of when there are problems within internal parts. Condition monitoring of paper insulation, including its age (cellulose) helps to predict the remaining useful life of power transformers, and also identifies problems in their early stages, hence increasing transformer availability and reliability. In this way, asset managers can make informed decisions when authorising optimum asset replacements [17]. Figure 2 shows failure of paper insulation of power transformer.

2.5 Maintenance Optimisation Model

Dekker [26] explained that condition monitoring techniques were used in the 1970's in order to predict potential failure utilising data on the actual condition of equipment (e.g., vibration monitoring, oil analysis, debris analysis). Moreover, Garg and Deshmukh [27] discussed the reliability concept established in the 1980's based on the RCM characteristics. Nowadays, many scholars are developing various models of mathematical maintenance to predict the measures of reliability and determine the optimal maintenance strategies and policies. However, these different types of optimisation models may be only suitable for capable maintenance engineers who can incorporating information about the

failure mechanisms, failure detection methods, maintenance strategy, and the repair policies, etc. Therefore, those capable engineers can give reasonable justification of assumptions and the applicability of using these models within specific environments, which can deliver greater confidence in predictions or estimates on the basis of production data.

Dekker [26] highlighted that the significant of successful application of maintenance optimisation models on problems and challenges of maintenance. He argued that maintenance an optimisation model can be used in several ways such as it can be utilised with real data to generate advice to senior assets managers on real problems. Also it can be used to overview real applications, or suggest applications that present examples with real information/data. The last type of model can be used as an expert system or decision support system. Further, there are numerous industries and areas in which these models have been implemented; popular industries are maintenance scheduling of power stations and road maintenance, whereas popular areas are vehicle replacements, equipment, and inspection optimisation. Furthermore, Garg and Deshmukh [27] discussed that equipment with different conditions may have various failure patterns, therefore it is not permanently possible to employ an optimisation model. Another challenge is the constant entrance of new equipment that leads to records of historical data being obsolete and hence affects replacement decisions. On the other hand, there are problems encountered in implementing models of maintenance optimisation mentioned in the previous case studies, concerning collection and analysis of data as well as difficulty in interpreting results [26-27].

Furthermore, in order to ensure TPM implementation is a success, Lawrence [28] states the significance of mathematical modeling in essential in introducing cultural change. According to Ng et al. [29] the use of integer programming, linear programming, and other methods and measurements (like mean time to repair “MTTR”, mean time between failure “MTBF”, degradation data, and other historical data) can optimise maintenance management processes and also define how such optimisation models and tools might be utilised to support cultural change by emphasizing the tangibility and objectivity of the TPM benefits to all employees. Mathematical models serve as an additional boost to speed up the implementation and success of TPM [28-29].

2.6 Prognostic Techniques for Predicting Remaining Useful Life

Prognostic is a predictive method that defines an asset’s remaining useful life (RUL). It also estimates the time to failure and failure modes in the future. Failure prognosis includes predicting asset degradation based on condition monitoring techniques [18]. Figure 4 shows the fundamentals of prognostic techniques for degradation failure.

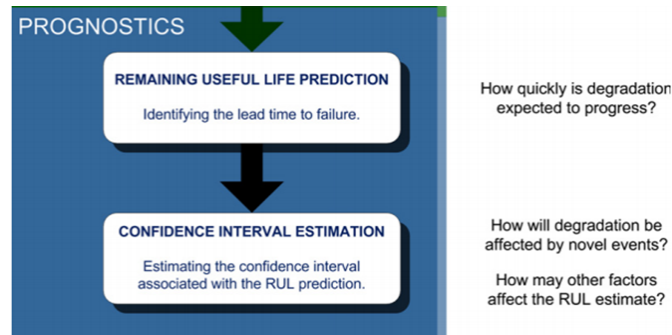


Figure 4 Prognostic Process. Source: [18]

RUL has four main models that can be seen in Figure 5; each model has a sub-model. Knowledge-based models assess the comparison between an observed condition and a database (failure event) of previous events in order to assume the life expectancy. It has two systems: expert and fuzzy systems. Life expectancy models define the life of single equipment components as well as determining expected risks from equipment deterioration. There are two models: stochastic models (Aggregate reliability functions and Conditional probability methods) and statistical models (Trend extrapolation, Auto-regressive moving average, and Proportional hazards modelling). Artificial neural network models calculate estimates for the remaining life of machines based on a mathematical representations from observation data. It has two models: direct RUL prediction, and estimation of parametrics for other models. Physical models calculate the estimation output for the remaining life of machines based on a mathematical representation of degradation processes [18].

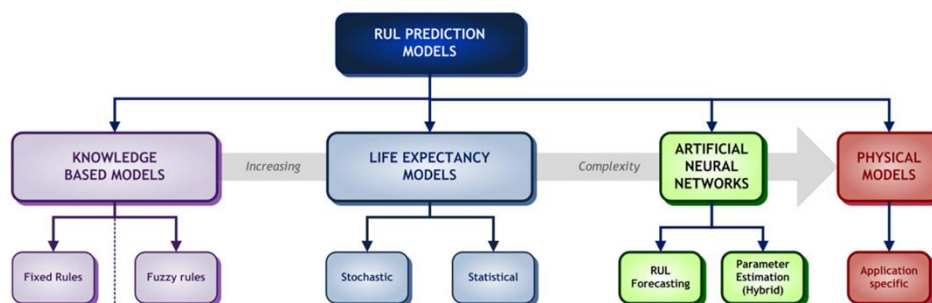


Figure 5 Main model categories for prediction of remaining useful life,
Source: [18]

2.7 The P-F Curve

Predictive technologies can be used in maintenance scheduling to build an essential PdM program. The P-F curve is significant for industrial assets; understanding the real meaning of this curve will lead to the implementation of appropriate maintenance strategies. PdM programs are therefore important during the P-F interval in order to detect component failures. It facilitates decisions to replace or repair parts of systems before faults occur, hence optimizing maintenance costs. Figure 6 illustrates how PdM can detect problems early during the P-F interval by using predictive technologies linked with predictive maintenance.

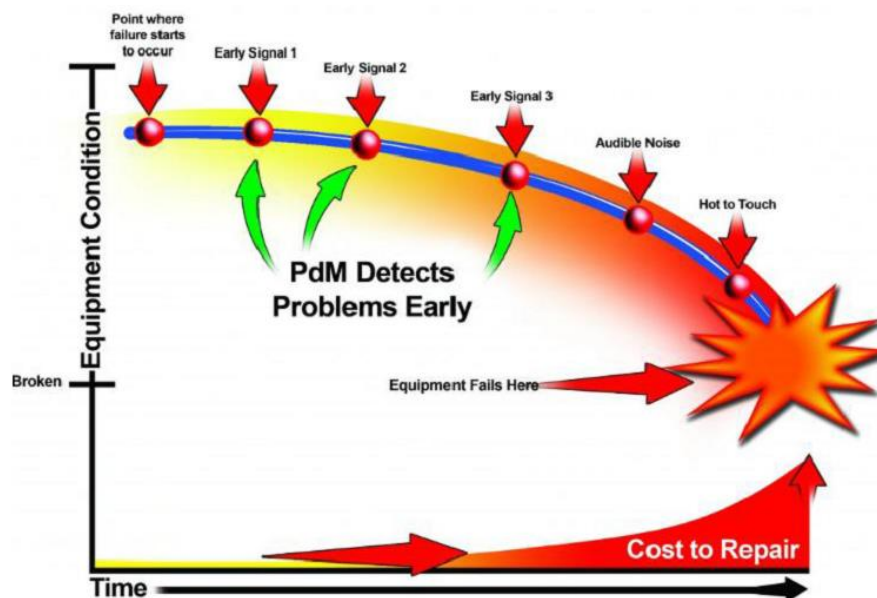


Figure 6. How PdM Detects Problems Early During P-F Interval, Source: [19]

3.0 Research Methodology

The needs and significance of integrating the participation of autonomous maintenance with using an optimisation mathematical model is well understood in many different industries to achieve successful TPM implementation. However, there has been almost no research applied in this area within Middle-East power plants. Thus, this research aims to investigate the critical role of prognostic techniques based on maintenance optimisation models and how they can drive successful participation of autonomous maintenance (operators) in maintenance

activities, through planned maintenance pillar. A power organisation in Abu Dhabi power industry was used as a case study to source data for the study to determine the successful TPM implementation [20]. Historical data (degradation measurements) from power transformers for five critical power distribution substations was collated. Furthermore, this power organisation conducts dissolved gas analysis (DGA) as an off-line condition monitoring technique to measure the power transformer's paper insulation by determining the degree of polymerisation (DP) values. Inspection is conducted yearly to gather the DP values of paper insulation. The paper is considered failed if the DP value is less than 200 (this is equal to the "F" point in the P-F curve). Moreover, a warning paper degradation level of 300 DP has been identified as a critical degradation. If the DP values less than 300, this is considered to be a sign of potential failure (this is equal to the "P" point in the P-F curve).

Power transformer paper degradation DP values were taken from condition monitoring data for a five year period, to perform required simulation analysis of prognostic techniques. The analysis required the application of ReliaSoft's Weibull++ 9 software (degradation analysis) in order to estimate the potential failure time of power transformers and hence select the correct maintenance policy based on a TPM strategy. The following steps give a brief description about how the paper degradation analysis was conducted through ReliaSoft's Weibull++ 9 software:

1. Select the degradation analysis from the main control panel tab of the Weibull++9 software.
2. Extract the condition monitoring data of the paper insulation (DP values) for these critical substations from 2006 until 2011.
3. Insert DP values of these critical power transformers in the Weibull++ 9 software (degradation analysis).
4. According to this failure mode (failure of paper insulation), select the suitable degradation model (Exponential Distribution) from the main control panel tab of the Weibull++9 software (degradation analysis).
5. Set the critical degradation to 300 in the main control panel tab of the Weibull++9 software (degradation analysis).
6. Run the simulation in order to generate a plot of degradation versus time that shows the warning limit ("P" point of P-F curve) and functional failure of paper insulation ("F" point of P-F curve).

After running the simulation, results will be generated to allow the P-F interval values to be estimated. When P-F interval is predicted, and based on criticality analysis, operators can allocate the right maintenance tasks. Before the simulation

analysis was applied it was essential to first evaluate the reliability and validity of this instrument to confirm that the findings would be valid and reliable.

4.0 Results and Analysis

As illustrated in Figure 7, ReliaSoft's Weibull++ 9 software is shown the prediction of warning limit (potential failure time in month) of power transformers paper insulation for five critical substations at Abu Dhabi power organisation. This warning limit is equal to the “P” point in the P-F curve and its prediction is based on a prognostic technique (Statistical Trend Extrapolation). Further, these paper insulations degrade over a long period of time due to poor maintenance practices, and they reach functional failure when DP values are less than 200. In this situation, the power transformers are replaced. Due to the power transformer renewal process and constant failure rate of paper insulation, the exponential distribution is adequate for this kind of failure mode (degradation of paper insulation). Therefore, exponential distribution is selected here to model the degradation data of paper insulation. After running the simulation, the Weibull++ 9 generates the potential failure predication time (P point in month) of the paper insulation for five critical power transformers at the Abu Dhabi power organisation, and it can be seen in Table 1.

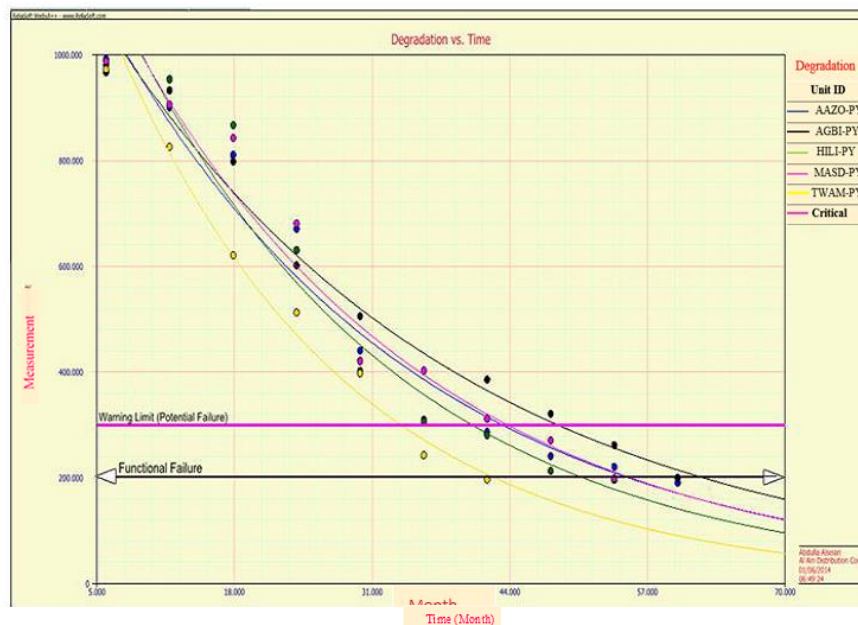


Figure 7 Estimating the P-F Interval of Power Transformer Paper Insulation at Abu Dhabi Power Organisation.

After running the simulation, the Weibull++ 9 software generates the above results, that can be seen in Figure 7 which shows prediction potential failures time (in months) of power transformer paper insulation for multiple units at Abu Dhabi power organisation.

P-F interval values can be estimated based on the above results (prediction of potential failures time “P” and functional failure time “F”). These results can be used to calculate the P-F interval based on the below equation:

$$\text{P-F interval} = \text{“F” values} - \text{“P” values} \quad (1)$$

$$\text{“P” values} = \text{“F” values} - \text{P-F interval} \quad (2)$$

where, F is functional failure time and P is the potential failure time.

Table 1 Prediction Potential Failure Time of Power Transformer Paper Insulation

Quick Results Report			
Report Type	Extrapolated Failure/Suspension Times		
User Info			
User	Abdulla Alseiari		
Company	Al Ain Distribution Company		
Date	1/6/2014		
Times			
	F/S	Time to F/S	Unit ID
	F	43.28137416	AAZO-PY
	F	48.513284	AGBI-PY
	F	40.41985555	HILI-PY
	F	43.74875214	MASD-PY
	F	33.69817705	TWAM-PY

The authors calculated the P-F interval using equation (1). According to Table 2 the average P-F interval value for multiple units of power transformers is (12.07 Month) and the functional failure of most critical paper insulation for multiple units of power transformer is (60 Month) which can be seen in the above Figure 7. The authors calculated the potential failures time (using equation, 2) to be detectable at $(60 - 12.07 = 47.93 \text{ Month})$. This means that the power transformer needs to be protected before its paper insulation reaches the functional failure level (DP less than 200) at estimated potential failure time 47.93 Month. Participation of operators in inspection activities as well as implementing condition monitoring technique (DGA) on power transformers will lead to create rich and accurate database through recoding historical degradation data. Also these data can be analysed by operators regularly to detect any abnormality and hence

early actions can be taken by them to prevent unpredicted failures and paper insulation deterioration. Moreover, maintenance costs (downtime, labours and materials) will be optimised by predicting the potential failure of paper insulation.

Table 2 Estimating the Average P-F Interval of Power Transformer Paper Insulation

Unit ID	Potential Failure Prediction Time "P"	Functional Failure Time "F"	P-F Interval
AAZO-PY	43.28	60	16.72
AGBI-PY	48.51	60	11.49
HILI-PY	40.42	54	13.58
MASD-PY	43.75	54	10.25
TWAM-PY	33.70	42	8.30
Average			12.07

5.0 Discussions

Successful electrical power companies have sufficient failure data that involves accurate prediction of time to failure of power assets based on condition monitoring data. These data can estimate the potential failure time of their assets and hence select correct maintenance strategies. In this research, the authors define that warning limits (critical degradation) need to be selected carefully because if critical degradation is too high, it could cause failures to occur before they are predicted [18]. Furthermore, the aim of the planned maintenance is to enable both maintenance engineers and equipment operators to analyse the root cause of system or equipment failures, and based on this analysis they can develop a system of planned maintenance in order to modify or repair the equipment and hence optimise maintainability of systems [4, 30]. Thus, the planned maintenance pillar of TPM can play a significant role by utilising predictive maintenance tools such as prognostic techniques and analysis through autonomous maintenance (operators). However, they should have the right skills, training and capability to use prognostic tools as well interpret historical data of power plants, and hence establish proper maintenance tasks to overcome any technical problems in early stages. Operator needs to understand the function, structure and inspection methods for each part of equipment [21-22]. Moreover, the usage of advanced technologies in order to predict and identify any abnormality or equipment deterioration also enhances the principle of predictive maintenance. Mad Lazim and Ramayah [30] stated that TPM combines both the predictive and preventive maintenance strategies with more focus on participation of operators. Parida and Kumar (2006) explained that a mixture of both predictive and preventive

maintenance approaches can lead to detection of potential early failures as well as avoid equipment deterioration through utilising effective inspection technology of CBM such as DGA for oil analysis, thermography, spectroscopy, vibration, and other different tools.

This research has recognised how effective prognostic techniques can lead to successful implementation of TPM through the planned maintenance pillar, as well highlighting that operators should collect, record and analyse data of power plants in order to predict potential failures before occurrence. Kodali et al. [23] elaborated that the TPM framework advocates the use of predictive maintenance, as it was promoted as one of the main pillar of Nakajima's framework. The authors realize that abnormalities, equipment deterioration, and failures can be detected as well as predicted by operators through integrating the autonomous maintenance pillar with utilisation and application of maintenance optimisation mathematical models that employ the operational steps of the planned maintenance pillar; therefore daily operations will be improved through obtaining high equipment availability and performance. In this study, the authors find out that the documentations process is a key point that needs to be addressed clearly when an organisation's target is to obtain the benefits of continuous improvement. Thus, activities that related to continuous improvement and light maintenance tasks such as cleaning, lubricating, and tightening should be maintained and recorded for regular analysis. This kind of consistent and steady analysis will lead to significant results that can be shared between all staff and hence enable them to observe the performance of equipment for further improvements. Mad Lazim and Ramayah [30] advocated that when developing entire systems of autonomous maintenance, all important data relating to the performance and state of the equipment should be recorded in order to enable the skilled operators to analyse the recording of data and hence the results utilised to enhance more effective maintenance. Furthermore, maintenance costs involve direct and indirect expenses; direct costs relate to materials and labour and indirect associated with six big losses [21] – [24]. According to the prognostic techniques utilised by operators, it will allow maintenance engineers and operators to use proposed maintenance tasks to create effective solutions and optimise maintenance costs [24] – [25]. Based on experience and identified potential failure during prognosis analysis, suitable tasks can be selected from maintenance policies and producers. Persons (operators or maintenance engineers) to perform tasks are identified according to complexity, and maintenance costs are calculated. This determines appropriate actions and resources (labour, tools, parts or instruments) required to implement the maintenance policies. The case study organisation needs to understand the crucial role of prognosis techniques and it has to integrate the participation of autonomous maintenance with using optimisation a mathematical model that employs the concept of planned maintenance pillar on critical power plants in order to drive successful implementation of TPM within power industry.

6.0 Conclusion

The research has revealed that electric power organisations have recognised a strongly held perception that a reactive maintenance system works when the equipment is repaired at the same time of failure. However, the cost of fixing equipment in reactive mode can be three times greater than preventive maintenance costs. It seems that inherent maintenance practices, which reinforce reactive maintenance, also affect any changes towards implementation of world class maintenance practices. Furthermore, an organisation aspiring to employ world-class maintenance such as TPM will need to build a robust teamwork culture and utilise predictive maintenance concepts and tools such as prognostics techniques in order to predict failures before occurrence. The current practices within the Abu Dhabi power companies are static, not dynamic, and are underpinned by many obstacles and barriers. The results of this research have shown that effective prognostic techniques can lead electric power companies in Abu Dhabi to develop a TPM approach through planned maintenance, autonomous maintenance, training and education on the job, and focused improvement pillars. In addition, the results have proven that collection and analysis of historical data through operators is possible by using effective prognostic tools. However, implementing this new maintenance strategy (TPM) in the Abu Dhabi power industry may be challenging. Whilst TPM strategies will allow operators to conduct maintenance tasks and prognosis analysis, maintenance engineer responsibilities will need to change to enhance and support equipment operators. These changes will significantly affect the responsibilities and roles of operation staff. This research confirms that prognostic techniques can have a positive impact towards successful TPM implementation in the power industry.



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Authors' Biography

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High Pressure Gas Compressor Dry Gas Seal System Enhancement Case Study

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Abstract The paper describes Saudi Aramco's, Khurais Producing Department's (KhPD) experience with their high pressure gas compressor (HP) dry gas seal (DGS) system issues. Throughout the paper, issue investigation will be explored as well as recommendations and findings.

Key words Rotating Machines, Condition Monitoring, dry gas seal, compressor.

1.0 Introduction

Khurais producing department (KhPD) consists of four oil trains, each oil train is responsible of receiving the crude oil from the wells, stabilize, and purify by removing sand, water, gas and H₂S contents to become ready for use and shipment to refineries. Each oil train rely on a high pressure (HP) gas compressor for its process, making the compressor an important part of the production process.

The HP compressors are fit with a dry gas sealing (DGS) system. The DGS system consists of two entering gases, fuel gas to the primary seal and nitrogen to the separation seal as seen in below *Figure 1*. There are two leakage lines, primary and secondary. The primary leak line directs the fuel gas to the flare system. The secondary leak line directs the injected nitrogen and partially leaked fuel gas from the secondary seal to an atmospheric vent. To create a convenient path for the gas, pressures at each seal location varies. Therefore, the primary leakage line has a lower pressure value than the fuel gas. The secondary leakage line has even a lower value than the primary leakage line.

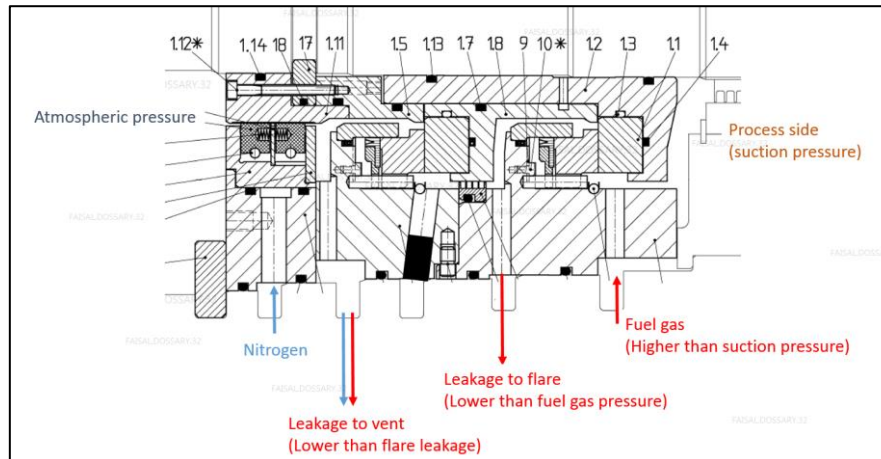


Figure 1: Cross sectional drawing of the installed dry gas seal with description.

KhPD DGS system depends mainly on the fuel gas as main supply gas, though the compressor media gas is connected to the DGS system as a backup and safety option in case of any disturbance occurrence on the supply of the main fuel gas (Figure 2). The backup gas is connected to the same fuel gas line, but regulated by pressures difference; the main fuel gas is designed to be 9 PSI higher than the backup gas at all time, to restrict the flow of the backup gas to the DGS system.

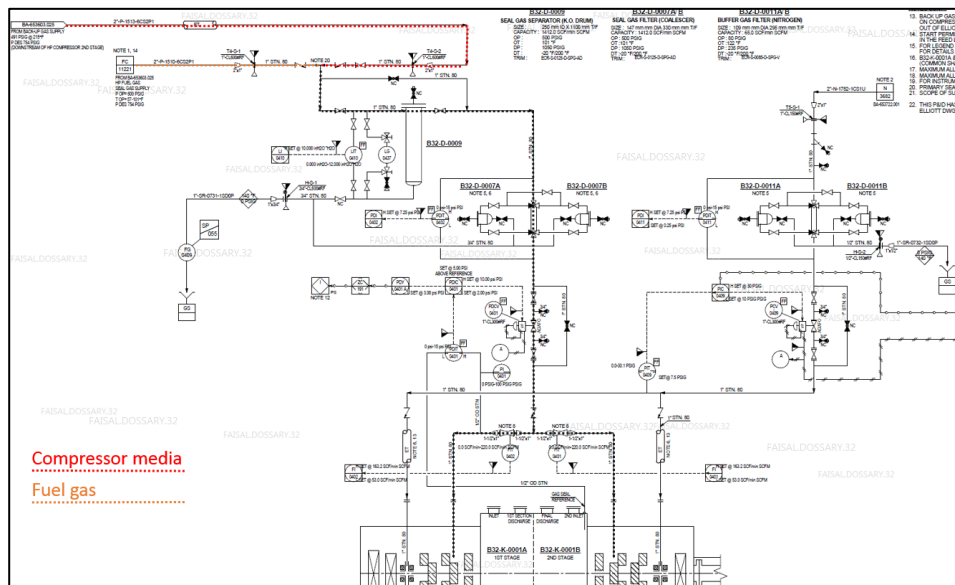


Figure 2: P&ID of the dry gas seal system highlighted the compressor and fuel gas lines.

As for the leakage protection system, the DGS is designed with a designated high flow alarm on the secondary leakage line. The primary leakage line contains both high and trip flow alarms as shown in Figure 3.

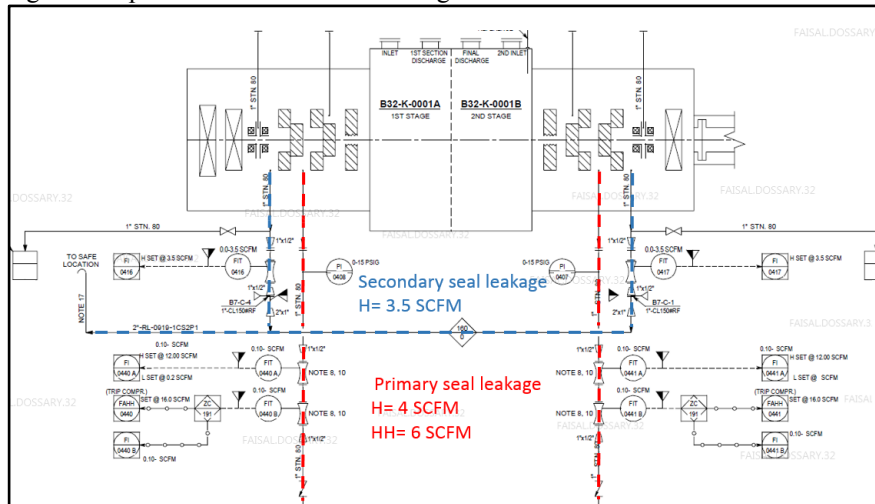


Figure 3: Seal leakage alarm setting on both primary and secondary leakage lines.

2.0 Background

After normal shutdown of the plant for scheduled maintenance activities, one of the compressors was started with normal parameters. Then it was noticed that the primary leakage of the inboard seal was increasing gradually reaching the alarm point. Consequently, operations decreased the nitrogen pressure from 7 to around 2.5 PSI, as shown in Figure 4, to reduce the primary leakage and prevent compressor tripping. The secondary leakage flow indicator is giving a “Bad” reading, indicating out of range while the alarm limit is 3.5 SCFM (the flowmeter range is 0-3.5 SCFM) while the primary showed low values at all time.

The nitrogen injection into the DGS’s separation seal, as seen in Figure 1, is mainly responsible to create the carbon ring’s lift, since it’s an aerostatic carbon ring design. In addition, the nitrogen pressure plays a major role in minimizing and ensuring no oil or contamination is entering the DGS from the journal radial bearings.

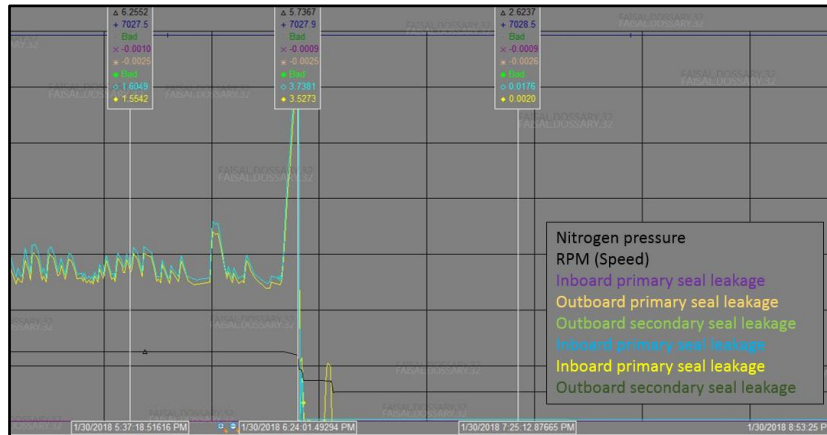


Figure 4: Trend of HP compressor's dry gas seal leakage system.

3.0 Investigation:

From analysis and investigation of trends, the following observations can be concluded:

- The secondary leakage line flow indicator is indicating high, out of range flow.
- The primary leakage line flow indicator is indicating low flow. This is considered abnormal since the primary leakage line is supposed to contain most of the gas leakages.
- The gas is directed to the most convenient route (less pressure). Currently, most of the gas is passing through the secondary leakage line (vent).
- Passing the secondary seal face to the vent shall occur only if the seal face is worn or in hang up condition.
 - Hang up may result from contamination/oil reaching the face spring.
 - Worn out condition may result from gas contamination.

Visual inspection of the secondary leakage line was conducted during a recent shutdown and revealed oil traces, as shown in Figure 5. This indicates possibility of contamination reaching the secondary face. Therefore, hang up condition is expected to occur due to contamination reaching the DGS thrust ring and resisting its closure, its normal operational movement.



Figure 5: Oil traces found in the secondary leakage line.

This explained the experienced scenario where the reduction of nitrogen pressure increased the leakage of the primary line, for which increasing the nitrogen pressure will result in increase of leakage resistance through the secondary leakage line (Figure 6).

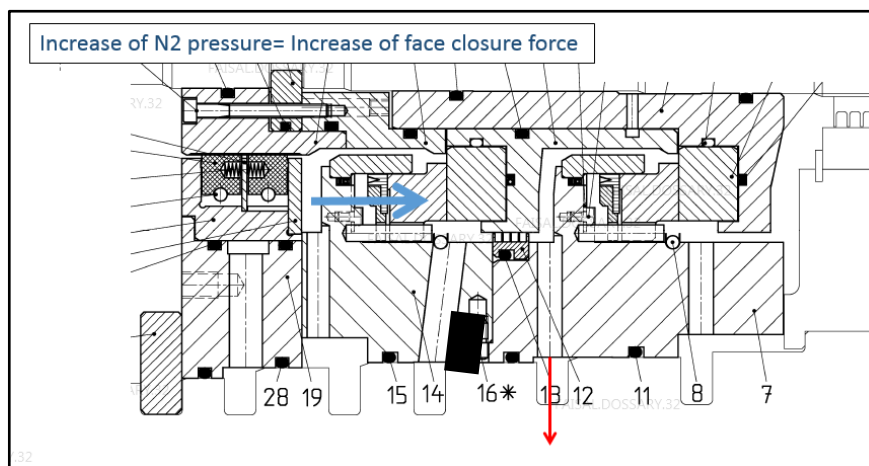


Figure 6: Oil traces found in the secondary leakage line.

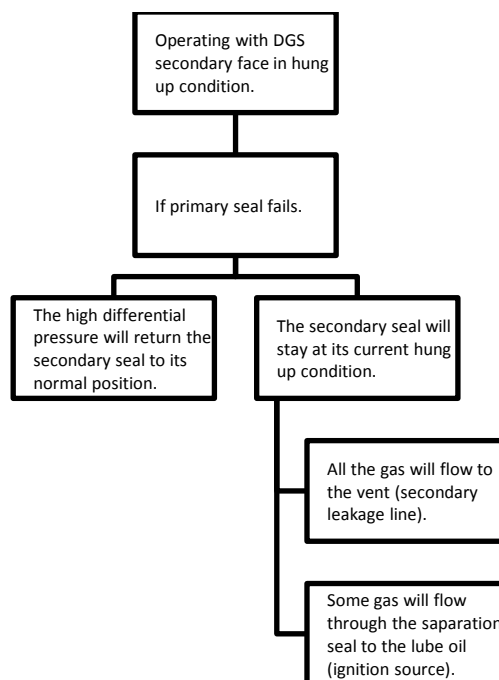
In addition, the secondary vent line to atmosphere was found with a vertical open end design, Figure 8. Such design increases the risk line blockage and water/dust contamination entering the seal.

4.0 Recommendation:

The high pressure compressor role in KhPD plant production process is vital since there are no redundant equipment available. When the compressor is shutdown, the oil train is recommended to be shutdown, since high gas flaring is forbidden. Therefore a failure mode effect analysis was conducted to ensure taking the right decision.

4.1 Failure Mode Effect Analysis:

Based on above investigation of the situation, it's suspected that the secondary seal face is in a hung up, on open position.



4.2 Rectification Actions:

Throughout the above brief FMEA chart, it can be concluded that a safety risk is associated with running the compressor with its current existing situation. Therefore the compressor was recommended to stop and perform the following recommendations:

1- Perform dry gas seal replacement:

Since the dry gas seal was suspected to be in hang-up condition, it was recommended to replace the seal and inspect its internals.

2- Rectify secondary leakage vent line end design.

The secondary leakage vent line-end design by adding a bent sleeve to restrict contamination during rainy and dusty weather conditions. Figure 8, shows the vent line design before and after rectification.



Figure 8: Dry gas seal secondary seal leakage vent line before and after modification.

3- Add secondary labyrinth seal on the radial bearings.

Since oil contamination was found within the seal leakage line, it indicated oil contamination migration from the labyrinth into the seal. Therefore it was reemphasized to operations the importance of keeping the nitrogen pressure at the recommended value at all times. In addition, another layer of oil vapor restriction was added through adding additional labyrinth seal on the radial bearings.



Figure 9: Dry gas seal found with oil contamination leakage during replacement.

4- Repair backup gas supply valve.

When the pressure of the backup gas supply was trended against the primary fuel gas supply, it was found that the fuel gas supply pressure have decreased multiple times to values lower than the backup gas pressure. Indicating that the DGS depended on the compressor media to feed the DGS, which is not recommended since the media is expected to carry impurities.



Figure 10: Dry gas seal secondary seal leakage vent line, before and after modification.

Figure 10 shows inspection of the DGS with dust contamination appearance. Therefore it was recommended to check the integrity of the regulating valve and rectify prior to equipment startup.

5- Change DGS leakage protection system.

Since the decision of compressor shutdown required human investigation and interaction, it was recommended to alter the protection system to a human-free interactive system.

Therefore with the support of Saudi Aramco Consulting Services Department specialists' consultation, the protection system was changed by eliminating automatic compressor trip on high-high primary seal leakage. Instead, the condition was made as a high-high alarm. For which a high alarm or high-high alarm on primary seal leakage, combined with a high alarm or high-high alarm on secondary seal leakage should trip the compressor automatically. In addition the seal leakage settings were changed as below:

	Primary New Recommended Setting		Secondary New Recommended Setting	
DGS	H Setting	12 SCFM	H Setting	8 SCFM
	HH Setting	16 SCFM	HH Setting	12 SCFM

Therefore with the increase of seal settings and having such voting system, production operation unnecessary interruption is expected to decrease. Furthermore human interaction is not required during DGS hung up condition.

5.0 Conclusion

Within completion of all recommended actions, the compressor was started and returned to service with healthy readings. Throughout the performed recommendations and system enhancement, the compressors dry gas seal life longevity was achieved. In addition to reduction of unnecessary operational interruptions through equipment trip, the plant safety and reliability was improved by achieving a human-free interactive protective system.

6.0 Acknowledgement

The DGS protection system modification mentioned in this paper was accomplished by participation of Saudi Aramco Consulting Services Department (CSD) Engineer Tariq Al-shaikh, CSD Sr. Consultant.

Authors' Biography



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Frailty Models for Survival Data applied to Maintenance Management

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Abstract Due to large number of equipment in industrial companies, maintenance management may not always be able to identify and quantify assets heterogeneity concerning failure data. Several statistical and mathematical methods are being developed in the last years looking for an improvement on the system reliability. We've been working on survival analysis applied to equipment failure data using Cox proportional hazards, however, we notice that individualization with respect to the risk must be considered. Frailty models allowed us to identify equipment not following patterns of identical distributed times to failure. Although there exist some controversy around *frailty models*, claiming its poor contribution to the model, the truth is that when clustering our equipment by its *id* with a non-observed frailty component, we quickly identify those with higher influence on the hazard. This is particularly useful whether the intention is to find a homogeneous sample or work with all samples considering frailty component, contributing either way, to an enhanced and adaptive maintenance management.

Key words reliability, maintenance, time between failures, Cox proportional hazards, frailty models.

1.0 Introduction

Within the scope of a joint project between Galp Energia, namely Sines' refinery (RS), the Portuguese Oil Company, and the Portuguese Foundation for Science and Technology (FCT), it has been proposed to study several equipment at Sines' refinery. Times to failure were at stake in order to improve efficiency on reliability issues together with an RCM (Reliability Centered Management) target, a methodology that has born in the 70's with Moubray [1] and helps organizations

to find and focus on the real problems. In order to do this, it is fundamental that companies have reliable failure registries data. ISO 14224:2006 [2] is a petroleum and petrochemical standard that indicates the better way to achieve quality data and normalizes equipment boundaries to report failures, statistical parameters, among others. Getting close to the standard will be useful for the Company to compare itself with others in the same industry. However, despite differences between taxonomic notation for equipment among GE and ISO 14224:2006, we decided to investigate behavior for some RS equipment classes. In this paper, we will show a particular class of pumps restricted to a factory plant that is subject to adverse environmental conditions: Alkylation unit. Ordinary survival analysis assumes that all individuals in a group have the same risk, however, when dealing with such a kind of environmental adversities, heterogeneity may be quite relevant on influencing the hazard. OREDA 2015 is the latest compilation on Oil reliability data from several offshore companies, and they hardly refer the particular relevance of heterogeneity on reliability parameters estimation. They purpose there to apply an analytical estimator to the failure rate (usually described by $\lambda = n/T$, with n the number of failures in the total period of time T), which they call multi-sample estimator- $\hat{\lambda}$, and contemplate a heterogeneity component, which is described in detail in the compilation. We propose here to reveal the extent of the contribution of a random effect in each equipment to influence, by a non-observed way the hazard function under a theoretical and mathematical survival point of view. For that, we've used survival models as Cox proportional hazards as well as parametric models including a frailty component that could measure the influence of that specific equipment in the hazard of the system. Following that way, it's easier to identify which are the equipment falling out of regular patterns, making possible to identify eventual homogeneous subgroups, previously defined or not, and using that information to infer, for each equipment of a given category, a different hazard curve and a reliability curve with respect to its own frailty value. Dynamic inspection instead of periodic identical one for all equipment can then be adopted if a significant costs reduction is verified based on the hazard curve, where a constant cumulative hazard policy [3] could be applied.

2.0 Related matters

This study is part of a larger project where hundreds of equipment were tested regarding its failure times. RS is composed of five main plants represented in figure 1. Each plant is composed itself by several other units. Failure data for all pumps were collected and several categories of RS pumps were tested, but let's focus first on the main two: Centrifugal and Positive Displacement. From simple statistics we notice that Plant II was responsible for the larger part of those failures in centrifugal pumps, our target group, in which its Alkylation unit responds for more than 27% of total. Survival analysis using Kaplan-Meier (KM) curves [4] and paramet-

ric survival regression (wide known methods to estimate hazard curves), were used and discussed, and examples of usage are illustrated in [5]. The proportional hazard model of Cox [9] is used here with no covariates. Lack of covariates is a common place in this study, which has made our work difficult. However we have tried to use a component that could explain heterogeneity among identical equipment.

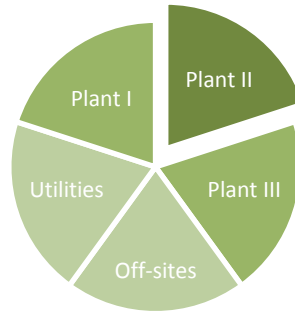


Figure 1 – Sines' refinery composition

A first approach was to use a non-parametric approach (Kaplan-Meier and Cox Proportional Hazards) to understand the real behavior of times to failure. Of course we are in the presence of repairable systems and recent developments have been made regarding imperfect repair models, including aging simulation [6], but we rather wanted to evaluate the already existing system, and most of all, times to failure behavior. We assume that we are in the presence of a *good as new* repair and although we know the risk of assuming that, we intended also to verify if the error of that assumption was enough mitigated with frailty component associated to each equipment *id*. With this method it was intended to identify in a global context, equipment with lower and higher reliability and its contribution for the system reliability and also allowing splitting data into homogeneous groups with specific characteristics. Following maintenance management staff advises and know-how was fundamental as well to achieve good sense results.

3.0 Methodology

In a first approach, we consider quite relevant evidences that we could took from a simple production of a cumulated failure plot – $N(t)$. The way the curve defined by this function changes over time and highlight periods of higher or lower stress that could be evaluated in order to understand what have led to its occurrence. Adopted methodology involved either non-parametric models, as already mentioned, and complemented with semi-parametric approaches as Cox PH, not in its usual form because of nonexistence of covariates. Parametric approaches using well

known distribution as Exponential, Weibull, Log-logistic and Lognormal were tried as well, so the best model could be obtained to make failure prediction and simulation. Failure collection was not always an easy task once information does not respect standard formats or were simply inexistent. However, with gather information it was possible to analyze mechanical intrinsic failures (recurrence events less than 30 days after an event were re-interventions instead of failures). It was adjusted a censor formulation to our real data as represented in figure 2.

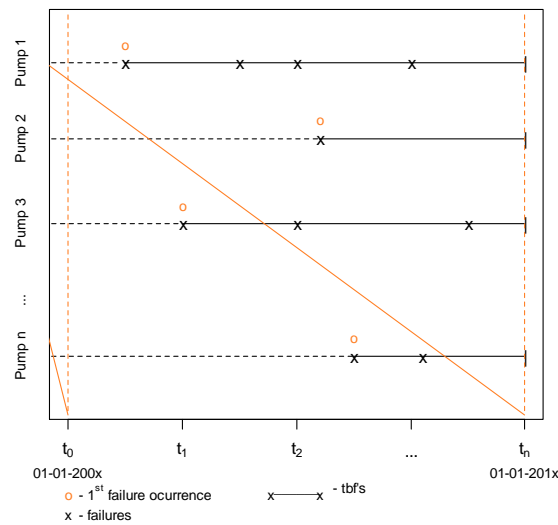


Figure 2 Sines' refinery composition

According to that formulation, times are not left truncated, avoiding that way noise made by equipment that possibly may have been out of service or having long reparation times. Time counts since the first failure subsequently to 01-01-200x and later failures are then registered. Test period ends on 01-01-201x being right censored. Equipment not revealing any kind of failure was subject to other kind of analysis even if it is not assured they really have not had any failure at all (hidden failures). Cumulated failures plot is depicted in figure 3 and it allows identification of *sad* and *happy* periods as defined in [7] and relates it somehow, with failures/improvements in the system along time. A careful management should question what have happened in critical periods. This plot allows, beyond evaluate critical periods, to understand that we are not in the presence of a system where times are not independent and identically distributed because of its nonlinear form.

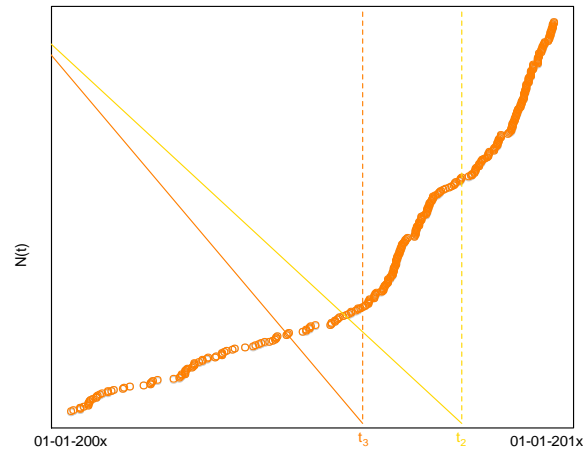


Figure 3 – $N(t)$ for Centrifugal pumps

Consequently, models that include recurrence factor were studied according Andersen and Gill formulation [8]. With gather data it was possible to identify in those two major categories of pumps, the really impact of some of those sub-groups in the global context, with plant II giving an already expected higher slope on reliability curve for centrifugal pumps according a stratified survival curve for each plant (figure 4). Knowing that Alkylolation unit has the highest number of centrifugal pumps' failures, a deeper analysis was made for that specific group of equipment's. Using R software [10], Cox model as well as parametric models with frailty component were tested and shown next. Different distributions can fit for frailty component and different mixed models can be obtained.

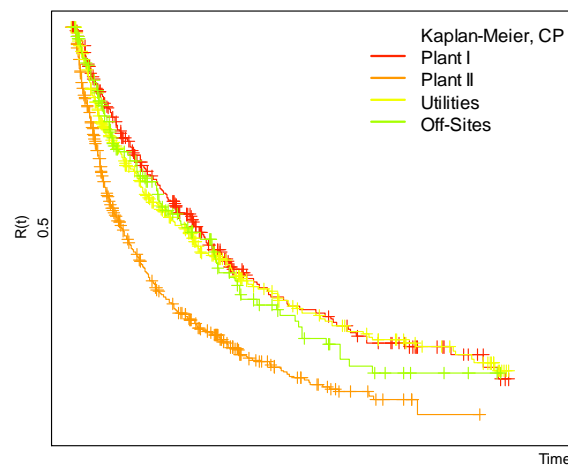


Figure 4 – Stratified survival curve by plant

3.1 Tested models

Description of frailty models can be found in [11] or [12], in adaptation to Cox proportional hazards. We have a frailty component following some distribution, influencing the baseline hazard as expressed by (1).

$$h_{ij}(t|u_i) = u_i h_0(t) e^{x_{ij}\beta^T} \quad (1)$$

with $i \in I = \{1, \dots, G\}$ and $j \in J_i = \{1, \dots, n_i\}$, where $\lambda_0(\cdot)$ is the baseline hazard function and u_i is the frailty term of the group i , and x_i is the vector of covariates for subject j in the group i and β is the vector of regression coefficients. This is the shared frailty model, once all subjects of the same cluster share the same frailty u_i . As in our case we are in the presence of no covariates, so we can resume the frailty model as being:

$$h_i(t|u_i) = u_i h_0(t) \quad (2)$$

that is a description for the univariate model irrespective of the baseline hazard distribution. In our specific case, we have i groups, which means, i equipments with respective frailty u_i . n_i is 1 for all groups and we have then, the univariate case. We have instead, i pumps with n events. Frailties were tested for three distributions (Gamma, Positive Stable and Inverse Gaussian) and for four parametric models (Exponential, Weibull, Lognormal and Log-logistic), which are briefly described in equations (3), (4), (5) and (6).

$$\text{Exponential: } h_0(t) = 1/\lambda, \lambda > 0 \quad (3)$$

$$\text{Weibull: } h_0(t) = \frac{1}{\lambda^\rho} \rho t^{\rho-1}, \lambda, \rho > 0 \quad (4)$$

$$\text{Loglogistic: } h_0(t) = \frac{\rho \left(\frac{1}{\lambda^\rho}\right) t^{\rho-1}}{\left[1 + \left(\frac{t}{\lambda}\right)^\rho\right]}, \lambda, \rho > 0 \quad (5)$$

$$\text{Lognormal: } h_0(t) = \frac{\phi\left(\frac{\log t - \mu}{\sigma}\right)}{\sigma t \Phi\left(1 - \frac{\log t - \mu}{\sigma}\right)}, \sigma > 0, \mu \in \mathbb{R} \quad (6)$$

Criteria for choosing best fit models were AIC and BIC as resumed in [13]. Figure 5 resumes AIC and BIC values for tested models when using all sample data with a better AIC and BIC values for Lognormal and Log-logistic distribution for all equipment on test. We must refer here that equipment with zero failures on test period was not considered, as it was not possible to ensure that it was really in service, even for a short period of time. Gamma and Inverse Gaussian revealed, according to the same figure, a good approach for frailty distribution, so we can arguably choose either one. Let's now make a prediction for frailty component using Gamma distribution, just because of its versatility. We can take now a deeper look on predicted frailties for each equipment id , illustrated in figure 6. It gave us a different perspective on equipment influence on the global hazard. All tested dis-

tributions have given similar results, revealing for all *id*'s an identical risk level for predictions. Nevertheless, the true is that even though an interval for the frailty value be considered, let's say $[0.8; 1.2]$, we notice a higher discrepancy for the five last equipments, which not necessarily may be those with more recurrence. Thus, we must be careful when considering higher frailty values corresponding to equipment with more events. Indeed, when using Andersen and Gill [8] formulation for recurrent events, frailty values are exactly one for all pumps population, giving us the idea that recurrence is identically distributed for clusters, and considering all population at once may not incur in a large bias.

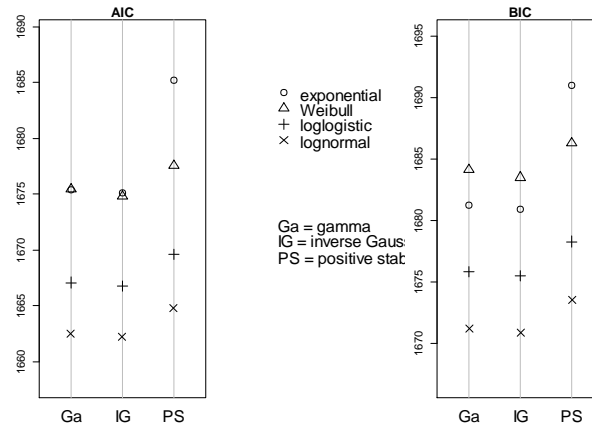


Figure 5 – AIC and BIC values for the parametric tested values

Frailty component indicates the level of risk of that specific equipment has when compared with others regarding global sample. It indicates that *times between failures* of a specific *id* traduce higher/shorter risk and thus, a higher/lower probability to occur an event. In short, we know that the frailty value indicates that:

$$\begin{cases} u_i > 1, \text{ increased individual level hazard} \\ u_i < 1, \text{ decreased individual level hazard} \end{cases}$$

So, we'll have a homogeneous sample whenever frailties values are around one, revealing a lower risk level over the reference risk. A different criterion was also made to confirm if *bad actors* match *id*'s with higher frailty predicted value, that is, equipment with a higher influence on the hazard. When making an isolated analysis to the slope of the Kaplan-Meier curve for all equipment, we notice that a few ones reach less than 50% of reliability before the Kaplan-Meier median for the global model (with all pumps). We think that is reasonable to think in those ones as being *bad actors*. Of course these are as well equipment with more of events. When we took off those five equipment out of the sample, we obtain the predicted values for frailty component, illustrated in figure 7. For *bad actors*, a

homogeneous sample was achieved either as proved by figure 8. For all distributions it's clear that homogeneous samples were achieved in both cases, revealing that *bad actors* actually match *id*'s automatically identified by the frailty model.

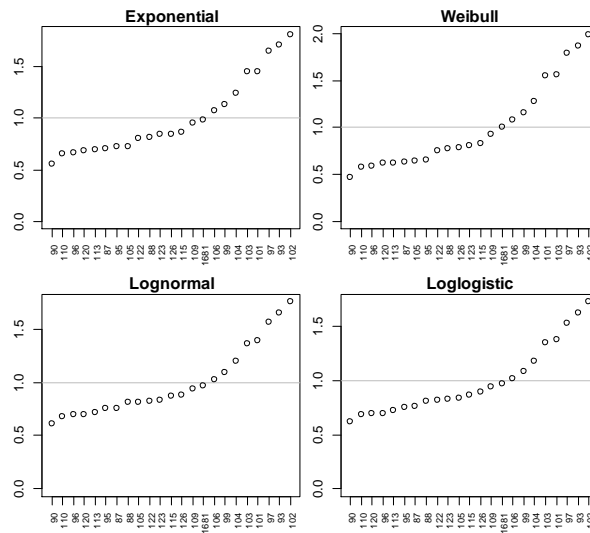


Figure 6 – Gamma frailty for all AL sample

AIC and BIC values revealed as well same distribution with better fit for all sub-groups: Lognormal. We have no doubts that two homogeneous samples were found and serve the purpose to make prediction with their fitted parametric models.

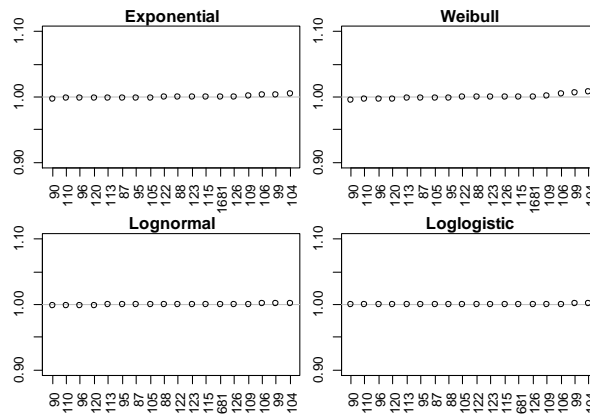


Figure 7 – Gamma frailty values for different distributions (AL sample removing bad actors)

But we are now interested on focus if large differences on the hazard are found when using ONLY the global frailty model, with the heterogeneous sample. Shall global model be a good approach with frailty components, with an acceptable error with respect to reliability values to homogeneous samples? [11] mention quite relevant information about homogeneity in subgroups, which show that caution is needed if heterogeneity is present through the existence of two subpopulations, each of them assuming to be homogeneous. They alert that “...can lead to quite unexpected results at the population level.” Examples for two subpopulations are there provided with an approach to mixture models, where $h_{1,p}(t)$ and $h_{2,p}(t)$ are the hazards for respective subpopulations, and $\pi(t)$ the proportion of equipments that are still working at time t in the first subpopulation:

$$\pi(t) = \frac{\pi(0)S_{1,p}(t)}{\pi(0)S_{1,p}(t) + (1 - \pi(0))S_{2,p}(t)} \quad (7)$$

with $\pi(0)$ the proportion of equipments in the first subpopulation at time zero.

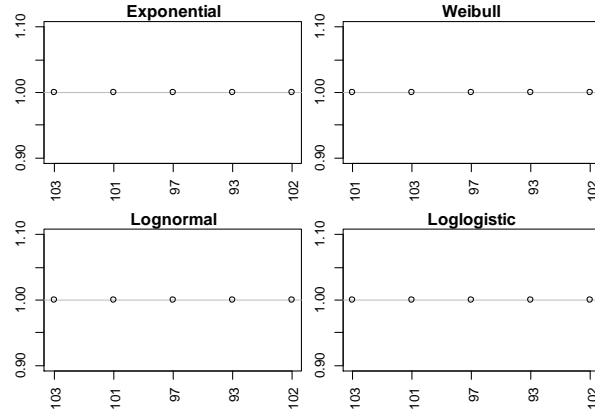


Figure 8 – Gamma frailty values for different distributions (for AL bad actors)

The hazard can then be given by:

$$h_p(0) = \pi(t)h_{1,p}(t) + (1 - \pi(t))h_{2,p}(t) \quad (8)$$

Approach to mixture models will not be discussed here, but a slightly different procedure for hazard calculation using mixture models when heterogeneity is revealed is discussed in [14] with good results for parameters and models estimation. We are, for the present case, focused on risk contribution of each individual in the model for the global hazard and understand if there is room for using frailties in a realistic perspective. Let's first observe behavior for population as well as

for samples. Parameters of tested models are shown for the three distinct situations in table 1: global model (all pumps - heterogeneous), *bad actors* (sample 1) and without *bad actors* (sample 2).

Global model	Distr.	θ	$\log \hat{\lambda}$	(se)	$\hat{\rho}$	(se)	AIC
	Exp.	0.24	6.459	0.131	-	-	1675.41
	Weib.	0.318	7.238	0.462	1.119	0.087	1675.42
	Loglog.	0.199	5.953	0.768	1.596	0.134	1667.08
			$\hat{\mu}$	(se)	$\hat{\sigma}$	(se)	
	Lognor.	0.21	5.97	0.13	1.07	0.08	1662.5

Sample 1	Distr.	θ	$\log \hat{\lambda}$	(se)	$\hat{\rho}$	(se)	AIC
	Exp.	0	5.728	0.125	-	-	757.534
	Weib.	0	7.191	0.57	1.243	0.125	755.402
	Loglog.	0	5.372	1.177	1.954	0.215	750.916
			$\hat{\mu}$	(se)	$\hat{\sigma}$	(se)	
	Lognor.	0	5.365	0.113	0.874	0.083	748.827

Sample 2	Distr.	θ	$\log \hat{\lambda}$	(se)	$\hat{\rho}$	(se)	AIC
	Exp.	0.001	6.845	0.125	-	-	898.278
	Weib.	0.002	7.362	0.592	1.119	0.114	899.826
	Loglog.	0.000	6.378	1.023	1.489	0.16	898.131
			$\hat{\mu}$	(se)	$\hat{\sigma}$	(se)	
	Lognor.	0.001	6.372	0.138	1.129	0.108	895.756

Table 1 – Parameters for parametric frailty models using different samples.

Large differences are observed, if we consider logarithm scale, however, we notice some consistence for Weibull model concerning both parameters against higher differences between parameters for other models even though AIC value is not the smaller. Lognormal distribution in turn, presents a consistent lower AIC for all models as well as its θ parameter for frailty variance is also lower (θ is obviously next to zero in homogeneous samples). A visual perception may also help decision as well as some practical results. Figure 9 illustrates how frailties influence the hazard with Lognormal parametric frailty model, which had lower AIC for all samples. For each pump there is a corresponding u_i random component influencing the hazard, and reliability curves for each one can be derived and plot-

ted. We are going now to compare some reliability results and medians (rather than means, once it's a more robust estimator) between global model with frailty and each sample (sample 1 and 2) with its respective fitted distributions whose parameters are from table 1. Table 2 illustrates for all equipment, their frailty parameter (u_i), the respective median (Med_i) and three reliability moments ($R(t_j)$, = $30ot$, $90ot$, $150ot$), with ot = *operational time* with non-disclosed units.

3.2 Models validation

A graphical perception and an overview on models fit with frailty component influencing the hazard are made and conceptual results will be shown. Frailties for sample 1 were one for all equipment while for sample 2 they were not strictly one, but differences were considered negligible. Since we know that that frailty has a multiplicative effect over the hazard, if we divide the global median by each individual frailty, we are then supposed to obtain an approximation of the respective individual median. Of course we found differences in some equipment, reaching from 30 to 44%, but again, we must not forget that it is the median that is mentioned, which may result in higher differences related with sample dimensions. Let's now consider pump 1 from sample 1 and pump 20 from sample 2. Reliability for instant $30ot$ for both equipment using global model of table 1 (Lognormal) with frailty parameters can be expressed as:

$$R_1(30ot) = \left(\Phi \left(\frac{-\log 30ot + 5.97}{1.07} \right) \right)^{1.76} = 0.41$$

$$R_{20}(30ot) = \left(\Phi \left(\frac{-\log 30ot + 5.97}{1.07} \right) \right)^{0.7} = 0.7$$

If no frailty is considered, then we'll have, using sample 1 and 2 parameters from table 1:

$$R_1(30ot) = \Phi \left(\frac{-\log 30ot + 5.365}{0.874} \right) = 0.35$$

$$R_{20}(30ot) = \left(\frac{-\log 30ot + 6.372}{1.129} \right) = 0.72$$

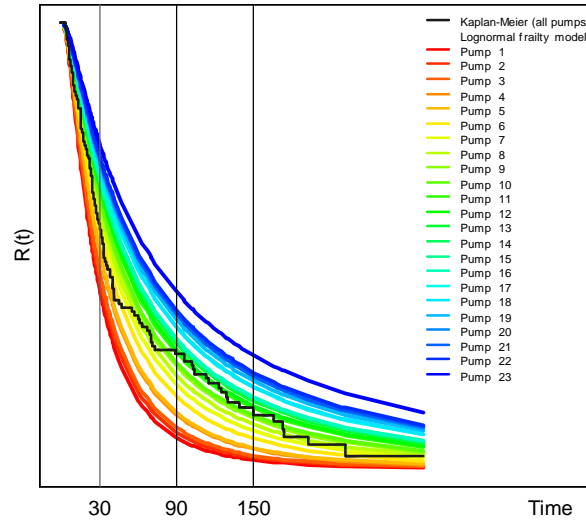


Figure 9 – Reliability curves according frailty parameter of each pump using Lognormal distribution and a Gamma frailty

Pump	u_i	Med_i	$R(30)$	$R(90)$	$R(150)$
Pump 1	1.76	24.2	0.41	0.07	0.02
Pump 2	1.65	25.8	0.43	0.08	0.02
Pump 3	1.57	26.7	0.45	0.09	0.03
Pump 4	1.39	29.4	0.49	0.12	0.04
Pump 5	1.36	30.3	0.5	0.13	0.05
Pump 6	1.2	33.6	0.54	0.16	0.07
Pump 7	1.1	36.8	0.57	0.19	0.08
Pump 8	1.03	38.2	0.59	0.21	0.1
Pump 9	0.97	40.6	0.61	0.23	0.11
Pump 10	0.94	41.5	0.62	0.24	0.12
Pump 11	0.89	45.4	0.63	0.26	0.14
Pump 12	0.87	45.4	0.64	0.27	0.14
Pump 13	0.83	47.5	0.65	0.28	0.15
Pump 14	0.82	47.5	0.65	0.29	0.16
Pump 15	0.82	55.0	0.66	0.29	0.16
Pump 16	0.81	55.0	0.66	0.29	0.16
Pump 17	0.75	55.0	0.68	0.32	0.18
Pump 18	0.75	55.0	0.68	0.32	0.18
Pump 19	0.72	55.0	0.69	0.33	0.2
Pump 20	0.7	57.2	0.7	0.35	0.21
Pump 21	0.7	57.2	0.7	0.35	0.21
Pump 22	0.68	60.6	0.7	0.36	0.22
Pump 23	0.61	66.8	0.73	0.4	0.25

Table 2 – Reliability results using global model with frailties for all pumps. Shaded area represents sample 1

Table 3 represents the medians for the three cases and we can conclude that each individual median calculated within the global model is closer to the median of the subgroup (sample 1) than to the median of the global model. This may indicate that using frailty technique could be a good bet when the balance for decisions over a set of equipment is needed.

<i>Model</i>	<i>Median</i>
Global	39.15
Sample 1	21.37
Sample 2	58.53

Table 3 – Medians for all 3 samples using Lognormal distribution

Figure 10 shows differences between frailty model and Kaplan-Meier curves. Kaplan-Meier with highest slope refers to sample 1 and we can observe high differences for both samples. As we have referred, KM only uses punctual time information, discarding cluster effect, which we think to be, for the case, considerably relevant.

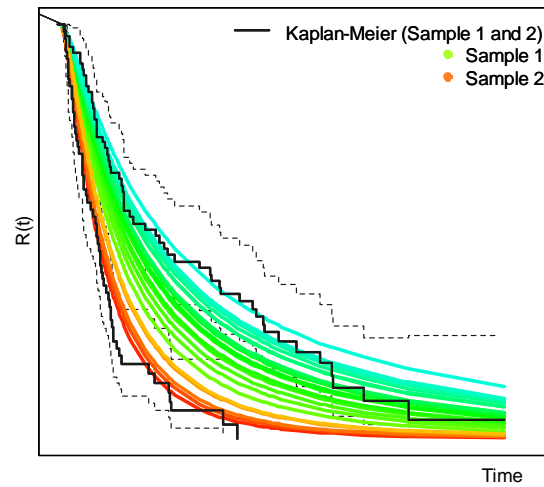


Figure 10 – Kaplan-Meier curves for sample 1 and 2 and reliability curves using global frailty model

4.0 Conclusion

We found frailty information very useful in quickly detecting heterogeneous samples, including *bad actors*, although a previous analysis shall dismiss some equipment only with censors, which we've verified to cause models bad estimations and bias for frailties. We found this models very effective on homogeneous groups identification, allowing to work either with global model with frailties, or in turn, with homogeneous subgroups. However, for this specific case, it was important for maintenance management to evaluate each element risk. When associated with other maintenance information, as costs, spare parts, availability, among others, it may reveal a more realistic statistic than using a single model for all equipment. Frailty models have thus, a great potential and can also be used in other context. Some investigations on costs association with frailty value have been made, but so far, no emphasis results were found. However, we strongly believe that an accurate analysis is possible if a frailty component were added. Another interesting investigation might include associating frailty as a risk level with spare parts components on maintenance stock.

Acknowledgements

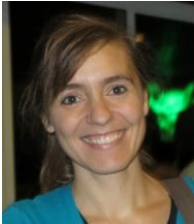


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Non-dimensional pattern recognition approach for the faults classification in rotating machines

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Abstract Maintenance industry has become more challenging and demanding, having an impact in technologies and engineering developments. The application of intelligent systems has arisen from the need of improved mechanisms for diagnosis generation. In literature, it is possible to find a wide range of methods developed for fault identification and diagnosis in rotating machines. Nevertheless, they have a narrow scope and their industrial application cannot be directly assessed. This work presents a machine learning application for the pattern recognition and fault classification in rotating machines through vibration signals. The proposed method is characterised by simple data preparation required with no need of high human proficiency in dynamics and vibration analysis, and its testing at different rotating speeds. Results obtained with non-dimensional features extracted in time domain are compared with frequency domain ones, suggesting a future possibility for centralised condition based maintenance according the Internet of things (IoT) of Industry 4.0.

Key words Rotating Machines, Fault Detection, Fault Diagnosis, Condition Monitoring, Pattern Recognition, Artificial Neural Networks.

1.0 Introduction

The increased interest in industrial maintenance has resulted into the permanent search for new and improved applications and techniques which provide the better practices to optimise the productive processes and achieve the desire performances by the organisations. Nowadays, the aim of the companies is to opt for maintenance strategies that allow them to have a permanent control over all the assets involved in their processes, avoiding unexpected and catastrophic failures. An opportune and adequate diagnosis at an early stage is essential to achieve this objective, and adds high value to the business. In this frame, it emerges the application of intelligent systems, such as machine learning applications, which

can identify certain patterns of failure and generate potential diagnoses, regardless of the human expertise.

Supervised machine learning methods are based on computational intelligence, and are trained through data with pre-assigned labels or targets for a fixed number of classes. A wide range of techniques have been developed under this classification, being the most popularly used for pattern recognition: support vector machine (SVM), fuzzy logic, principal component analysis (PCA) and artificial neural network (ANN).

ANNs are based in the human brain operation, being able to memorise and learn from external inputs, with the capability of adapting to produce consistent responses. It has been evidenced, by Nahvi and Esfahanian [2], the capability of ANNs of dealing with a high number of features and provide acceptable results for the fault detection, however the 100% of accuracy is not achieved at any of the conducted experiments by them. Bearing faults have been also studied by this method [3], [4], demonstrating an ability for damage detection at an early stage. Other researchers have focused their studies into localise the failures as well into quantify the damage [5], [6].

These models have simplified the fault identification stage through the introduction of learning assessment. However, the revised works still present a high dependency on complex data preparation procedures due pre and post signal processing. Additionally, most of them are focused in the identification of a unique fault. With the aim of eliminate the human expertise need, a simple non-dimensional approach is proposed in this study, which uses as input the vibration signal and provides as output a potential diagnosis, based on healthy condition and selected typical rotor faults. Computational tools supply the support required to conduct the study.

2.0 Experimental rig and data

Data collection is conducted in an experimental rig at the University of Manchester, United Kingdom. This rig represents a multi-stage rotating machine (Figure 1). It consists in two shafts connected by a rigid coupling (C2). The driven shaft (Sh1) has a length of 1000 *mm* and it is coupled by a flexible unit (C1) to a three-phase electric motor (0.75 *kW*). This shaft, has installed two balancing discs (D1, D2), while the shorter shaft (Sh2) of a length of 500 *mm* has one balancing disc (D3). The assembly is mounted over a total of four grease lubricated ball bearings (B1, B2, B3, B4). The bearings are mounted on bearing pedestals (P1, P2, P3, P4), which are secured by bolts to a steel base that acts as foundation of the machinery within a high mass.

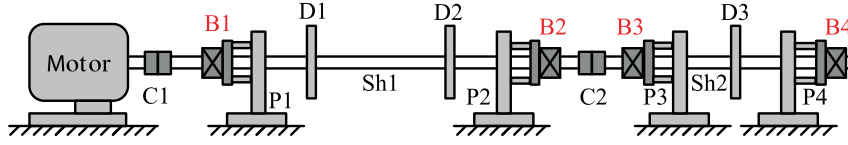


Figure 1. Experimental rig [7]

There are four faulty conditions considered for this study, in addition to a fifth class, corresponding to the ‘healthy’ condition. The ‘healthy’ condition provides the baseline to identify the changes on vibration patterns when additional failures are introduced. The base condition presents, as in industry, residual misalignment and residual unbalance. The four failures are considered occurring independently one from another, and they are misalignment, loose in bearings, bow and rub. It is important to note that each failure is introduced twice into the rotor, at different locations and/or within a different severity.

Vibration signals are acquired simultaneously from four uniaxial accelerometers, located in each of the four bearings at 45° from the horizontal line in anticlockwise direction. Data are collected at a sampling frequency of 10^4 Hz, with the rotor running under steady state, at a speed of 1800 RPM or 30 Hz and at 2400 RPM or 40 Hz.

3.0 Proposed approach

3.1. Features extraction

Samples of 5 seconds length, with an 80% overlap, are extracted from data in steady state. Since the used datasets do not have a uniform length, the number of samples is variable for each rotor condition, being extracted the maximum possible amount (Table 1). From the samples, features are separately extracted in time and frequency domains.

Table 1. Number of samples per class studied, per bearing

	Healthy	Misalignment	Bow	Looseness	Rub	Total
1800 RPM	86	121	204	192	114	717
2400 RPM	45	82	104	92	58	381

From time domain, four scalar features have been selected to form the features vectors. The first value is root mean square (RMS), typically used on engineering. It is defined in Equation (1), where N is the number of points contained in the sample and z_i is the i -element of the sample z . The variance (V), contains information due the signal power [8] and it is defined as it is shown in Equation (2) [9],

with $\bar{z} = \frac{1}{N} \sum_{i=1}^N z_i$ the mean of the data sample. Taking as reference value the sample mean \bar{z} , the asymmetry of the measurement is represented by skewness (S). Its definition [10] is in Equation (3), where $E()$ denotes mathematical expectation, and $\sigma = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (z_i - \bar{z})^2}$ is the standard deviation. The last feature selected, kurtosis (K), also provides information about the shape distribution of the sample and it is defined in Equation (4) [10].

$$RMS = \sqrt{\frac{1}{N} \sum_{i=1}^N z_i^2} \quad (1)$$

$$V = \frac{1}{N} \sum_{i=1}^N (z_i - \bar{z})^2 \quad (2)$$

$$S = \frac{E(z - \bar{z})^3}{\sigma^3} \quad (3)$$

$$K = \frac{E(z - \bar{z})^4}{\sigma^4} \quad (4)$$

Those values are calculated for each sample of vibration data at the four bearing simultaneously and used to build the inputs of the network. For instance, in Equation (5) it is shown the j -input in time domain.

$$\text{input}_{tj} = [RMS1_j \ RMS2_j \ RMS3_j \ RMS4_j \ V1_j \ V2_j \ V3_j \ V4_j \ S1_j \ S2_j \ S3_j \ S4_j \ K1_j \ K2_j \ K3_j \ K4_j]' \quad (5)$$

Besides, in order to obtain the features from frequency domain, the frequency spectrum is calculated from each data set using the fast Fourier transform (FFT). The amplitude values at 0.5x, 1x, 1.5x ... 4x times the rotational speed (30 Hz or 40 Hz) are extracted, accordingly the studied scenario, and divided by the amplitude value at the same frequencies when healthy condition. By this, non-dimensional values which represent the variations of the samples from the baseline condition are used. Similarly to time domain, the calculated values from samples acquired simultaneously at the four bearings are organised as shown in Equation (6) to create the input vectors, where, for instance, $FFI_{0.5x, j}$ represents the frequency feature from B1 at 0.5 times the operating speed, and so on.

$$\text{input}_{fj} = [FFI_{0.5x, j} \ ... \ FFI_{4x, j} \ FF2_{0.5x, j} \ ... \ FF2_{4x, j} \ ... \ FF3_{0.5x, j} \ ... \ FF3_{4x, j} \ FF4_{0.5x, j} \ ... \ FF4_{4x, j}]' \quad (6)$$

3.2. ANN's architecture

A multilayer perceptron (MLP) is used in this study to perform the pattern recognition task. This is a feedforward network where signal components pass the input

layer and move forward along the four hidden layers, finishing with the result delivery from the decision layer. Each hidden layer has a variable number of nonlinear neurons, m_1, m_2, m_3, m_4 , which varies regarding time or frequency domains. The proposed architecture is in Figure 2, with m_i the size of the input vectors and 5 classes in the output representing the rotor conditions.

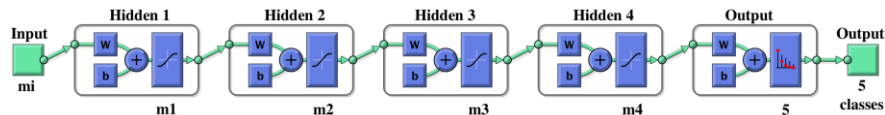


Figure 2. Neural network architecture proposed

In this work, supervised learning is used for training the network, therefore the processed data have already set the wanted outputs. The weights are adjusted according the actual error of the outputs against the desired ones during this process. The error is calculated through the performance function, being for both domains cross-entropy. The details of each study are shown in Table 2.

Table 2. Specifications of ANN architectures for time and frequency domains

	Time domain		Frequency domain	
	Hidden layer number	No. of Neurons	Hidden layer number	No. of neurons
ANN Parameter	1	1000	1	1000
	2	100	2	1000
	3	100	3	100
	4	10	4	10
Transfer function hidden neurons	Hyperbolic tangent sigmoid		Hyperbolic tangent sigmoid	
Transfer function output neurons	Softmax		Softmax	
Training function	Bayesian Regulation Back-propagation		Scaled Conjugate Gradient Backpropagation	
Performance Function	Cross-entropy performance		Cross-entropy performance	

During the training process, the network could be subject of overfitting. In this work, early stopping method is used to avoid this occurs. By this process a cross-validation of independent data is carried out [8], grouping the total available in 3 sets. This is applied to the samples at 1800 RPM and 2400 RPM separately, where the first set of data (70% of samples) is used for training the network, modifying the weights according the learning rule. The second set (15% of samples) is for validation, processing conducted by testing in the trained network these data until their classification error reaches a desired point of minimum error, giving the order to stop the training process. At this point, the weights correspond to the opti-

mal for the network and the last group of unknown data (15% of samples) is tested, providing the generalisation of the network [11].

Afterwards, the network already trained and validated with data at 1800 RPM is tested with the inputs made from data at 2400 RPM, in order to verify the capability of the model of being applied when operational conditions change, i.e. the rotational speed.

4.0 Results

The overall performances obtained using non-dimensional features extracted from time and frequency domain at 1800 RPM and 2400 RPM are summarised in Table 3. At 1800 RPM, the highest accuracy obtained is 100% when features only from time domain are used and a slightly lower value of 99.7%, when frequency domain features made the input vectors. The high performances are explained by the consistent and complete information provided about the machine during its operation, mapping the dynamics along the rotor through the calculated features from the vibration signals.

The proposed method has shown its adaptability when it is processed with values acquired at a different rotating speed, namely 2400 RPM. When the entire process is carried out with this data, the obtained results are similar to the ones at 1800 RPM, achieving a 100% of successful classifications in time domain and a slightly lower performance of 96.6% in frequency domain.

Table 3. Performance achieved, with features extracted from time and frequency domains at 1800 RPM and 2400 RPM

	1800 RPM		2400 RPM	
	Time	Frequency	Time	Frequency
Training	100.0%	100.0%	100.0%	97.8%
Validation	100.0%	99.1%	100.0%	94.7%
Testing	100.0%	99.1%	100.0%	93.0%
Overall	100.0%	99.7%	100.0%	96.6%

At both speeds in frequency domain there are false healthy diagnoses identified, made by 0.56% of the samples at 1800 RPM and 0.79% at 2400 RPM. Thus, the method does not perform in a reliable manner in this domain, implying a high risk not just because of the lack of accuracy in the classification of the rotor conditions, but also because there are detected hidden faults among the misclassified pieces of data. Those cases are critical because they are hiding a failure, whose

certain effects are unknown, being possible even the occurrence of catastrophic events. All the misclassified faults belong to misalignment samples.

Table 4. Performance achieved in testing at 2400 RPM, with learning process carried out at 1800 RPM

Features domain	Class 1 Healthy	Class 2 Misalignment	Class 3 Bow	Class 4 Looseness	Class 5 Rub	Overall
Time	100.0%	0.0%	100.0%	100.0%	100.0%	78.5%
Frequency	44.4%	1.2%	0.0%	45.7%	36.2%	22.0%

A third setup is tested regarding the operational speed of the machine. This consists on carrying out the learning process with data taken at 1800 RPM, and then providing to the network input vectors generated with data acquired at 2400 RPM. In this opportunity, it is observed a considerable better performance with time domain features. The detailed results are shown in Table 4.

On the one hand, for time domain, it is seen that none of the samples of misalignment was identified as itself, being confused with other faulty conditions. Nonetheless, the model could separate with a 100% of accuracy the healthy from the not healthy samples, independently of the specific type of defect. On the other hand, the classification carried out with features from frequency domain presents an extremely poor performance, having just a 22.00% of success in the classification task, with a large number of hidden faults made by 52.23% of the tested samples. On Figure 3 are visible the hidden faults at all the studied scenarios for both proposed domains.

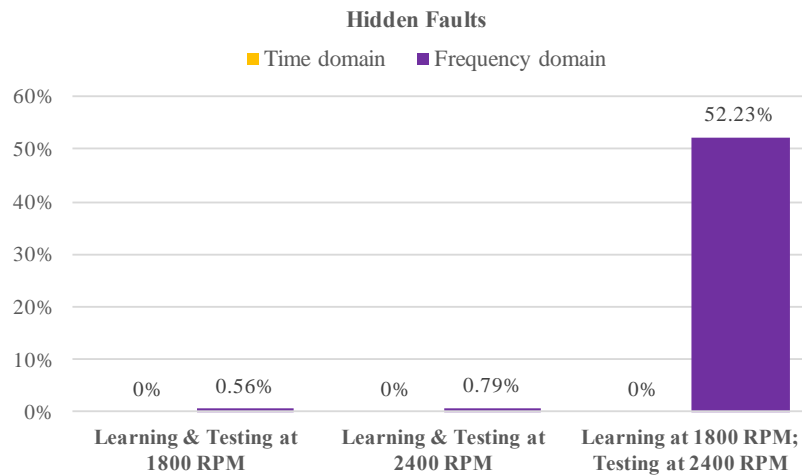


Figure 3. False healthy diagnoses rate per studied scenario

5.0 Conclusions

The application of a supervised artificial neural network resulted suitable for pattern recognition and classification of faulty states in a rotating machine. The usage of data sets acquired simultaneously from different locations along the machines allows the extraction of features that could represent the machine condition, being possible a proper separation and differentiation among the set classes, therefore the classification of the analysed samples. The maximum reliability of the model is obtained when features from time domain are used, achieving a 100% of accuracy in the fault diagnoses when the entire process, learning and testing, are conducted with samples acquired at the same speed. This means the network is adaptable for being processed with sets of data at different speeds, nevertheless further studies are required to extend this statement. When the network is tested at a speed different from the one used in the learning process, even though the model cannot identify all the specific failures, it is capable of separate into two categories the samples, healthy and faulty, with a 100% of accuracy.

The proposed intelligent approach could be applied under the concept of *Internet of Things* (IoT). The implementation of IoT could help to overcome the limitation of supervised methods regarding the vast amount of data required. Moreover, it allows an optimisation of the resources, avoiding the redundancy of tasks related with fault diagnosis and offering a standard procedure among the organisation.

6.0 Acknowledgment



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ME2018_1138

Journey Towards Vessels Replacement Program

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Abstract Saudi Aramco/ South Ghawar Producing Department has exerted substantial efforts towards executing a seldom project of replacing numbers of extraordinary vessels (e.x: Weight: 160 ton, Dimensions: 150 ft long x 13 ft dia.) during turnarounds. Several horizontal pressure vessels were recommended for replacement due to major and excessive Step Wise Cracking, irregular blister, inclusions identified in several courses of the old non HIC (Hydrogen Induced Cracking) resistance vessels. The presentation summarizes the most challenges and obstacles experienced during execution phase and optimal way to handle such mega project safely and successfully. Throughout the presentation, full implementations of the Re-Engineered Shutdown Process, maintaining a strong quality assurance plan, Planning and scheduling ahead of time, Managing work scope, controlling the maintenance cost and setting a detailed on-site execution strategies , which are major factors to accomplish this critical millstone on time and with no safety infractions, are addressed. Furthermore, several safety best practices that have been implemented during the replacement program will be shared. Those safety best practices have proven their effectiveness during such major events and since then, they have been practiced and implemented in several turnaround across different organisations. Saudi Aramco/ South Ghawar Producing Department believes that sharing such experience will be beneficial to all organisations.

Key words: Vessels replacement, HIC, T&I

1.0 Introduction

South Ghawar Producing Department (SGPD) operates 14 GOSPs extending across a distance of 180 km from Haradh area to Mubarratz and going through Uthmaniyah and Hawiyah.

Within these (14) facilities, around (121) vessels operating are in sour service. Given the sour service and the material of construction, these vessels are susceptible to Hydrogen Induced Cracking, known as (HIC).

2.0 Types of Hydrogen Induced Cracking (HIC)

HIC is a subsurface crack parallel to the surface due to hydrogen blistering in Wet Sour Service.

There are three types of HIC that could impact vessels:

1. First is the Linear HIC:-

Usually occurs when the H₂ atoms start diffusing in the metallic structure.

2. The second type is the SWC, which is the most critical type of HIC damage. It starts as multiple HIC's, usually at 45 degree from each other and with time and permeation of hydrogen, they form the step wise crack.

3. Third and usually at the base of the vessel, is the blister. All blisters start as an HIC, but with time and the immigration of hydrogen it will transform into a blister.

To identify any development of these types of HIC in our vessels, SGPD, in collaboration with CSD and Inspection Department, was one of the first departments in the company to complete a full assessment program during 2011 and 2014

3.0 Assessment Program

The assessment program includes: Advanced NDT scanning, engineering evaluation and fitness for service tests.

The comprehensive assessment revealed that 30 vessels out of our 121 vessels are impacted with different types of HIC:

21 vessels as having SWC (step-wise cracking) and 9 vessels as having linear HIC. In addition, some minor blisters.

The identification of this high number of impacted vessels generate several challenges to SGPD. Some of these challenges are:

- 1- The safe and reliable operation of these vessels which has always been our first priority.
- 2- Continuation of production from these vessels
- 3- Also, controlling further development of HIC in the impacted and un-impacted vessels

To overcome these challenges, we developed a robust action plan which consists of two parts:

Long Term Plan ... which is replacing the impacted vessels

And Short Term Plan to continue the safe and reliable operation of our impacted vessels until the vessels are replaced.

4.0 Long Term Plan:

For the long term plan, The major recommendation is to Replace (16) vessels out of the (28) SWC impacted vessels. These 16 vessels have shown consistent HIC growth.

As a result, BI-10-01522 was initiated with FPD to handle the replacement. The cost of the BI is \$ 124 MM with an ERA and ERC of October 2016 and October 2018 respectively.

It is worth noting that in 2013, the LPPT vessel at UGOSP-4 was in critical condition and required immediate action, SGPD led the engineering and execution of the replacement in house. The vessel was purchased as part of a BI-19 project. It cost around \$ 2.3 MM and required (45) days of S/D.

This is an example of our vigilance to mitigate HIC issues without affecting our safety or production continuity.

5.0 Short Term Plan

It was very important to confirm that we can continue our production SAFELY and RELIABLY until these vessels are replaced. To fulfill this:

1. De-rated all HIC affected vessels in accordance to Fitness of Service tests.
2. Conducted a detailed in-house relief study and accordingly we adjusted more than 100 RVs' set points, and all applicable ESD and operating set points, without affecting our production capacity.
3. Increased the frequency of internal coating to extend the operating lives of these vessels.
4. Established a semi-annual and annual ANDT testing, to closely monitor HIC growth in the impacted and un-impacted vessels.

With the short and long term action plan, we controlled HIC concern in SGPD vessels.

6.0 Conclusion

As Replacement program will continue till 2021. SGPD have established solid program and control measures to manage and monitor HIC growth which is part of SGPD commitment toward maintaining its production and preventing property loss. Although the project considered as one of the challenge milestone, the execution phase was managed smoothly and safely with no incident that would not be happen without well-developed execution plan and effective synergy between the T&I I and project leaders.

ME2018_1140

Mono Sensor Empirical Curve-Fitting Determination of Acoustic Attenuation Coefficient for Pipeline Monitoring

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Abstract Acoustic pulse reflectometry is a monitoring method that offers non-destructive detection by measuring the echo from leakages and blockages in pipelines. In this paper, we present the fundamental study of wave propagation model in a plane wave region for pipelines with different diameters and excitation frequency of input pulse. The theoretical attenuation coefficient is established and compared with attenuation coefficient obtained using single sensor acoustic pulse reflectometry experiment and then proposed a modified equation.

Key words: acoustics; pulse reflectometry; attenuation coefficient, pipeline, maintenance, inspection tool, leakage detection.

1.0 Introduction

Over the years, pipeline networks worldwide grow with the demand of energy and are regarded as one of the integral parts of world economy. In 2014 the estimated data on pipeline network in over 120 countries the world, gives a staggering total of up 3.5 million km length of pipeline laid at various terrains around the world [1]. In assuring a high standard of service, the conditions of these pipelines are to maintain at the highest standard through multiple asset management procedures. Although various method of non-destructive testing were introduced over the years [2-4], the acoustic method offers many advantages as it offers a robust solution based on propagation model of sound wave in the fluid and acoustic media. The fundamental of acoustic inspection application in pipelines rely on the information of input signal and the responses from test object. Comparative analysis of

the input signal to the reflections permits to create a reconstruction model of the defects within a remote section of any duct entity. Not only limited to engineering solutions, method such as the 'layer peeling algorithm' is also used to reconstruct musical instrument by analyzing the impulse response [5].

As sound travels along a medium, the losses occur depending on the travelling media conditions. These losses will be the determining factors to the travelling potential of an input signal used in the investigation. Studies on the propagation model were carried out in two types of media i.e. the solid and the fluid domain of the pipeline. Working in the solid media, the propagation model often deals with greater complexity due to the occurrence of dispersion as the wave travel in its ultrasonic frequencies [6]. Identifying the responses in time domain is a difficult process as the signal is often buried in the dispersive modes of propagation. The time domain method is also limited to only detection of defects within solid domain of the pipe and limited length of investigation.

In maintaining pipeline integrities, early detections of blockages and leakages can reduce the risk of failures [7]. Leakages due to severe corruptions or hydrates blockages in gas pipeline have been detected by previous researchers using the acoustic pulse reflectometry (APR) method [8]. A straight forward flight time calculation will indicate the location of blockage, however, the severity such as the percentage of blockage to the pipe diameter needs an additional signal processing method. Contradictory to the ultrasonic method, the signal processing complexity reduced in the APR. The less dispersive propagation is apparent in time domain and would simply be truncated for further frequency based analysis.

Amir *et al.* [9-10] revealed that the presence of corrosion can be observed using the APR method with findings such that the negative and positive reflections are due to the constriction and dilation respectively. One of the most recent blockage reconstruction methods is the use of power reflection ratio of the incident and the reflections pulse to determine the geometry of blockage. Researcher established that additional information of the blockage length can be reconstructed using the phase change information of the incident wave and the reflection [11]. The factor of attenuation used in the prediction was obtained from mathematical model and can be improve with an empirical solution.

The APR method relies heavily on the input pulse signal or often referred as the incident waves. It is a transient's pulse where the width of the pulse determines the frequency of signal. Although it is obvious from recent literature that lower frequencies offer greater potential in term of inspection length[12] there are limitations due to the dependencies of attenuation to the diameter of inspected pipe and the cut-off frequency of plane wave propagation. It is very important for operators in real industrial application to understand the effect of attenuation during inspection apart from only the reflection from blockage's impedance.

The effect of attenuation can be modelled by deriving the wave equation of sound propagation in cylindrical duct. With the introduction of damping due to losses, the decay of peak amplitude along the longitudinal distance from the source can be established. This paper presents the analytical model of propagation within the

plane wave mode with various combinations of excitation frequency and pipeline diameters. A single microphone APR experiment was performed using multiple length and diameter PVC pipe. The analytical and empirical results are compared and a correction was introduced to the attenuation coefficient governing equation by curve fitting the multiple pipe length peaks amplitude. The theory on sound wave in duct propagation is discussed in the theoretical section of this paper. Later in this manuscript, the experimental apparatus and measurement method are described followed by the results.

2.0 Theory

The fundamental aim in solving wave equation in cylindrical duct is to limit the mode of propagation. Propagating modes can be divided into three modes which are the spherical, the cylindrical and the plane wave. Dealing with the other two modes apart from the plane wave requires the modelling of propagation in the transverse direction.

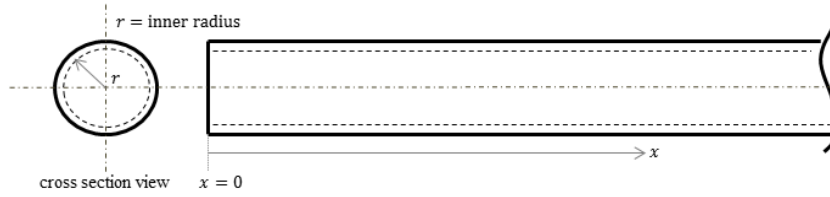


Figure 1 – Fundamental sound source location and travelling direction in cylindrical duct.

With the restriction of excitation frequency of below cut-off frequency of plane wave, the analysis deals only with planar and straight forward propagation. Assuming that there is no change to cross sectional area of the pipe along the propagation, the peak decay of input pulse pressure will be dependent to only the attenuation coefficient, α . The peak decay along the positive direction x can be described as the following equation:

$$p(x) = p_i e^{-\alpha x} \quad (1)$$

where p_i is the pressure of initial input pulse in the acoustic investigation. By factoring the viscous absorption and the heat conduction along the propagation, the attenuation coefficient can be determined by the equation;

$$\alpha = \frac{\omega}{cr} \left[\sqrt{\frac{\mu}{2\rho\omega}} + (\gamma - 1) \sqrt{\frac{K}{2\rho\omega C_p}} \right] \quad (2)$$

where ω is the angular frequency, c being the speed of sound of the medium sound wave travelling in, r is the pipe radius, μ is the shear viscosity, ρ is the density, γ is the ratio of specific heat, K is the thermal conductivity and C_p is the heat capacity. By determining the coefficient of attenuation, the peak decay rate of any frequency of input sound wave signal can be obtained along the travelling time at any particular distance from the source. As a result, the travelling potential of each input pulse can be determine with the knowledge of excitation frequency and diameter of the pipe.

3.0 Experimental set-up

A detailed study is conducted to determine the attenuation coefficient by experiment. This experiment concentrated on the acquisition of responses from the various frequencies of input pulse. There are two variables that determine the attenuation rate, which are the inner diameter of the pipe and the frequency of excitations. In designing the experiment a clear aim was put in place for those two parameters, diameter size and injected frequency. The experimental measurements are taken at room temperature of 24 degree Celsius in isolated laboratory to eliminate the noise during data acquisition (Figure 2). In validating the pipe end reflections, the speed of sound, c is taken to be 343.2 m/s with the density of air in the pipe $\rho = 1.225 \text{ kg/m}^3$.

The signals are acquired through the microphone at sampling frequency of 40 kHz using data acquisition program designed in LabVIEW software. Every test is taken at a sampling period of 0.5s. The excitation signals designed for every $d_n L_n$ starts at $f_i = 200 \text{ Hz}$ up to 2 kHz for all tests. Subsequently, the attenuation rate of empirical model is established from the rate of decay over time and distance based on the speed of sound with assumption that there is zero damping from the loudspeaker. The test is done on five different pipe lengths shown in Figure 3 for all different pipe diameters with the travelling distance for every single reflection measured as $2L_n$.



Figure 2 – The experimental set-up, sensor attached, pc and DAC, loudspeaker etc.

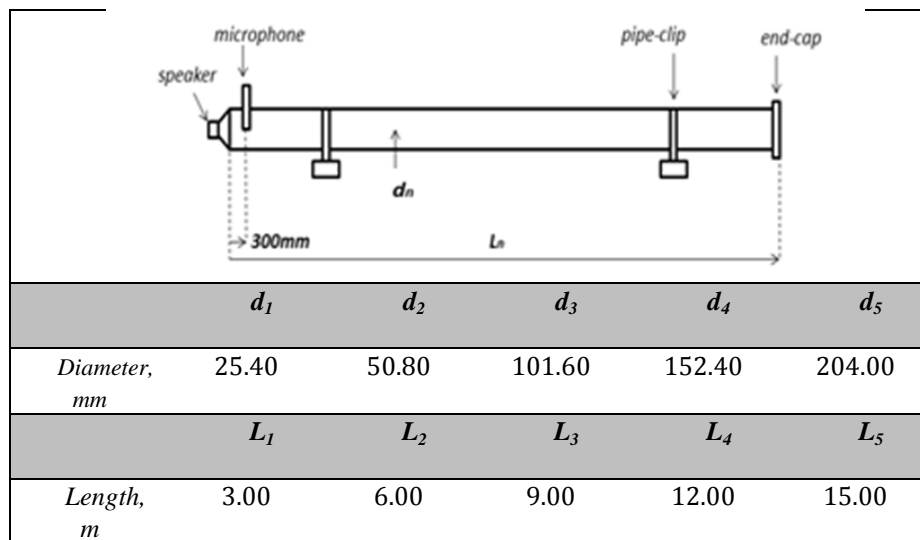


Figure 3 – Schematic of pipeline rig for the experiment

4.0 Results

With single microphone, it is shown that detection of propagation is possible within time domain. All flight time calculations based on the speed of sound confirmed that the visible reflections cross correlate to the experimentally acquired responses. By observing the time domain responses, it was established that the first reflection peak as the incident wave and the following reflections were caused from the pipe end. With no changes of cross sectional area, the losses from impedance at the pipe end are assumed to be zero. From Figure 4 it can be observed that the peak of reflection signal reduce over time and the rate of losses is less at lower frequency excitation throughout the experiment.

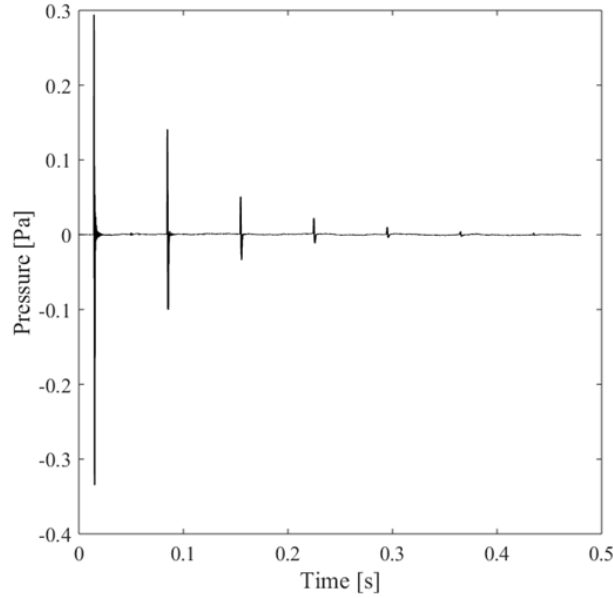


Figure 4 – The typical time domain responses of d_1L_2 at 300 Hz excitation[13]

From the peak amplitude acquired in Figure 5 and the exponential curve fit in Figure 6 the attenuation coefficient values for d_1 based on the excitation frequency are determined. With the establishment of the coefficient, α by experiment, a correction factor can be introduced to the values obtained in analytical model. This can be achieved by solving a non-linear regression of the variance ($\alpha_e - \alpha$) between the analytical solution and the experimental results against the frequency of the excitation, where α_e is the experimentally obtained coefficient. The variance can be observed in Figure 7. However, the correction can only be accurate for a particular d_n due to the dependency of the attenuation to both, frequency and radius of pipe. For d_5 , as the frequency exceeded the plane wave limit, the attenuation coefficient is influenced by higher order modes of excitation within the pipe.

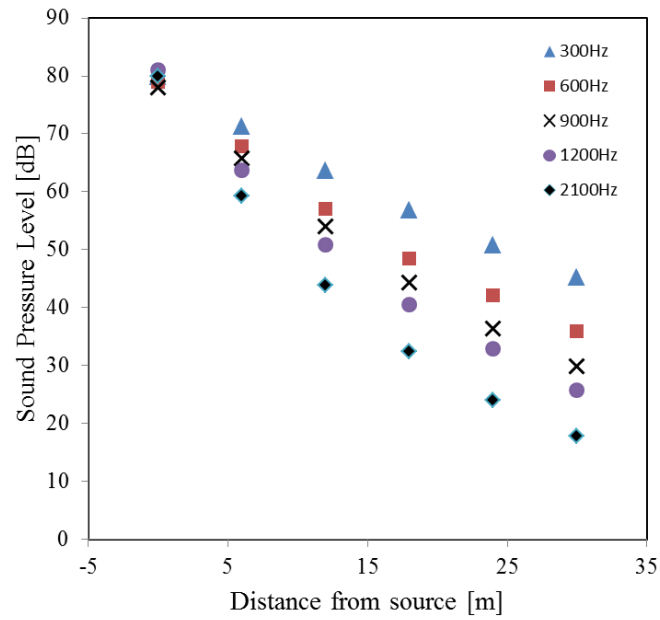


Figure 5 – Peak amplitude acquired in experiment for d_1 at sensor location with consistent initial input pulse amplitude measured by distance travel,

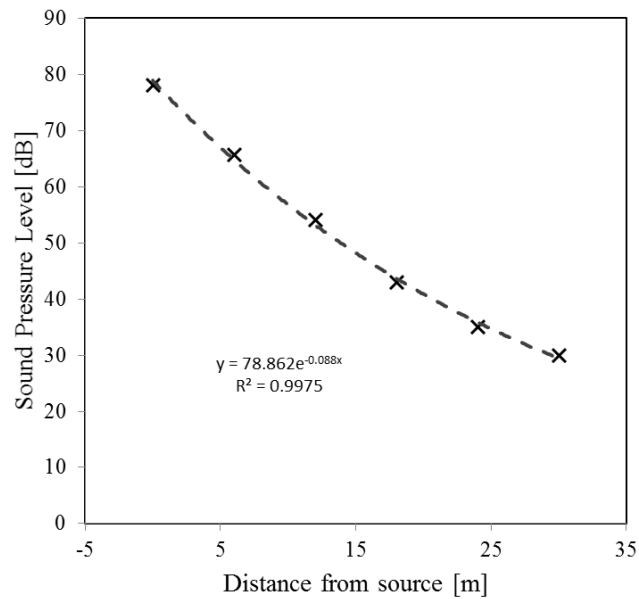


Figure 6 – Typical exponential curve fit for d_1 at 900 Hz

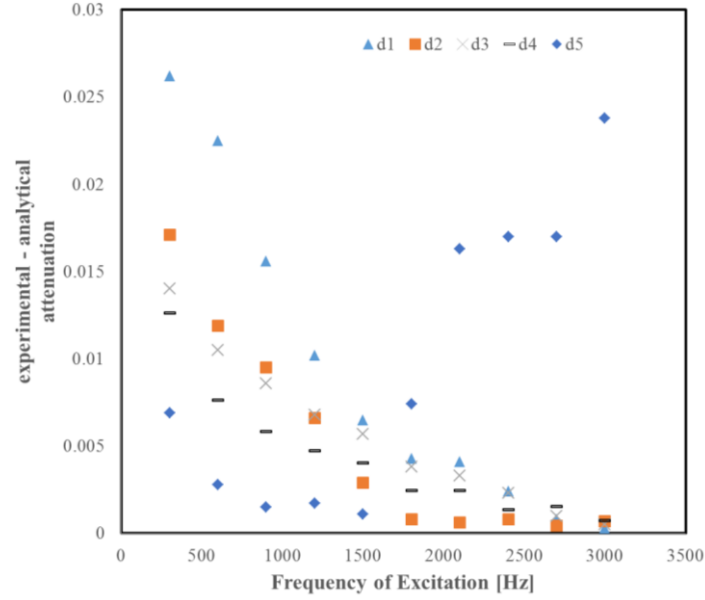


Figure 7 – Variance ($\alpha_e - \alpha$) between the analytical solution and the experimental results [13].

Considering the variance of experimental and the analytical results, the correction β to the initial equation (2) can be introduced for every frequency of excitation. Therefore, an introduction of curve fit to the initial β values for different d_n , yield the modification to the attenuation equation, α_m .

$$\alpha_m = (\alpha + \beta) \quad (3)$$

where β is the different between the theory and experimental decay of peak from table 3, which yield the new equation;

$$\beta = (0.0395 - 0.0001r)e^{-0.001\frac{2\pi}{\omega}} \quad (4)$$

5.0 Conclusions

The understanding of input pulse frequency is critical to the distance of investigation in APR application. Although the choices of lower frequency offers extended distance of detection, the longer wavelength will reduce the sensitivity of detection. It is also shown through the experiments that the attenuation coefficient can be observed with single sensor experiment for different pipe diameters and center

frequency of excitation. Hence, the determination of attenuation coefficient can be made by exponential curve of peak decay along travelling distance with the assumption that impedance from transceiver assembly is zero.



The attenuation coefficient obtained from empirical solution is higher than the theoretical prediction; therefore the travelling input pulse energy dissipation is higher in the experiment. This could be due to the laboratory condition that can vary from the condition established for input used in the theoretical model. The modified attenuation coefficient value can be factored into the acquired response during pipeline detection for a better classification based on the amplitude change. For real industrial applications, the determination procedure of attenuation coefficient introduced can be applied practically by having reasonable length of healthy pipe and the future work is to include the losses from joints and other standard components.



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ME2018_1141

Reliability of Composite Materials based on Accelerated Life Tests

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Abstract As the demand for reliability information is increasingly frequent, and sometimes mandatory, accelerated life tests are often used to obtain failure data on reduced time to forecast failures over longer usage periods.

The present work describes the main methods usually applied for accelerated life tests, following models such as the Arrhenius model, Eyring model, the Inverse Power Law model and the Temperature-Nonthermal model.

In order to implement the concepts it is presented a case study using a composite material subjected to accelerated UV radiation. A degradation of its mechanical properties was recorded over the exposure time through uniaxial tensile tests. With the results obtained by accelerated life tests it was possible to understand failure behaviour and to describe reliability prognostics for normal operating conditions of such material. The methodology presented in this work can be applied to other materials, components or systems in order to anticipate failures and give a complete knowledge of their reliability over time without being necessary to wait for real failure data.

Key words Reliability, Accelerated Life Test, UV Radiation, Fiberglass-Epoxy, Accelerated degradation.

1.0 Introduction

One of the main concerns of maintenance activity is related to items or system failures. The knowledge of reliability may be obtained by testing under normal conditions or under accelerated conditions. The tests carried out under normal conditions of use are carried out in conditions close to those of use of the items. However, these tests are time-consuming since they require long periods of testing. On the other hand, accelerated life tests allow faster results. They also

allow the determination of the life characteristics of an item in a few hours, days or weeks which in normal conditions of use would take months or years to be determined. Therefore, accelerated life testing is an added value to meet the expectations concerning reliability, maintainability and availability.

In the present work it was performed a reliability analysis of composite materials subjected to ultraviolet solar radiation based on accelerated life tests. The importance of such study relies on the fact that composite materials under weather conditions suffer a notorious degradation of their mechanical characteristics that is important to know in the field of reliability and maintenance.

The paper is organized into 6 sections. Section 1 refers to a brief introduction of the topic, Section 2 deals with reliability and accelerated life tests and Section 3 presents some characteristics of composite materials and their mechanical degradation mechanism under ultraviolet exposure. Section 4 presents the case study performed and the results obtained regarding a reliability forecast based on some models. In Section 5 are stated some conclusions and future works that can be developed in the follow-up of the present study.

2.0 Reliability and Accelerated Life Tests

The maintenance and reliability of components and systems have become more important than ever. Global competition and other associated factors have made manufacturers to produce highly reliable and easily maintained engineering items. Nowadays, the reliability of engineering systems has become an important issue because of the increasing reliance on the satisfactory functioning of these systems [1] [2]. The following paragraphs present some information about the most common reliability models and about accelerated life tests and some models usually used for reliability determination.

Reliability means the probability of success (or probability of non-occurrence of a failure) of an item within a certain time horizon. It results from the design and the quality (intrinsic characteristics) and, on the other hand, on the loading and environmental conditions in which its operation will take place (extrinsic characteristics) [3]. Reliability is then the probability of a component, product or system to perform its designed functions without fail, in a specified environment, for a desired period, in a given confidence interval [4]. The Mean Time to Failure (MTTF) can be determined by the statistical mean of the failure times of the various components of the sample tested, and can be mathematically defined as [5]:

$$MTTF = \int_0^{\infty} R(t) dt \quad (1)$$

There are several probability distribution functions that allow to describe the fault characteristics of components. The most frequently probability distributions used to represent component life phenomena are:

- Weibull distribution;
- Normal distribution;
- Exponential distribution;
- Lognormal distribution.

Each one of these distributions is characterized by a probability density function $f(t)$ that represents an instantaneous probability. This function represents the percentage of components that are failing per unit time, relative to initial population N_0 , at time t (or time interval dt). By integrating the function $f(t)$ between zero and a time t , it is obtained the cumulative probability of failure $F(t)$ as:

$$F(t) = \int_0^t f(t)dt \quad (2)$$

Thus, for the reliability point of view the difficulty is to obtain information about failures (life data) that allows adjusting the most appropriate distribution.

Life data analysis usually involves the analysis of times to failure obtained under normal operating conditions. However, obtaining these life data can be difficult.

As it is fundamental to observe product failures for a better understanding of failure modes and their characteristic life, that is, to obtain reliable data, it was necessary to develop methods to force products to fail earlier, that is, to accelerate their failures.

These methods are called Accelerated Life Tests (ALT), which aims to accelerate faults for the purpose of quantifying the life characteristics of a product under normal service conditions.

According to Hietala et al. [6] accelerated life tests refer to "*a deterioration / aging induced in a component to cause normal failures, operating at levels of requests much greater than would be expected under normal conditions of use*".

According to Pallerosi [7] the accelerated tests are tests in which the applied levels of request are chosen so as to exceed the values specified in the reference conditions, in order to reduce the time required to observe the reaction of the component or to amplify this reaction over a period of time.

To be valid, the accelerated test shall not change the basic failure modes and failure mechanisms.

The main objective of quantitative accelerated life tests is to obtain information about the time to failure to understand and predict the failure modes and to be able to proactively act on them [8].

Escobar [9] defines that accelerated life tests are divided into qualitative accelerated life tests and quantitative accelerated life tests. Accelerated qualitative life tests only identify failures and failure modes that potentially may occur without making any predictions of product life under normal conditions of use. On the other hand, quantitative accelerated life tests allow making predictions of the life of an item under its normal operating conditions, with data obtained on accelerated life tests.

Table 1 shows the main differences between the quantitative and qualitative accelerated life tests.

Table 1 Main difference between qualitative and quantitative accelerated life tests

Qualitative Accelerated Life Test	Objective: <ul style="list-style-type: none"> - Failure detection on design and product development - Improvement of product reliability Test requirements: <ul style="list-style-type: none"> - Detailed knowledge about the item under test - Personal experience about life tests Mathematical models: <ul style="list-style-type: none"> - No mathematical/statistical models
Quantitative Accelerated Life Test	Objective: <ul style="list-style-type: none"> - Determination of time to failure distribution - Obtain information about degradation process - Identify the dominant failure mechanisms Test requirements: <ul style="list-style-type: none"> - Detailed test plan (duration, number of samples, confidence interval, acceleration factors and test environment) Mathematical models: <ul style="list-style-type: none"> - Stress-life relationship: Arrhenius, Eyring, Coffin-Manson, Norris-Lanzberg, ... - Probability distribution: Weibull, Lognormal, Exponential, ...

The quantitative tests can be divided into two main methods, namely regarding the one that increase the operating rate and the one regarding the increase in the wear rate. For items that do not operate in a continuous way, the time is accelerated until failures appear, increasing the utilisation rate of these items. This type of test is called "Usage Rate Acceleration". On the other hand, it is possible to increase the level of stress to which the component is exposed. This type of test is called "Overstress Acceleration" [8]. The interpretation of the data obtained through accelerated tests requires models that relate acceleration variables (such as temperature, radiation, voltage or pressure) with the acceleration of time. The general idea is to test the acceleration variable(s) at high levels to accelerate the fault process and then to extrapolate to lower stress levels [9]. According to Pallerosi [7] there are several mathematical models of accelerated tests, being the most common the Arrhenius relationship, the Eyring relationship, the Inverse Power Law, the Temperature-Humidity Ratio and the Non-Thermal Thermal Ratio.

According to Elsayed [5] there are four types of models to relate the fault data in accelerated conditions with reliability measures:

- Parametric statistical models;
- Non-parametric statistical models;
- Physical-statistical models;
- Physical-experimental models.

When using any of the models it is necessary to verify that components operating under normal conditions have the same failure mechanism as those under accelerated test conditions.

3.0 Composite Materials and Degradation

Currently composite materials are used in applications where it is desired to obtain improved properties than those achieved with common heterogeneous materials. According to ASTM D3878 [10], composite materials are defined as "*a substance consisting of two or more materials, insoluble in each other, which are combined to form an engineered material with mechanical properties different from its phases constituents*".

In general, composite materials consist of two materials: a reinforcing material called fibre and a matrix material. These two materials differ in shape, chemical composition and properties. Their union provides a different set of constituent parts, maintaining their individuality, that is, they do not completely dissolve or merge into one another, although they act together, forming a material with the best mechanical properties of its constituents than the materials conventional methods [11]. The resulting material has heterogeneous and anisotropic properties, ie, it presents more than one phase and its mechanical properties depend on the direction of the fibres [12].

Stiffness, mechanical strength, low weight, corrosion resistance, adjustable thermal properties, fatigue life and wear resistance are some of the properties that can be improved through the formation of composite materials.

Taking into account all these advantages of using composite materials, its application has grown and has covered several areas such as aeronautics, shipbuilding, automotive and biomedical applications, among others, making its application advantageous over traditional materials [13].

When composite materials are in an outdoor environment, they are subject to various environmental conditions, from high and low temperatures, solar radiation, rain, moisture and erosion. These conditions can directly affect mechanical properties and endanger structures and components. In certain materials the degradation caused by solar radiation is determinant.

The UV radiation present in the solar spectrum and the humidity are the two main environmental factors that directly affect the physicochemical properties of the composite materials, causing the molecular structure to break down [14].

UV radiation represents a portion of the solar spectrum and plays a very important role in many processes in the biosphere. It has many benefits, but can be quite harmful when in excessive values. UV radiation is an electromagnetic radiation with a wavelength between 100 and 400 nm [15] and has wavelengths shorter than visible light and larger than X-rays. UV radiation constitutes about 10% of the total light emitted by the sun.

UV radiation is usually divided into UVA, UVB and UVC radiation [16]. UVA radiation constitutes 99% of the solar radiation that reaches the ground. The UVB radiation constitutes the remaining 1%, being the radiation that causes the greater visible damages in the skin of humans. The C component of UV radiation does not reach the ground as it is absorbed by the ozone layer and oxygen.

The knowledge of the degradation of composite materials is of the utmost importance for the full knowledge of its behaviour when subjected to the conditions of use.

The degradation caused by solar radiation is called photodecomposition and involves the degradation of the material through UV rays. This degradation arises as discoloration, loss of brightness, cracks, loss of mechanical resistance or disintegration of the material. The effects of UV attack increase with exposure time and the intensity of sunlight. This degradation can be reduced with the use of UV absorbers inhibiting its effect.

In order to evaluate the degradation of composite materials under normal service conditions, they can be subjected to accelerated life tests or to tests under normal operating conditions. For composite materials, the temperature, UV radiation and humidity are normally used as stress variables.

Next Section presents a case study performed on composite material using accelerated life tests and for reliability and maintenance purposes.

4.0 Case Study

The main objective of the study is to analyse the accelerated degradation of polymeric materials through the rapid aging caused by the simulation of sunlight obtained by ultraviolet radiation lamps.

In a more detailed way, it is intended to make samples of glass fibre mat and polymer matrix (epoxy resin) that will be subjected to solar radiation emitted by UV lamps simulating the radiation emitted by the sun. These samples will be exposed to different exposure times (32, 64, 96 and 128 hours). The light emitted by the lamps will physically and chemically degrade the samples, causing colour change, cracking and degradation of the mechanical properties of the samples. To prove this, they will be subjected to tensile tests, where it is intended to compare the mechanical properties of the samples at different exposure times.

After obtaining the different values of the mechanical properties for the different exposure times it is intended to carry out a study about reliability. Through the results obtained in the accelerated life tests it is possible to extrapolate reliable data for normal exposure (sun).

For the acquisition of UV intensity value it was used the ML8511 sensor. The ML8511 is equipped with an internal amplifier that converts photo-current to voltage depending on the UV intensity. The sensor produces an analogic voltage that is linearly related to the measured UV intensity [mW/cm^2].

It was also necessary to build a chamber to place the samples of composite materials under the effect of the UV lamps.

The samples were manufactured taking into account the standards ASTM 3039 [17] and ISO 527-1 [18].

Taking into account the ASTM D 3039 [17], it is defined that at least five samples should be used in a tensile test for each test condition. Table 2 describes a compilation of the conditions of the UV radiation test.

Table 2 Test conditions

Temperature inside test chamber	50.8 °C
Temperature outside test chamber	27 - 29 °C
Relative Humidity inside test chamber	10.1 %
UV radiation intensity inside test chamber	17.7 W/m ²

At the end of the exposure time for each group of samples an evaluation is performed to determine the properties as a function of the exposure time. These properties are analysed through tensile tests, where the specimens were tested until fracture occurs. To obtain the corresponding data referred to normal conditions it is necessary to have knowledge of the real UV intensity to which a sample would be exposed. In the case study were used values of UV Index in the city of Lisbon for 2016. The value used for the analysis performed in the work was the average UV intensity so that it can be compared with the intensity of the UV emission lamps.

In order to ensure the reproducibility of results, the test conditions and procedures are in accordance with the standards or specifications and shall be recorded in the test report whenever deviations occur. With the monitoring of the test it is possible to obtain the tension-extension response, such as tensile strength, tensile modulus of elasticity and Poisson's coefficient. The tensile strength, also known as the ultimate tensile force, is given by the division between the maximum load just before the failure and the cross-sectional area of the specimen.

After carrying out all the tensile tests and obtaining the mechanical properties of the samples for the different exposure times to the test conditions, an analysis of the obtained results is then possible. Table 3 shows the different values of the ultimate tensile force obtained for the different samples as a function of the exposure time.

Table 3 Results

Exposure Time [h]	Ultimate Tensile Force [MPa]					Mean [MPa]	Standard Deviation [MPa]
0	90.76	97.85	117.08	116.31	108.67	106.13	11.02
32	95.23	124.55	99.76	91.34	85.88	99.35	13.40
64	94.10	89.44	77.56	91.32	88.91	88.27	5.65
96	82.11	81.73	86.43	90.21	83.80	84.86	3.15
128	71.17	70.87	78.76	85.35	74.07	76.04	5.45

With the increase of the time of exposure simulated by the UV radiation lamps, it is verified that the mechanical resistance decreases progressively, that is, as expected the specimen breaks down in smaller tensile forces with the increase of the exposure time. Another important change that also occurred in the material was the change in its colour. This change of colour is caused by photo oxidation achieved by UV radiation that degrades the epoxy resin making it less resistant.

Then it is time to proceed to the application of the accelerated life test model and present the conclusions about reliability prognosis for the composite materials under analysis. Reliability analysis will be performed taking into account two approaches. The first approach aims at implementing the Inverse Power Law model, where UV radiation is considered the stress variable. The second approach involves the use of the Non-Thermal Thermal model that considers two variables (the temperature and the UV radiation).

To determine the statistical distribution that best characterizes the data used, were used adherence tests (Kolmogorov-Smirnov test, correlation coefficient test, likelihood value test) to determine which one best fits the considered data set. Taking into account the data obtained in the accelerated tests, the Lognormal distribution is the one that best fits the input data. After choosing the statistical distribution, it is necessary to define the most appropriate degradation model (linear, exponential, power, logarithm, Lloyd-Lipow) to represent the change of the location parameter with time. These models can be used to predict when the degradation of a particular unit reaches a default level of failure.

Table 4 shows the different estimated times for different values of reliability, namely for 90%, 75% and 50% for different stress levels (5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80 MPa).

Table 4 Times related to several critical tension and reliability requirements

		R(t)=0.90	R(t)=0.75	R(t)=0.50
	Critical Tension [MPa]			
	5	1222.5	1243.5	1266.9
	10	935.1	956.1	979.5
	15	767.0	788.0	811.4
	20	647.7	668.7	692.1
	25	555.2	576.2	599.6
	30	479.6	500.6	524.4
	35	415.7	436.7	460.1
	40	360.3	381.3	404.7
	45	311.4	332.5	355.9
	50	267.8	288.8	312.2
	55	228.2	249.3	272.7
	60	192.2	213.2	236.6
	65	159.0	180.0	203.4
	70	128.3	149.3	172.7
	75	99.6	120.7	144.1
	80	72.9	93.9	117.3

It was also simulated the same approach but considering two variables of stress (UV radiation and temperature). The model of extrapolation that contemplates these two variables is the Thermal Non-Thermal model. This model considers two variables, one thermal and the other non-thermal, and results in the combination of the Arrhenius model and the Inverse Power Law model.

It was observed that the statistical distribution that best fits the data is again the Lognormal distribution and the degradation model is again the Linear one.

A comparison between the two simulations shows that the results obtained are very similar, with a deviation lower than 10%. It is verified that the life expectancy using the Inverse Power Law model is higher than when using the Thermal Non-Thermal model. This was expected once in the second approach the material faces two variables of stress. However, it is noticeable that temperature has not a great influence on material life expectancy.

5.0 Conclusions

The use of accelerated life tests is very important for the development of new materials and new solutions for engineering because in this way it is possible to make predictions of materials life.

However when carrying out the accelerated life tests, it is necessary to make sure that the stresses that are induced in the items under study do not cause different failure modes than those that would happen in normal conditions of usage.

The main objective of the present study was to obtain degradation data of the mechanical properties of composed material exposed to UV radiation. This degradation was achieved through two UV lamps that simulate the effect of solar radiation in an accelerated way. The degradation of the materials was achieved by tensile tests.

In the tensile tests it was possible to prove the degradation of the mechanical properties of the samples when exposed to UV radiation.

It was verified that the analysed properties (ultimate stress and modulus of elasticity) degraded with the time of exposure to UV radiation. The UV radiation directly degrades the epoxy resin that is present in the samples also causing photo-oxidation. The main objective of the work was to demonstrate that is possible to obtain reliable data for normal conditions based on accelerated life tests.

After defining the distribution that best fits, the degradation model and the mathematical model it was possible to obtain reliability data for normal conditions.

A special comment should be done once the results obtained with the accelerated tests were different from those initially expected. It was found that the reliability for the samples under normal conditions of use is very low, values which were expected to be higher taking into account that the UV radiation achieved in the chamber using two UV lamps was about 99.83 times higher than the radiation that a sample would be exposed under normal conditions of use. In order to validate these results obtained it will be necessary to expose the samples to normal conditions of use during the referred time and analyse their degradation in order to be able to prove the results achieved and prove the advantages of accelerated life tests.

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Authors' Biography

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Identification of Outliers in Failure Data

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Abstract A review of tests that can be used to identify outliers from failure data is conducted. The tests allow performing a more accurate analysis of maintenance related data, as required to define the best maintenance strategies. This is important for condition based maintenance in particular for predictive analytics. On the other hand, the increasing use of Big Data and the necessity to select only the “good data” through the implementation of intelligent algorithms brings up the importance of these methodologies. Tests like the Simple Test, the Grubbs Outlier Test, the Natrella-Dixon Outlier Test, the Rank Limits Test or the Modified Thompson Tau Test are presented showing inherent characteristics and describing how to apply them. Based on these tests it is possible to clean erroneous data usually mixed with important failure data and understand their influence on the accuracy of the estimation of reliability and life characteristics.

Key words reliability, statistical distributions, outliers, data quality.

1.0 Introduction

Reliability analysis is often performed to estimate the behaviour of items in time and give inherent information as for example the probability of failure in a given period or the failure rate on a given instant. This type of analysis allows to understand items characteristics and to define strategies for maintenance and operation of such items. Industry, and particularly some areas such as the nuclear or the petroleum, petrochemical and natural gas industries, pay great attention to equipment safety, availability, reliability and maintainability. The unavailability and related costs are sometimes very high and some failures can have a huge impact on safety. Thus, failure data, failure mechanisms and the operational data are crucial to develop accurate analysis and define the adequate strategic decisions. To be effective and decisive, a good quality of data is vital.

For managers and engineers data collection can be seen as an investment because for most of the installations it can be necessary to have data covering several years of operation to give confident analysis results. To perform more accurate reliability analysis it is fundamental to have data that can be given by manufacturers, be collected in the field or even simulated. Field data is undoubtedly more adequate and realistic once it interprets the real conditions of operation of the item and thus more appropriate to use in the analysis.

However, field data is not always faithful due to some human and technologic difficulties when gathering the condition or degradation parameter under observation. To overcome this situation it must be looked the quality of data by identifying possible outliers.

The quality of data undoubtedly plays a great role on a successful data analysis, mainly when the results of such analysis are the basis for technical and strategic decisions in the maintenance field. This has a special importance when data analysis gives information to define maintenance activities upon a condition based maintenance (CBM) strategy applied to physical assets. This allows predicting the right moment to perform maintenance. Assuming the importance of good data as the primary objective it is fundamental to describe how to achieve this goal through some tests just to discard bad data (outliers).

Based on this, the paper is structured into four sections. The first one is an introduction about the theme and the importance of having a good quality data, section 2 refers to data quality and data characteristics, section 3 presents and details some tests to identify possible outliers and section 5 presents some conclusions about the developed work.

2.0 Quality of data

In accordance to ISO 14224 [1] the confidence in the collected reliability and maintenance data, and further analysis using the gathered information, is highly dependent on the quality of the data collected. According to this standard high-quality data are characterized by the following:

- Completeness of data in relation to specification;
- Compliance with definitions of reliability parameters, data types and formats;
- Accurate input, transfer, handling and storage of data (manually or electronic);
- Sufficient population and adequate surveillance period to give statistical confidence;
- Relevance of the data to the need of the users.

There are some measures that should be taken prior to the starting of the data collection process, which will be important for the achievement of the objectives of any study or analysis. The data collected must be relevant taking into account the objective or purpose of the analysis to be performed, no matter if it is a Quantitative Risk Analysis (QRA), a Reliability, Availability and Maintainability Analysis

(RAM), the development of a Reliability-Centred Maintenance (RCM) or a Life Cycle Cost Analysis (LCCA). Then, the sources of such data must be checked to see their quality. The taxonomical information to be included in the database must be defined, as well as other important information (population, operating period, etc.). It is also very important to define the boundaries for equipment and use clear definitions for failure and their classification.

Merino et al. [2] refer that in a Big Data environment the management of quality of the data becomes a challenge. They refer that despite the existence of data quality models, none of them have been adapted to the reality of Big Data. In fact, recent developments regarding the fourth industrial revolution bring new challenges for the management of cyber-physical systems and data analytics.

Big data brings lots of “big errors” in data quality and data usage. This felling was presented by Liu et al. [3] that summarize the problems faced by current big data studies with regard to data collection, processing and analysis. The authors refer these problems where include inauthentic data collection, information incompleteness and noise of big data, unrepresentativeness, consistency and reliability, and ethical issues.

Song et al. [4] point out that the issue of data quality is common in any cyber-physical system bringing great challenges to its efficient operation referring in their work how to deal with defective data generated by improper operation. Regarding equipment (cyber-physical or not) and the data related to their operation and maintenance there are some works where data quality is referred as fundamental to achieve good analysis and good decisions. Madhikermi et al. [5] present a paper where state that the quality of enterprise maintenance services are closely linked to the quality of maintenance data and associate the poor reported data to wrong decisions and loss of money. Based on this the authors developed a maintenance reporting quality assessment dashboard allowing to assess or rank maintenance data quality. Bicalho et al. [6] focus the role of an organisation in the Life Cycle Assessment data collection process and investigate the adequacy of this process on data quality. In fact, data quality has a fundamental role in a positive analysis. In industry, regarding maintenance and reliability, the main categories of data to be collected are [1]:

- Equipment data (e.g. equipment taxonomy, equipment attributes);
- Failure data (e.g. failure cause, failure consequence);
- Maintenance data (e.g. maintenance action, resources used, maintenance consequence, down time).

The main areas where such data are used are reliability (e.g. failure events and failure mechanisms), availability/efficiency (e.g. equipment availability, system availability, plant production availability), maintenance (e.g. corrective and preventive maintenance, maintenance plan, maintenance supportability) and safety and environment (e.g. equipment failures with adverse consequences for safety and/or environment).

The importance of data quality and the inherent data analysis is illustrated in Figure 1 showing the feedback and impact of that analysis on design and manufactur-

ing, on the improvement of a concept or on adjustments and modifications from operation and maintenance.

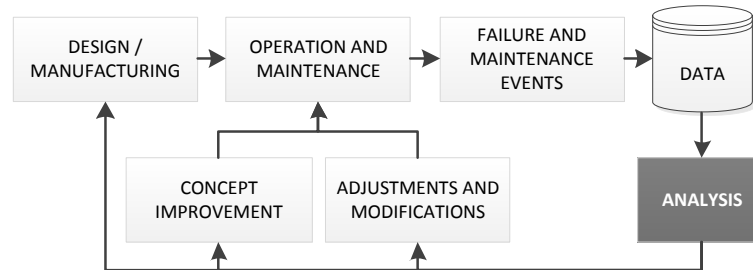


Figure 1 Feedback of data analysis (adapted from [1])

3.0 Outliers and identification methods

For the quantitative evaluation of a system reliability and maintainability it is important to estimate accurate distribution parameters using the observed equipment collected data using statistical techniques. In failure analysis, and regarding times to failure (TTF) or times to repair (TTR) it is common to have in data some misleading data or outliers. Once cleaned of these outliers the data will be purified for subsequent parametrically analysis and better results for reliability or maintainability will be achieved. The process that usually is used to perform a reliability analysis is shown in Figure 2.

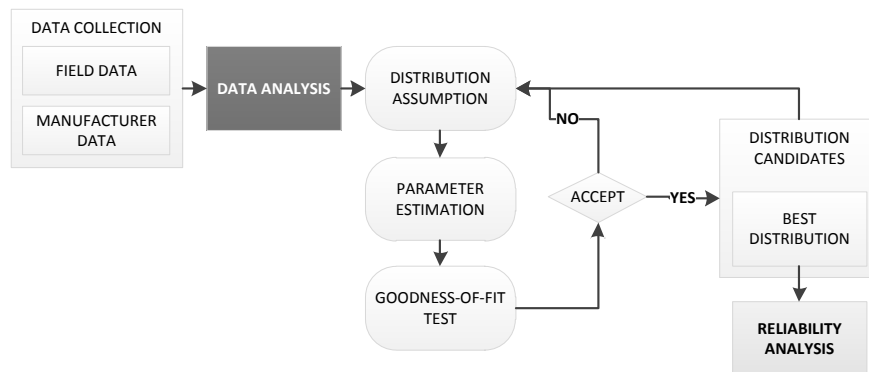


Figure 2 Reliability analysis process (adapted from [7])

To find the best or most appropriate distribution that describes the data there are several steps to be taken into account:

1. The first step refers to data collection given by the manufacturer or gathered from field by manual or automatic means;
2. Follows an analysis of the data collected in a way to “clean” it from possible errors reflected by the existence of outliers;
3. After data analysis one can establish some distributions a priori as potentially candidates for the reliability analysis. These distributions, referred by their probability density functions, usually include distributions as the Exponential, Normal, Lognormal, Weibull, Gamma, or others. A single distribution will be assumed at this stage just to pursue the next steps;
4. The estimation of the parameters for the assumed distribution can be performed using methods as the least squares, the matching moments, the modified moments, the maximum likelihood or probability plotting.
5. There are several goodness-of-fit tests that can be used to find out if the assumed distribution fits the sample data as the chi-squared, the Kolmogorov-Smirnov, the correlation coefficient, the likelihood ratio and the Anderson-Darling or Cramer-von Mises tests, among others. If the assumed distribution is accepted it will be placed as a candidate for the analysis and steps 3, 4 and 5 must be repeated choosing a different distribution in step 3. If the assumed distribution is rejected it will be discarded and steps 3, 4 and 5 are repeated until all the distributions be evaluated;
6. The best distribution is selected comparing the sample values of the goodness-of-fit statistic of all distribution candidates. The goodness of the estimators can be, for example, measured by their consistency, biasedness, efficiency or variance;
7. The selected distribution will be used to evaluate the item reliability.

The present work is focused in step 2 of the reliability analysis process presenting some tests to identify outliers in a sample data. With this procedure a more accurate estimation of all life characteristics is determined. The objective is to identify outliers in a sample of a set of time to failure observations (TTF). The outliers are observations points that are distant from other observations and appears to deviate markedly from other members of the sample in which it occurs [8] or is an observation that is far removed from the rest of the observations [9].

These outliers are values that are very low or very high in the set of observations and may be the result from the faulty data, variability of measurement, human error when calculating or recording the numerical value or even related to a failure that occurred in special conditions that should not be mixed with regular failures. It can also point out that an experimental error is occurring or be the result of gross deviation from prescribed experimental procedure. It can also be verified in a plotting paper where some points are substantially below or above the fitted line. For heavy-tailed distributions with high skewness one must be cautious if using tools or methods that assume a normal distribution. Thus, it is very important to discard these outliers and promote a better quality of the data for the further steps illustrated in Figure 2, avoiding a naive interpretation of the results of a reliability analysis.

Several studies and publications can be referred where the issue outliers is discussed. Some of them present tests and methods while others propose new tools or modifications for the existing ones. Angiulli [10] published a paper where an overview of unsupervised data mining outlier detection techniques is provided. The author considers different families of approaches, including statistical-based, distance-based, density-based, isolation-based, angle-based, subspace-based, ensembles, and methods providing explanations. Advantages, drawbacks and potential applicative scenarios are also highlighted.

Sample data can be classified as complete or incomplete (truncated or censored) sample. The present work only deals with complete samples. Some methods to treat truncated or censored data can be observed in literature [11] [12] [13] [14].

3.1 Simple Test (ST)

The first test to be described is called Simple Test due to its simplicity. This test gives relatively accurate results when the values of the collected data are normally (or approximately normally) distributed or when data are Weibull distributed with a shape parameter (β) between 2.6 and 3.7, where the probability density function has an approximate Gaussian shape [7]. The normality of the values can be previously checked with other tools and methods as the Shapiro-Wilk test or the Kolmogorov-Smirnov test. The schema for Simple Test is shown in Figure 3.

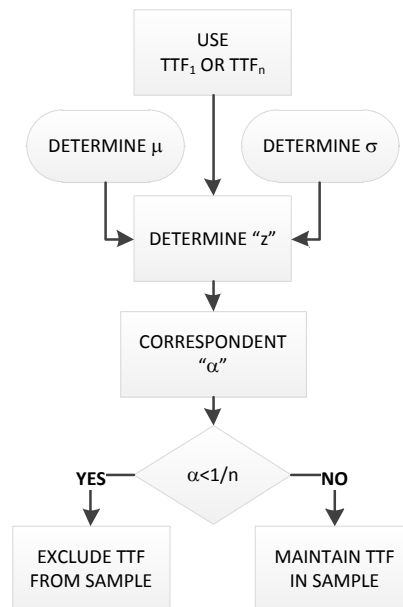


Figure 3 Simple Teste schema

Firstly it must be determined the sample mean (μ) and sample standard deviation (σ) based on the complete set of observations (times to failure). Then, it must be seen if the suspected outlier observation is between $[\mu-k.\sigma; \mu+k.\sigma]$ or not. If not, it means that there is a chance of that specific observation be an outlier and thus be discarded. Next, must be calculated the value of “z” through expression (1), that represents the quantity of standard deviations of the observed time to failure (TTF) regarding the sample mean and standard deviation values.

$$z = \left| \frac{TTF_i - \mu}{\sigma} \right| \quad (1)$$

To this value of “z” will correspond a cumulative probability (cumulative normal distribution) of “ α ”. Ordering the sample data from TTF_1 to TTF_n in a set of “n” times to failure collected it is possible to see, for example, that TTF_1 is an outlier if “ α ” is less or equal to “ $1/n$ ” (that represents the probability of any TTF be an outlier in “n” observations).

It can also be studied through percentiles. For example, five percentile value will correspond “ $z=1.64485$ ”, as represented in Figure 4.

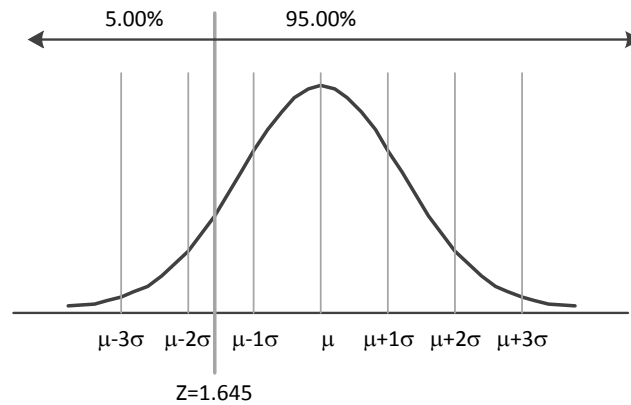


Figure 4 Percentile five

Based on that value and using expression (1) it can be seen which time to failure will correspond to that percentile ($TTF_{5\%}$). Thus, if TTF_1 is lower than $TTF_{5\%}$ it means that the probability of TTF_1 is an outlier is over 95% or, in other words, the risk of assuming TTF_1 as an outlier is less than 5%.

3.2 Natrella-Dixon Test (ND)

This test may be used when the sample mean and sample standard deviation are unknown [7]. Again, the observed times to failure must be ordered in an increasing way ($TTF_1 < TTF_2 < \dots < TTF_n$) and the statistic of the test " r_{ij} " described in Table 1 can be determined.

Table 1 – Statistic of test for Natrella-Dixon test

N	r_{ij}	TTF_n is suspect	TTF_1 is suspect
3 to 7	r_{10}	$(TTF_n - TTF_{n-1}) / (TTF_n - TTF_1)$	$(TTF_2 - TTF_1) / (TTF_n - TTF_1)$
8 to 10	r_{11}	$(TTF_n - TTF_{n-1}) / (TTF_n - TTF_2)$	$(TTF_2 - TTF_1) / (TTF_{n-1} - TTF_1)$
11 to 13	r_{21}	$(TTF_n - TTF_{n-2}) / (TTF_n - TTF_2)$	$(TTF_3 - TTF_1) / (TTF_{n-1} - TTF_1)$
14 to 25	r_{22}	$(TTF_n - TTF_{n-2}) / (TTF_n - TTF_3)$	$(TTF_3 - TTF_1) / (TTF_{n-2} - TTF_1)$

With a sample size of " n " times to failure, assuming a confidence level of " α " and regarding the Tables developed by Natrella and Dixon, the critical value of " $r_{\alpha/2}$ " is selected. Then we must compare the value of " r_{ij} " with the value of " $r_{\alpha/2}$ ". If " r_{ij} " is higher than " $r_{\alpha/2}$ " it means that the suspected observation is an outlier with a confidence of " $100(1-\alpha)$ " percent if there are suspect observations in both sides of the sample and a confidence of " $100(1-\alpha/2)$ " percent if the suspect observation is only at one side of the sample. Figure 5 illustrates the schema for the Natrella-Dixon test.

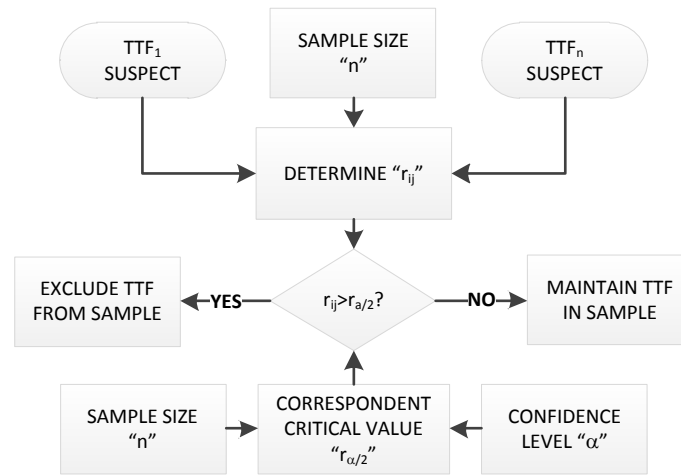


Figure 5 Natrella-Dixon test

For example, for " $n=20$ " and 5% risk level (confidence level of 95%) where only the lowest value of the sample (TTF_1) is suspect to be an outlier, the statistic of test " r_{22} " is determined by:

$$r_{22} = \frac{TTF_3 - TTF_1}{TTF_{18} - TTF_1} \quad (2)$$

Then, with “ $\alpha/2=0.05$ ” using Natrella and Dixon Tables is achieved a critical value of “ $r_{\alpha/2=r_{0.05}}=0.450$ ”. To complete the test we must compare the value of “ r_{22} ” determined by (2) with the value of “ $r_{0.05}$ ” and if “ $r_{22} > r_{0.05}$ ” it is assumed that TTF_1 is an outlier with 95% of confidence.

3.3 Grubbs Test (GB)

To use Grubbs test it is also necessary to order the “n” observations of time to failure in an increasing way. Then, the statistics of test “ v^2 ”, “ v_1^2 ” and “ v_n^2 ” must be determined according to (3), (4) and (5), respectively [7].

$$v^2 = \sum_{i=1}^n (TTF_i - \mu)^2 \quad (3)$$

$$v_1^2 = \sum_{i=2}^n (TTF_i - \mu_1)^2 \quad (4)$$

$$v_n^2 = \sum_{i=1}^{n-1} (TTF_i - \mu_n)^2 \quad (5)$$

Where:

$$\mu = \frac{\sum_{i=1}^n TTF_i}{n} \quad (6)$$

$$\mu_1 = \frac{\sum_{i=2}^n TTF_i}{n-1} \quad (7)$$

$$\mu_n = \frac{\sum_{i=1}^{n-1} TTF_i}{n-1} \quad (8)$$

Using Grubbs Table for a sample size of “n” observations the critical value for a confidence level of “ $(1-\alpha)$ ” is selected. Then, depending on the suspect observed value being TTF_1 or TTF_n it must be calculated “ v_1^2/v^2 ” or “ v_n^2/v^2 ”, respectively, and compare with the critical value. If the critical value is higher the observed value is considered as an outlier with the specific confidence level. The schema for Grubbs test is shown in Figure 6.

3.4 Rank Limits Test (RL)

In this test time to failure observations are also put in an increasing order of values and it will start checking for the lowest and highest value (TTF_1 and TTF_n) to see if they are considered as outliers. To do that it is determined the parameters of the most common distributions without knowing which one is the most adequate. After that, for each distribution are determined the cumulative probability of failure for TTF_1 and TTF_n . Assuming a significance level “ α ” the lower and the upper one side rank limit (“ $r_{1,n,\alpha}$ ” and “ $r_{n,n,1-\alpha}$ ”) are determined using rank tables [7].

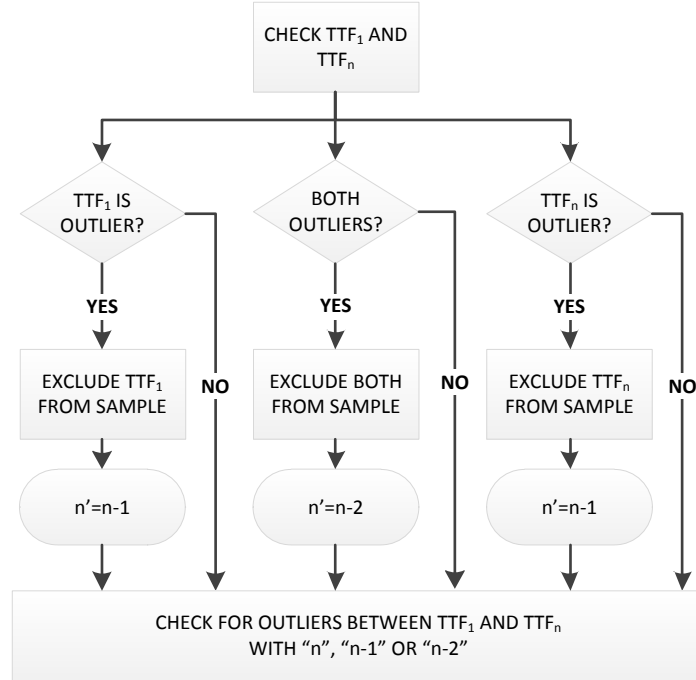


Figure 7 Schema for Rank Limits test

To analyse if the limit observations are considered as outliers one must compare the values, and if:

$F(TTF_1) \leq r_{1,n,\alpha}$, then TTF_1 is an outlier at a confidence level of $(1-\alpha)\%$

$F(TTF_n) \geq r_{n,n,1-\alpha}$, then TTF_n is an outlier at a confidence level of $(1-\alpha)\%$

After this stage we are able to check if any other TTF (in between TTF_1 and TTF_n) are outliers. To pursue the method the dimension of the sample data regarding observations of time to failure is updated (or not). In this step “n” remains the same if neither TTF_1 and TTF_n were previously considered as outliers, “n” assumes the value of “n-1” if only one of them was considered outlier and “n” assumes the value of “n-2” if both were considered outliers.

In the case it is concluded that neither TTF_1 nor TTF_n are outliers the cumulative probability of failure for each one of the remaining TTF is determined. For a dimension of “n” observations and a significance level “ α ” the two sided rank limits are found for each observation (“ $r_{i,n,\alpha/2}$ ” and “ $r_{i,n,1-\alpha/2}$ ”). Then, all pairs of individual values are compared, and if:

$F(TTF_i) \notin [r_{i,n,\alpha/2}; r_{i,n,1-\alpha/2}]$ then TTF_i is an outlier at a confidence level of $(1-\alpha)\%$

In the case of prior having discarded one or both limit observations as outliers the method is quite similar. It is only needed to update the estimation of distribution parameters with the new sample data dimension.

3.5 Modified Thompson Tau Test (TT)

The Modified Thompson Tau test is used to determine if an outlier exists in a sample data of “n” observations taking into account the sample standard deviation and the sample average giving a statistically zone of rejection. The first step is to determine the referred standard deviation and average. Then, the absolute deviation between each observation and the sample average are determined. The Region of Rejection is determined using (9):

$$\frac{t_{\alpha/2}(n-1)}{\sqrt{n} \cdot \sqrt{n-2+t_{\alpha/2}^2}} \quad (9)$$

Where $t_{\alpha/2}$ is the critical value selected from t-Student distribution with “n-2” degrees of freedom. A TTF is an outlier if “ δ ” \leq Region of Rejection, being “ δ ” determined by expression (10):

$$\delta = \left| \frac{TTF - \mu}{\sigma} \right| \quad (10)$$

Similarly to Rank Limit test, if the TTF_1 or TTF_n are outliers, they are removed from sample and the test is repeated with a new average, standard deviation and Region of Rejection, until no outliers are identified in the sample data.

3.6 Other Methods

Other methods can be referred to determine if an observation is outlier. Some are more graphical (e.g. normal probability plotting) and others are based on models assuming that the sample data is approximately normally distributed as for example the referred Grubbs test and Natrella-Dixon test or others like Chauvenet’s criterion and the practice recommended in ASTM E178-16a [15]. In descriptive statistics are used box plots that are a hybrid solution once they are model based where it is graphically possible to depict groups of numerical data through their quartiles. It displays the behaviour of data in the middle as well as at the ends of the distributions using the median and the lower and upper quartiles (25th and 75th percentiles).

In data mining processes related to Big Data projects other approaches are used such as the distance based and density based. In this processes it is common to observe methods based on the k-nearest neighbours [16]. The Local Outlier Factor is a method that is based in an algorithm for finding anomalous data points by measuring the local deviation of a given data point with respect to its neighbours [17].

The method shares some concepts such "core distance" and "reachability distance", which are used for local density estimation.

4.0 Conclusions

The present work shows how to treat data collected from failure occurrences in a way to eliminate possible outliers and thus make further analysis more accurate and reliable. In a world that is changing rapidly the way how physical assets become to be connected and where data is more accessible and available (Big Data), the "bad data" could have a significant impact on the distribution parameter estimation process and influence the results concerning item life characteristics.

It must be noticed that most of the reliability studies rely on failure data and some important decisions are made based on the analysis and corresponding results. When Condition Based Maintenance is selected to be applied as maintenance primary strategy the failure prognostic is by far an important issue to be considered. Predicting failures becomes fundamental to do the right things at the right time. This is only possible if input data is trustfully selected.

This circumstance makes the knowledge of the presented methodologies a valuable tool to help asset managers and maintenance engineers and technicians to obtain credible data for reliability and maintainability analysis.

Although outliers are often bad data observations they should be investigated carefully because they may contain valuable information about the process under investigation or the data gathering and recording process. Before discard outliers from sample data one should try to understand why they appeared.



Future works may show the influence of ignoring outliers on risk, linking the degree of deviation of the outliers and the error produced on reliability, giving some examples of the application of the methodology using distinct statistical distributions.

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Authors' Biography

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ME2018_1143

New Maintenance Methodology Implemented For Wells Re-manifolding

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Abstract:

Saudi Aramco/South Ghawar Producing Department has exerted substantial efforts to achieve significant reduction in turnaround time for re-manifolding of the oil and water wells. After completion of workover activities, the wells are connected to the oil manifold through the oil flowlines and after final inspection, the wells are put into production. The turnaround time for re-manifolding of the wells is critical in terms of the locked potential of the wells and oil producing capacity. Re-manifolding involves many activities and resources which need to be planned, aligned, and implemented in the shortest possible time, ensuring safe execution. This presentation summarizes the new maintenance methodology, which resulted in a significant reduction of turnaround days against the set KPI. Saudi Aramco/South Ghawar Producing Department believes that sharing such experiences will be beneficial to all organisations.

Key words

Re-manifolding, oil manifold, turnaround time of re-manifolding, Wellhead Spool, Anchor Spool, Well pad.

1.0 Introduction

The re-manifolding process is a set of activities starting after a workover rig is released from a well. By leveling of the well pad area, installation of wellhead piping spools and flowline piping spools, anchor foundation, and the well pad accessories, the well becomes mechanically completed, with the exception of swinging the blinds at the tie-in point.

A total of 24 activities are involved during the re-manifolding process of a well with modification of the wellhead and flowline piping spools.

After completion of workover activities, the wells will be connected to the oil manifold through the oil flowlines and put into production.

Saudi Aramco/South Ghawar Producing Department has exerted extensive efforts to achieve a significant reduction in the turnaround time for re-manifolding oil and water wells, and unlock potential wells.

2.0 Involved Organisations for Re-manifolding Completion

Eight organisations are involved in re-manifolding activities.

3.0 Challenges

- Coordination among several organisations
- Remote locations and sand encroachment
- Major pipeline modification
- Materials requirements
- Engineering procedures issuance for each repair
- Variation of wellhead height after workover rig release
- Resources availability such as heavy equipment

Delay re-manifolding and longer duration result in:

- ☐ Locked potential of the oil /water well
- ☐ Difficulties to achieve production priority compliance
- ☐ Noncompliance of production targets
- ☐ Corrosion due to delayed cathodic protection (CP)

The challenge is to maintain a continuous workflow between several organisations to complete the re-manifolding in 21 days for a well requiring piping spools modification, and 9 days for a well requiring no piping spools modification, despite the fact that the different organisations may have other work priorities.

4.0 Enhancements

- Assigned the responsibility of completing the re-manifolding activities to South Ghawar Maintenance Service Division (SGMSD), including installation of wellhead piping spools, flowline piping spools and well accessories. This is one of the several benefits of re-organisation of the task by management.
- Developed and implemented Long Form Contract (LFC).
- Assigned a contract coordinator for coordination, follow-up and execution of re-manifolding activities in timely manner.
- Closely monitored and ensured contractor's compliance with safety procedures and safe execution.
- Advanced planning and modification of flowline sections during workover rig operation.
- Advanced planning by tracking the workover rigs movements.
- Cooperation between the team members.
- Continuously monitoring and implementation on areas of improvement/lessons learned.

- Regular follow-ups, meetings and better planning with all the concerned organisations.
- Conducted Lean Six Sigma Study to minimize the re-manifolding turnaround time and came out with these recommendations.
- Developed a checklist to be filled out during the KICK OFF meeting with all the concerned parties.
- Developed effective tracking and follow-up reports to monitor the progress and the contractors' payment release.
- Generated Re-manifolding Tracking System (RTS).

5.0 New Methodology Outcome

The average number of days is 21 days for the Modified wells. This is according to the Key Performance Indicator (KPI) for the re-manifolding with piping modification.

- The new maintenance methodology resulted in a significant turnaround day's reduction from 2009 to 2017, against the set KPI.
- For example, in 2017, the team successfully managed to reduce the turnaround days for Modified re-manifolding activities by 57% from the set KPI turnaround time. In other words, in 2009, the re-manifolding activities took 71 days to be completed 100%, whereas it took only 9 days to be completed 100% in 2017.

The average number of days is 9 days for the Non-Modified wells. This is according to the Key Performance Indicator (KPI) for the re-manifolding without piping modification.

- The new maintenance methodology resulted in a significant turnaround day's reduction from 2009 to 2017, against the set KPI.
- For example, in 2017, the team successfully could manage to reduce the turnaround days for Non-Modified re-manifolding activities by 78% from the set KPI turnaround time. In other words, in 2009, the re-manifolding activities took 45 days to be completed 100%, whereas it took only 2 days to be completed 100% in 2017.

6.0 Main factors assisted for Success

Study → Plan → Procure → Execute

Of course, there are other factors that assisted in getting wells producing in a very competitive turnaround time, such as:

Awareness and training sessions to the crafts and implementers for the Operation Instructions Manuals and Procedures.

Applying the best practices and continues management engagement to assure high performance were also major contributors of this success.

On employees' level, weekly meetings were conducted to assess performance and bridge the gaps.

Utilizing effective tools to monitor performance and forecast targets.

Finally, our continuous collaboration to maintain a solid platform of understanding for the requirements.

7.0 Conclusion

The re-manifolding team is continuously exploring ways to sustain the reliability of wells, to run safe and smooth operations. As a result, the re-manifolding team has set more challenging goals and objectives for 2018 and future years, and is exerting more efforts to ensure much more success is achieved.

It must be noted that the workforce has proven to be the **most valuable pillar in the success of our re-manifolding efforts.**

ME2018_1144

SGPD Best Maintenance Practice: Flange Weld Test Plug

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Abstract:

As one of the best maintenance practices, Saudi Aramco/ South Ghawar Producing Department uses an approved tool, the High Lift Flange Weld Test Plug, to conduct hydrotesting of pipe to flange weld joints. This approved technology is replacing the old conventional way of hydrotesting the flange to pipe weld joints, without the need to fill the entire piping system with water, and without pressurizing the whole system. This tool has proven its merit in many aspects by improving safety, saving time, effort, conserving water, and eliminating associated costs. This presentation summarizes the benefits of implementing this best practice through a case study. South Ghawar Producing Department believes that sharing such experience will be beneficial to all organisations.

Key words: Flange and Pipe weld joint, Hydrotest, Flange Weld Hydrotest

1.0 Introduction

Piping repairs and welding new flanges to the piping spools are one of the major and time consuming activities during Turnarounds and Shutdowns.

After welding a flange on to the pipe, the integrity of the weld joint is established by conducting a hydrotest, where the conventional methods involve filling the pipe spools, and sometimes the whole piping system, with water. An approved technology, the Flange Weld Test Plug, is replacing the old traditional way of hydrotesting the new welded joints at the site, without the need to fill the entire system with water.

As one of the best maintenance practices, Saudi Aramco/ South Ghawar Producing Department uses the High Lift Flange Weld Test Plug to conduct hydrotesting of Pipe to Flange weld joints.

2.0 Case Study; Hydrotest at Oil Trunk Line

The flange to pipe weld joint, on a 12" diameter trunk line, required hydrotesting during a turnaround inspection. The required hydrotest pressure was 1500 psig and the length of the line is 2 km. To conduct hydrotesting to establish the integrity of the weld joint, the whole line was required to be filled with 145,738 liters (38,500 gallons) of water, and subjected to a pressure up to 1500 psig.


Instead of using the conventional hydrotest, it was decided to use the Flange Weld Test Plug. The implementation of this best practice resulted in:

- Cost savings of \$40,800.00.
- Water requirement reduced from 145,738 liters (38,500 gallons) to 30 liters (8 gallons)
- Down time of turnaround reduced from 2 weeks to 1 week
- Reduced preparation time from 3 days to the same day
- Hydrotest time came down from 12 Hrs. to ½ hr.
- Considerable reduction in the amount of work required
- Enhanced safety
- Disposal of less water, conserving natural resources

3.0 Conclusion

Using the Flange Weld Test Plug for hydrotesting is very economical, quick, and an environment friendly solution for testing requirements. This tool has proven its merit in many aspects, by improving safety, saving time, efforts, conserving water, and eliminating associated costs.

Authors' Biography

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ME2018_1145

The Internalisation of the Maintenance Function – A Strategic Vision

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Abstract The future of the maintenance function has a new paradigm, concentrating his concerns about the right approach and format, how organisations should organize their maintenance structures, in order to ensure that best operational and maintenance practices are applied and adopted. Ensure and perform all operational or maintenance activities, by using in-house maintenance solutions have proven that in most part of the cases, it didn't lead to the desired results, either due to the lack of commitment with the business risk and their consequences, or due to the decision to celebrate traditional maintenance service contracts using the unit price system, where specifications are simple in their structure and implementation. The implementation of prescriptive-based specifications reduces though the flexibility of the agreements and limits the possibilities of the internal maintenance structures or traditional service contractor to improve asset/plant performance. Furthermore, the management of the contract faces difficulties such as poor performance of the assets and ineffective follow of the best maintenance management processes. Performance Maintenance Based Contracts (PMBC) attains an alternative means for outsourcing of operation or maintenance based on a win-win approach. The strategy for PMBC attains high potential of cost-savings in TCO (2-10% minimum) and improved Overall Plant/Asset performance. A clear Asset Management program adopted by the organisation, allows and provide the opportunity for the implementation of a performance scheme to incentive maintenance function, it should be considered as a vehicle to set the right level of reference, regarding the implementation of the maintenance best practices and to set the right roadmap to move forward, particular in those competitive times organisations are facing, and where the search for optimisation and up-time becomes one of the key-success factors.

Key words Maintenance Function, Best Maintenance Management Practices, Performance Maintenance Based Contracts (PMBC), Win-Win, TCO Optimisation, Key Success Factors, and Asset Management Program.

1.0 Introduction

These days, maintenance services contracts based on operational and maintenance performance are at the center of the organisations attention and at the agenda of CEO's, the main objective is the achievement of desired results according world-class business performance and an overall increase of competitiveness in comparison with his commercial competitors. The decision to outsource the maintenance function and the application of an asset management program, allows organisation to increase performance, optimize costs and mitigate the business risks. The application of consolidated processes, following the implementation of best practices and the comparison of the obtained results, with international references (benchmarking), promotes a continuous improvement culture which can lead the organisation to the success and to sustainable results.

2.0 The Maintenance and Organisational Context

Nowadays, we are increasingly seeing a reduction in maintenance budgets, providing in many cases several constraints and bottleneck about the strategies those maintenance departments have, in order to implement corrective actions for defect elimination and achieve the desired reliability.

Other cases are known, even with additional financial resources the results do not achieve the expectations or reflect the use of best maintenance practices, resulting in most part of the cases on, a high turnover of the maintenance staff. The maintenance activity must be self-sustaining and must be "economical fed", according his results and qualitative excellence, being an extension of the operational function, in general maintenance provides a "service" for the business. In this increasingly competitive world any service company only survives, when as the capacity to deliver a service and results according excellence by earning profits or losses from those same results. This approach shall be extended to maintenance and it reflects the difference, with rare exceptions, from an internal maintenance structure in an organisation and a maintenance service provider. The first will hardly recognize the need to deliver a quality service, simply because the main core business of the organisation is not the maintenance activity, it was adopted or implemented only because there is a need to keep the asset in operational conditions and technology demands it. Several organisations have tried to standardize working methodologies and processes, oriented to ensure a better control and performance of the maintenance, such methodologies and processes have not resulted and will never result in general, since the maintenance should be considered as a business with very specific processes, that requires own strategies, different from others operational management processes.

The future of maintenance activity according the international context , particularly for medium-large organisations, must pass in the coming decades through the

total outsourcing of the maintenance services , but not under the traditional service models, the vision must be more comprehensive and global, it means converting the traditional provision of maintenance services in a closer relationship between organisation and external entities, based on a mutual relationship and in a win-win approach, in sum adopting performance base contracts , with transparent costs , gains and losses

3.0 Best Practices and Key Success Factors in Maintenance

Below are listed some of the areas and "key success factors“, that requires an on-going improvement analysis, strategy, and consequent action plan to “boost” the maintenance performance;

- Maintenance Organisation and Structure aligned with the business plan and suitable to implement a pro-active maintenance approach;
- Staff skills and competences , supported by an adequate recruitment strategy and training program;
- Workflow management process;
- Planning and Scheduling best practices;
- Implementation, use and optimisation of the suitable CMMS;
- Shutdown and Turnaround Strategy;
- Preventive and Predictive Maintenance Program , based on criticality assessment;
- Materials/Interchangeable management and materials procurement strategies;
- Promote the culture of autonomous maintenance and basic maintenance practices;
- Subcontractors Management;
- Performance Management;
- Root Cause Analysis routines , based on a defect elimination approach and a clear Reliability Program;
- Asset Life Cycle Cost Projection;
- Asset Data Management;
- Maintenance Process Audits (MPA).

The use of a “benchmarking culture” develops a stimulus for continuous improvement in the organisations, promoting the assessment of the results, identify-

ing the gaps and opportunities for each case. Table1 provides an overview about several key performance indicators achieved by world class maintenance organisations; however an idea shall be retained, a reference value today, will be a normal value tomorrow and a mediocre value in the future. The level of maturity of the organisation will dictates the level, ranges and the priorities to close the gaps.

Area	KPI	Word Class
Costs	Maintenance Costs as per the Equipment Replacement Value – ERV	2-5%
	Material Costs	25-35%
	Maintenance Workforce Costs per Sales Level	0,5-2,5%
Planning and Scheduling	Planned Maintenance (HH)	>90%
	Wrench Time	60-65%
	Overtime	< 5%
	Backlog Level	2-4 weeks
	HH of Preventive/Predictive Maintenance	25-30%
Material Management	Inventory Turnover	1,5-3 year
	Inventory Costs as per the Equipment Replace Value-ERV	2-8%
Training	Training as a percentage of payroll	3-5%
	Technology Training/Total Training Expenses	>50%
HSE and Emergency	The number of lost-time injuries per 200,000 person hours worked (OSHA Incidents)	< 2
	Lost-time accident frequency rate (per 100 workers)	< 1
	Man-hours unplanned maintenance / Total Man-hours available	< 3%
Asset Performance	Asset/Plant Availability	>97%
	Overall Equipment Effectiveness (OEE)	80-85%
Services	Subcontractor Costs / Total Maintenance Costs	35-65%
Organisation	Ratio Technician per Maintenance Supervisor	(8-15):1
	Ratio Technician per Maintenance Planner	(15-25):1
	Personnel Turnover	<3,5% /y
	Average Overtime – Hourly Maintenance	< 8%
	Absenteeism Rate	<4%

Table 1 Benchmark KPI's for World-Class Organisations

4.0 The Win-Win Concept

Organisations and entities providing maintenance services in particular are recognizing that both must follow a convergent business and maintenance strategy, in

which both will obtain the results if the objectives are setup common and focus in the business plan of the organisations and clients.

These objectives generate the opportunity for the organisation to choose an outsourcing strategy, sharing the challenges, risks and obtain the commitment of external entities, where their core business is the maintenance services, partners with consolidated processes, technical knowledge, and qualified human resources. It is therefore important to define the most appropriate collaboration model for both parties, but always based on a performance concept, where the profits/losses are directly connected to the objectives of the organisation, thus ensuring that the interest to obtain the best performance is mutual (Win-Win: both parties win following the same strategy), something that in many organisation may be more difficult to obtain through internal solutions, or between operational and maintenance departments.



Figure 1 Win-Win Alignment Strategy

In the past, organisations only thought of getting the best prices from their maintenance service providers, smashing their profit margins, consequence of that, they did not promote any interest for invest and consequently could not improve their productivity, performance and quality related to the services provided, maintenance contracts with fixed cost budget are a risk and a barrier to the continuous improvement and generates economical conflicts and lower transparency between organisations and partners.

The Win-Win strategy aims on the development and optimisation of organisations and their service providers/partners, based in the old maxim that “together we are stronger, alone more weak.”

5.0 TCO Optimisation – The Objective

The optimisation of the total cost of ownership of an asset (Total Cost Ownership-TCO) is the main objective of the organisations, to achieve this goal is essential the contribution of the maintenance function, improving the reliability and operational availability of the assets. The maintenance function impacts many areas, either it is normally responsible for managing different activities, achieve excellence requires a direct linked between the performance level and the benefits organisations would acquiring from that.

An optimisation of the maintenance function can represents a gain of 2-10% (Figure 2) in the business, increasing the profit by the difference of the results obtained in the improvement of the performance and the reduction and optimisation of the costs. In most part of the cases the hidden costs are the basis of the profit, looking for the “big picture”, instead of the standard direct maintenance costs, the iceberg model, presented in figure 3 is a great example of the concept and approach.

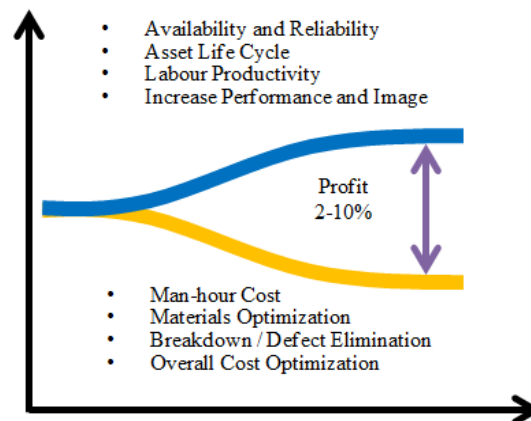


Figure 2 Maintenance Optimisation Saving for TCO

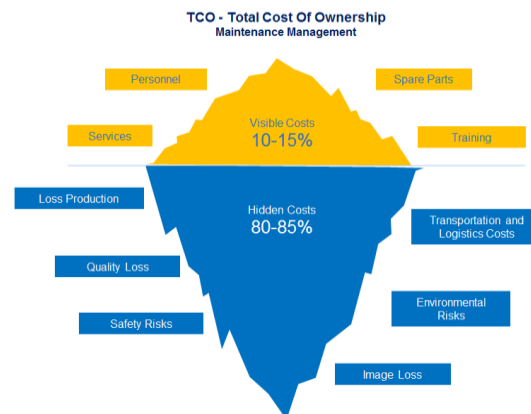


Figure 3 Iceberg Model – Maintenance Costs

6.0 Maintenance Services Portfolio

At the current times, maintenance service providers offer portfolios that cover different models of collaboration with between them and the organisations, the decisions are mainly based on two factors, the trust level existing both parties (in many cases based on past business relationships, e.g. Machinery provider/manufacture or by the experience and knowledge of the partner) and based on the “factor value” it would represents, i.e., what additional value, the collaboration provides.

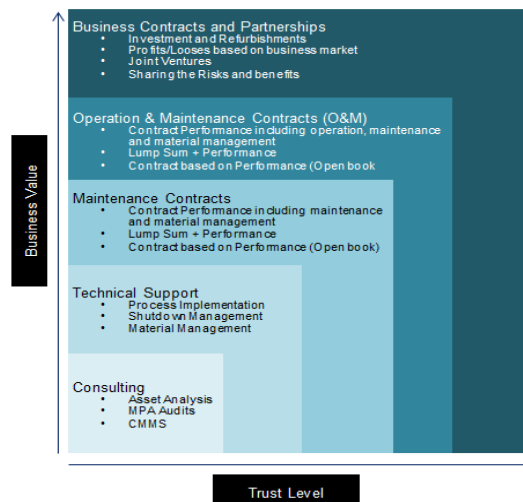


Figure 4 Maintenance Services Portfolio

Figure 4 shows an example of the solutions associated with a portfolio of maintenance services, including the operation of the assets, and where risk and benefits are directly related.

7.0 Performance Based Maintenance Contracts (PMBC) – An Approach

Performance Based Maintenance Contracts (PBMC) can be considered as an asset management model, which imposes on the maintenance service provider (The contractor) the obtainment of bonuses or penalties according to their performance, thus encouraging them to achieve the objectives (KPIs) with organisations, resulting in an increase or decrease in payments to the contractor according to reference values and based on an agreed incentive scheme system or matrix (figure 5).

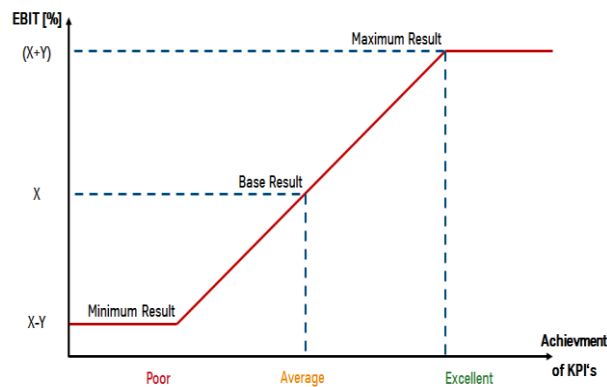


Figure 5 Example of an incentive scheme for KPI's achievements, in a potential performance based maintenance contract

The approach promote the establishment of a collaboration and partnership , being exclusively controlled by the performance, thus obliging the service maintenance provider to adopt and implement the best practices in order to achieve excellence and release additional profit.

Measuring	% KPI	Poor	Acceptable	Good	Excellent
Performance	100	[85% or less]	[85.1-90%]	[90.1-95%]	[95.1-100%]
Cost + % Fee		All costs + No fee	All costs + 50% of agreed fee	All costs + 100% of agreed fee	All costs + 150% of agreed fee

Figure 6: Example of payment system associated to a PBMC

The celebration of performance maintenance based contracts, particularly at the industrial level, presents advantages and disadvantages to the organisations, as the ones listed below;

Benefit(s)

- Low needs for specialized knowledge;
- Long-term financial risk reduction;
- Significant cost reduction;
- Improved performance and service.
- Stimulates the use of new technology and processes according to the best practices;
- Reduction of the bureaucracy level.

Disadvantage(s)

- Requires a strategy based on medium / long term contracts between organisations and maintenance service providers;

8.0 Implementation of Performance Based Maintenance Contracts - Challenges

There are some challenges that organisations and service maintenance providers should consider and identify before and during the implementation of a performance based maintenance contract, in order to mitigate the risks of potential barriers that are in many cases responsible for the failure of an operation & maintenance contract or by the successfully implementation of a asset management

program, that everyone would like to see as long-term collaboration. Some of the most common challenges regarding the implementation of an asset management program, including a possible maintenance outsourcing contract, are explained by the following factors;

- Wrong Organisation Setup and inflexible local labor laws;
- Lack of resources with adequate skills and training, as well as the incapacity of the organisations and service providers to define upfront a clear strategy and a training program to close-out the gaps;
- Lack of a clear workflow process and procedures, developed according to best practices and adjusted to the business;
- Inadequate use of management and control/reporting tools;
- Monitoring strategy and commercial relationship between organisations and service providers;
- Lack of understanding about the cultural and ethnic context of the organisations according to the geographic location;
- Poor Logistic Plan ;
- Upfront understanding and clear strategy about the existing of hard working conditions and accessibility to material, Interchangeable and consumables;
- Adaptation of the procurement and financial processes to respond to the requirements and characteristics of the operating and maintenance areas;

Definition and control of key performance indicators non-adequate to the contract, based on baselines defined in assumptions or wrong projections.

9.0 The Asset Management Strategy as a Vehicle to Set a Global Maintenance Service Level

The implementation of an asset management program requires the total involvement of the maintenance function in order to achieve the desired an excellent performance. Figure 7 presents an overview of the "great journey" that organisations and service maintenance providers must consider and walk together, in the sense of achieving the major following objectives

- Improve performance;
- Optimize costs;
- Mitigation and control the risks.

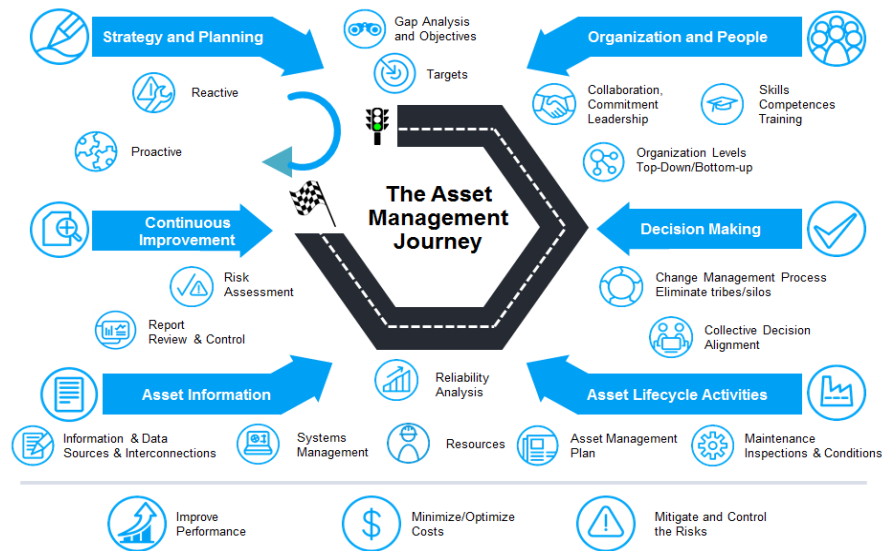


Figure 7 The Asset Management Journey and the main objectives of the maintenance function

In general there are six main stages which must be consolidated, to achieve a successful implementation of an asset management program, and where the maintenance functions as a key-role. Below are listed the baselines that require the total focus of organisations;

- Strategy and Planning;
- Organisation and Personnel
- Decision Making
- Asset Life Cycle , based on a clear maintenance and operational risk analysis;
- Asset Information;
- Continuous Improvement Process;

10.0 Conclusion

The worldwide demand for business optimisation based and focus on an asset performance strategy bring organisation to the need, about the mission and involvement of the maintenance function as a key success factor to achieve the objectives,

what in many cases leads to a conclusion to challenge internal maintenance organisations or for a common decision for a close agreement with a partner expert on that matter. The partner is seen as someone that has and can implement the best practices, in order to achieve the best indicators, with focus in TCO optimisation, and consequently increase business margins.

Select the right maintenance service portfolio offered by different maintenance service providers, is directly connected with the thrust level existent between both parties and the add value it represents. The result might origins a performance maintenance/operational based contract, established in a clear incentive scheme that measure on a fair way the performance of the contract and goes aligned with the goals and targets of the organisations, based on a win-win concept.

Challenges regarding the implementation of an agreement or partnership should be target of a clear strategic plan, in order to mitigate the risks and monitor the success. These strategic plans are part of the overall asset management program, that can support in many cases the change process, yes because that is all about, the paradigm of a unique and clear “change management process”.

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Authors' Biography



Pedro Viegas

Certified Reliability and Maintenance Engineer by *Escola Superior de Tecnologia de Setubal/Portugal – IPS*, with almost 20 years' experience in Maintenance Management, training and over the last years on the implementation of operation and maintenance service contracts (O&M Outsourcing) worldwide, supported by Asset Management Programs. Across his professional experience he has been working in several industrial sectors as, but not limited, mining, cement, material handling/harbor operations, fertilizer industry, etc...

The professional career has been driven and conducted by the delivery of excellence & performance results, through the implementation of the best maintenance management practices and processes in many organisations. Experience in industrial management projects is highlighted, as well as, about the improvement and optimisation of operational/maintenance departments, supported by joints Operational and Maintenance audits/gap analyses (MPA), and the technical/commercial support in several performance maintenance based contracts negotiations.

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Vibration-based diagnosis for different bearing clearances in a gear transmission system

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Abstract-Bearing is an essential component in a gear transmission system. Due to the harsh working conditions such as extreme loads and inadequate lubrication, bearing wear is inevitable, which could aggravate the bearing clearance, and subsequently alter vibration characteristics of gear transmission system. This study aims at investigating the influence of bearing clearance on gear vibration characteristics for gearbox condition monitoring. Based on gear dynamics, mesh forces due to enlarged bear clearances are studied, which gains understanding that inadequate bearing clearance can lead to inappropriate mesh position and radial fluctuation, then induce extra force component at tangential direction and alter the distribution of friction force. Experimental studies based on three incremental bearing clearances show that with the increase of bearing clearance, vibration changes can be observed at the third and fourth mesh components, which are significant and consistent with the predicted effects of radial fluctuation and friction excitation, therefore, these components can be an effective diagnostic feature to indicate deteriorations in bearing health conditions.

Key words Vibration, Fault diagnosis, Bearing clearance, Helical gearbox.

1.0 Introduction

Gear transmission systems are the most important applications which are widely used in various fields for transmitting power and movement. Gear transmission systems are always subjected to high speed and load which could result in various types of failure, such as gear failures, bearing faults, broken shaft and lubricant pollution which may result in catastrophic accidents and huge economic losses. According to the incomplete statistic studied in [1], bearing failure takes up nearly 70% of all failures occurred in gear transmission system. Therefore, conducting condition monitoring of bearings are very meaningful for extending gearbox service life, preventing failure occurrence and reduce economic losses.

Bearing clearance is essential to provide the proper lubrication between roller and inner race and outer race [2]. However, in some harsh working conditions like inadequate lubrication, high speed and load, dusty and humid environment, the rotational components in a bearing could get inevitable wear which could result in improper bearing clearance. While improper clearance, large or small, will affect the dynamic performance of working bearing, further will result in abnormal operation state and tremendous vibration of the whole system. Especially for precision transmission device and machine field, large clearance will lead to the inaccurate transmission and major machining error, and small clearance will aggravate the wear process and shorten the service life of bearings. Ref [3] studied the effects of bearing clearance on dynamic performance in a turbocharger, the results suggest that the variations of bearing clearance induced by working temperature shouldn't be ignored. Moreover, the nonlinearity effects of bearing clearance will generate more translational vibration. The nonlinearity and chaotic behaviour induced by bearing clearance has been investigated in some studies [3–6] while most of which are carried out on rotor, wind turbine or turbocharger. Ref [7,8] investigated the interactions between bearing clearance and gear backlash, which resulted in that when mesh and bearing modes coupled with each other, bearing clearance will influence gear dynamic characteristics.

Usually, when a fault occurs in a bearing, some additional vibration will be motivated, and such vibration could pass onto the body of gearbox which can be detected by accelerometer mounted onto the gearbox. For some typical faults like pitting, spalling and crack, modern techniques for condition monitoring can detect such failure successfully. While as for improper bearing clearance caused by installation or progressive wear, the signal induced by such bearing fault are usually very weak, which also increases the difficulties for fault diagnosis and condition monitoring. Some simulated analysis [9–12] have been conducted to investigate the bearing clearance, while most of which are just simulation studies without experimental validations.

Based on the analysis above, this study concentrates the influence of bearing clearance on gear vibration characteristics. To achieve this, dynamic responses of a gear mesh process were analysed by taking into account the bearing clearances. Then, a dedicated test was carried out under three incremental bearing clearances based on a helical gearbox test rig. Furthermore, the vibration characteristics of gearbox was studied by employing TSA analysis.

2.0 Gear mesh process analysis

Bearing clearance can induce the radial fluctuation of the gear shaft, which alters the contact point of mating gears and cause changes in contact forces. Not only does the change happen in the contact stiffness but also in the friction force. As shown in Figure 1 (a), under the static state, bearing clearance of both side are

symmetrical and are at half of its value. However, when the bearing is under operating condition, a dynamic fluctuation induced by bearing clearance is generated due to the dynamic mesh force, as shown in Figure 7 (b), the clearance at one side could be reduced to zero, and the other side could be increased to $\delta_{g,y}$ correspondingly. Because of this effect, the gear axle centre can be changed from O_g to O_{g1} or O_{g2} , thereby the deviation of mesh geometry is formed. Therefore, there will be a non-zero component F_{px} of the contact forces in the tangential direction (x-direction) induced by the deviation. Similarly, there also will be a non-zero component F_{fx} of the frictional force in the tangential direction. In addition, with the rotation of a meshing gear pair, the direction of friction force will change to the opposite direction when the mesh line passes through the pitch line, correspondingly, the directions of tangential components will also be changed. Both these changes of the forces induced by bearing clearance need to be considered when analysing the gear mesh process.

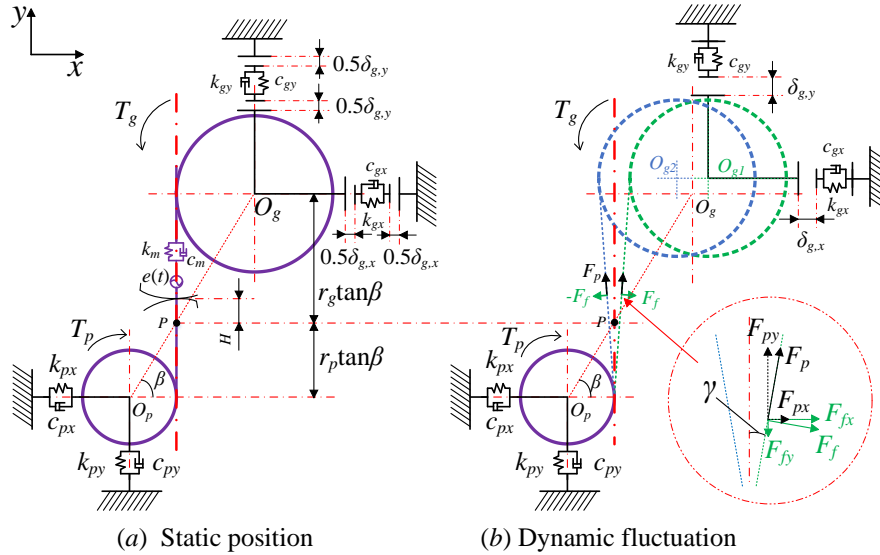


Figure 7 Schematic of gear dynamics with bearing clearances

According to Figure 7, the coordinate vector of dynamic model for the 6 degrees of freedom can be described as

$$\{\delta\} = \{\theta_g, x_g, y_g, \theta_p, x_p, y_p\} \quad (1)$$

where θ_g, θ_p are the rotational angle of gear (g) and pinion (p); x_i, y_i ($i=p, g$) are the translation displacements.

Correspondingly, the mesh force and friction force will be influenced due to the fluctuation of the axle centre, according to the force diagram shown in Figure 7 (b), the mesh force F_p can be expressed as:

$$F_p = k_m (y_g + r_{bg} \theta_g + 0.5 \delta_{g,x} - y_p + r_{bp} \theta_p - e(t)) + c_m (\dot{y}_g + r_{bg} \dot{\theta}_g + 0.5 \dot{\delta}_{g,x} - \dot{y}_p + r_{bp} \dot{\theta}_p - \dot{e}(t)) \quad (2)$$

where k_m is the gear mesh stiffness; c_m is the gear mesh damping coefficient; r_{bg} , r_{bp} are the base radius of gear and pinion; $\delta_{g,x}$, $\delta_{g,y}$ respectively represents the x -radial displacement and y -radial displacement of the gear; $e(t)$ is the dynamic transmission error.

Time-varying frictional force at the mesh point can be calculated based on the following equation in which a time-varying coefficient $\mu(t)$ is considered as mentioned in [13],

$$F_f = \eta(t) \mu(t) F_p \quad (3)$$

where $\eta(t)$ is the sign function of the direction of frictional force.

According to the rotational angle of the mesh line induced by the fluctuation, the projection of mesh force (F_{px} , F_{py}) and friction force (F_{fx} , F_{fy}) in x and y direction can be calculated as follows:

$$\begin{cases} F_{px} = \eta(t) F_p \sin \gamma \\ F_{py} = F_p \cos \gamma \\ F_{fx} = F_f \sin \gamma \\ F_{fy} = F_f \cos \gamma \end{cases} \quad (4)$$

where γ is the rotational angle of mesh line induced by the offset of gear axle centre.

A 6-freedom nonlinear dynamic model by taking into account the effects of bearing clearance and frictional force can be defined as

$$\begin{aligned}
I_g \ddot{\theta}_g &= -T_g - F_p \cdot r_{bg} + F_f (r_{bg} \tan \beta + 0.5 \delta_{g,y} + \eta(t) H) \\
m_g (\ddot{x}_g + 0.5 \ddot{\delta}_{g,x}) + c_{gx} (\dot{x}_g + 0.5 \dot{\delta}_{g,x}) + k_{gx} (x_g + 0.5 \delta_{g,x}) &= F_{px} + F_{fx} \\
m_g (\ddot{y}_g + 0.5 \ddot{\delta}_{g,y}) + c_{gy} (\dot{y}_g + 0.5 \dot{\delta}_{g,y}) + k_{gy} (y_g + 0.5 \delta_{g,y}) &= F_{py} - F_{fy} \\
I_p \ddot{\theta}_p &= -T_p - F_p r_{bp} + F_f (r_{bg} \tan \beta + 0.5 \delta_{g,y} + \eta(t) H) \\
m_p (\ddot{x}_p + c_{px} \dot{x}_p + k_{px} x_p) &= -F_{px} - F_{fx} \\
m_p (\ddot{y}_p + c_{py} \dot{y}_p + k_{py} y_p) &= -F_{py} + F_{fy}
\end{aligned} \tag{5}$$

where I_i ($i=p, g$) is the gear inertia; T_g, T_p are the input and out torque respectively; m_i ($i=p, g$) is the gear mass; β is the pressure angle; H is the distance from the mesh point to pitch point which is illustrated in Figure 7 (a).

According to the analysis of gear mesh process, bearing clearance has a significant influence on gear mesh characteristics. As shown in Figure 7, under the effect of gear mesh force and friction force, the radial fluctuation of the shaft will be amplified with the increase of bearing clearance. This radial fluctuation will induce extra gear mesh impact, and thereby results in more vibration. Additionally, it can also alter the distribution of frictional force along the gear tooth face and accelerate the gear wear process. Therefore, it is essential to investigate the influence of bearing clearance on gear vibration characteristics.

3.0 Test rig setup and procedure

In order to investigate the influences of bearing clearance on gear vibration features, three bearings with different clearances were tested on a gearbox test rig, which is illustrated in Figure 8 and Figure 9.

3.1 Test rig setup

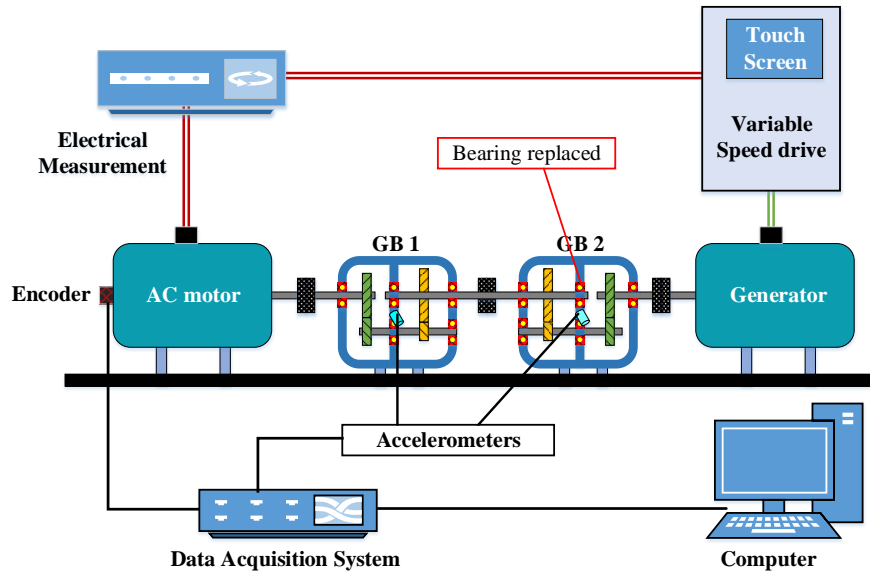


Figure 8 Schematic diagram of the test rig

The schematic diagram of the gearbox test rig utilised in this study is shown in Figure 8. Two two-stage helical gearboxes are installed back-to-back, Gearbox 1 (GB1) is used as speed reducer while Gearbox 2 (GB2) is used as speed increaser. The operational speeds needed are provided by a three-phase induction motor which is controlled by a variable speed drive (VSD), and the loads applied onto the test rig are provided by a DC generator which also connected to the VSD. Two accelerometers are employed to detect the vibration characteristics of GB1 and GB2 respectively, and both the lubricant temperature of GB1 and GB2 are monitored simultaneously to supervise the operational conditions of the gears.

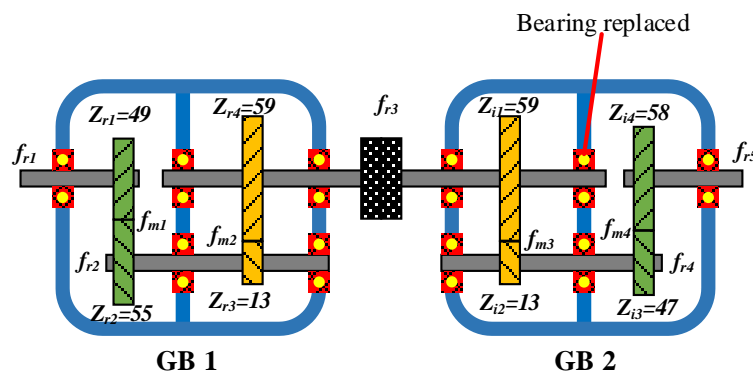


Figure 9 Schematic diagram of two gearboxes

Notes: the f_{ri} ($i=1,2,\dots$) represents the rotational frequency of the i th shaft; the f_{mj} ($j=1,2,\dots$) represents the mesh frequency of the j th stage in each gearbox, Z_{rp} , Z_{ip} ($p=1,2,\dots$) represents the tooth number of the p th gear in each gearbox.

3.2 Test procedure

Table 1 Specifications of ball bearings

Clearance grade	C2	C3	C5
Bearing Type	6207 Deep Groove Ball Bearing		
Bore Dia (mm)		35	
Outer Dia (mm)		72	
Width (mm)		17mm	
Clearance (mm)	0.006	0.028	0.051
Notation	Small-C2	Midium-C3	Large-C5

The position of the replaced ball bearing and the tooth number of the gears are shown in Figure 9. The first set of tests was conducted with the recommended ball bearing C3 which was used for supporting the input shaft of GB2. Then bearing C2 and bearing C5 with different bearing clearances were assembled to replace bearing C3 respectively. The specification of each ball bearing used in this study is shown in Table 1.

4.0 TSA analysis

Time synchronous averaging (TSA) is an effective method for reducing random noise or incoherence components in signals and widely used for vibration-based gear monitoring and diagnosis [14,15].

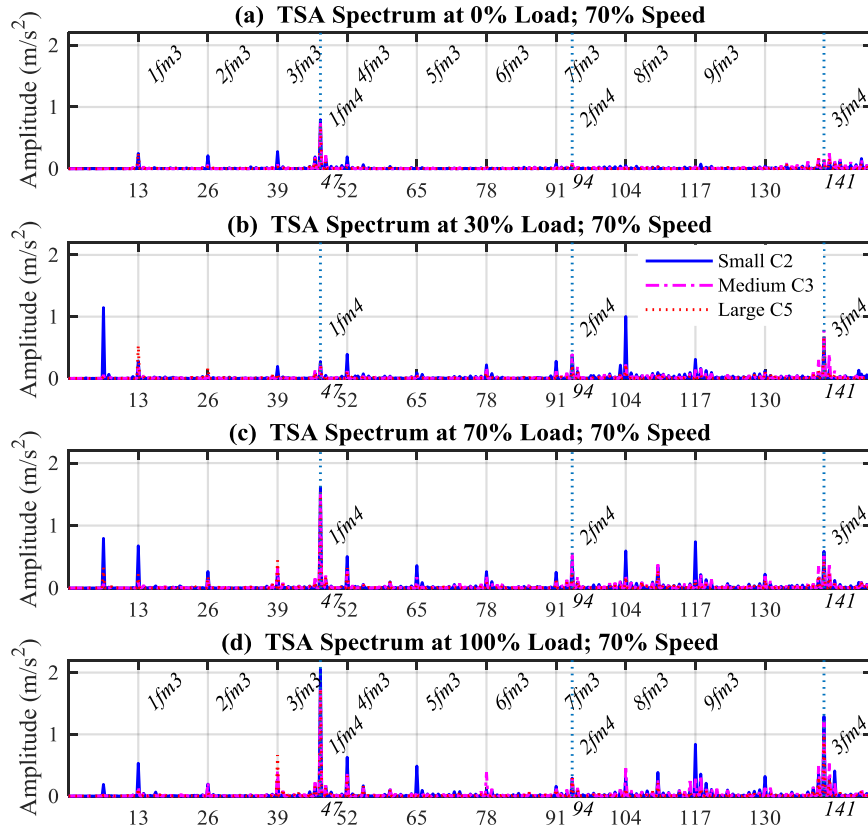


Figure 10 Spectrum of GB2 vibration at 70% speed and different loads

To extract the vibrations from the 3rd mesh gear pair, TSA is applied to the vibration signal measured from GB2. Based on the angular pulse train from the AC motor, instantaneous angles of shaft 2 are calculated and the time domain vibration signals is then decomposed onto instantaneous angles with a cubic spline interpolation. The TSA signal obtained thus can show the mesh components for both stages of gear transmits in GB2, allowing a comparison between them for showing the effects of the bearing clearances. Moreover, with the data length available the average times can be over 100 times, which is sufficient to suppress the random noise and interference components. This obtain a more accurate TSA signal, compared to that of less averages when decomposing the signal into shaft 3.

Figure 10 shows the TSA spectrum of GB2 vibration under 70% speed of the AC driving motor under different loads. Clearly, it shows that random noise is significantly suppressed, which make the mesh components much more outstanding. According to the position of the testing bearings, the vibration behaviours at the mesh frequency of the first stage in GB2 (f_{m3} for brevity) should be mostly influenced as analysis in Section2. As shown in Figure 10 the orders with multiple integers of

$Z_{i2}=13$, which is associated with shaft 3, at 13, 26, ..., 130 do show clear differences among different bearing clearance cases across the tested loads. On the other hands, the vibration at f_{m4} or at the orders of $Z_{i3}=47, 94$ and 141 show little variation. This observation shows that the small amount of bearing clearances can cause a significant influence on gear dynamics and hence mesh quality.

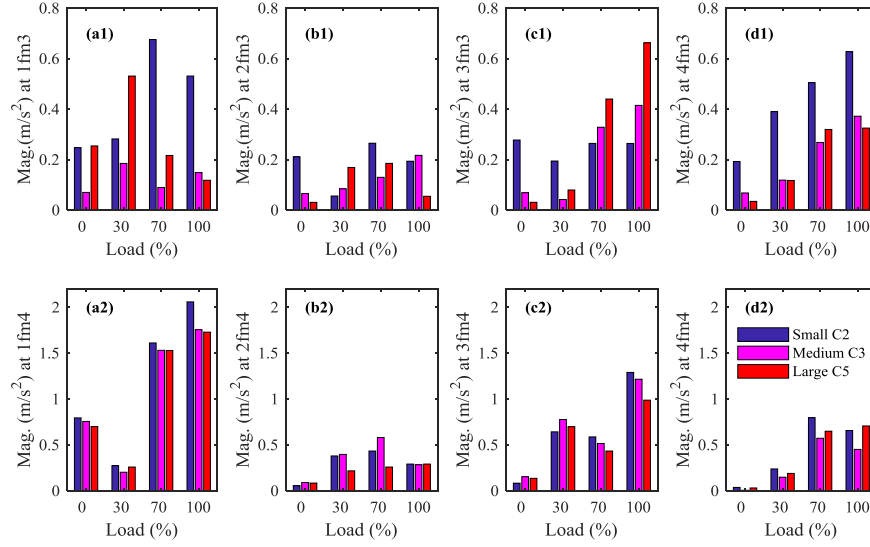


Figure 11 Amplitudes of the first four harmonics of f_{m3} and f_{m4}

To gain more detail of the changes in vibrations, the spectral components at the first four harmonics of mesh frequencies are extracted and presented in Figure 11. It can be seen from Figure 11 (a1) to (d1) that there are significant differences between different clearance cases. For the small clearance, the 1st harmonic and the 4th harmonic i.e. at $4f_{m3}$ show higher amplitudes. This may be attributed to gear eccentricity that is more sensitively reflected by gear dynamics due to less tolerances of the tight clearance. In addition, this too small clearances also likely cause more metal-to-metal contact and induce more friction forces [16]. Particularly, once the clearances become sufficiently large such as Medium-C3 and Large-C5 the vibrations at the 1st and the 4th harmonics are significantly reduced. Moreover, the amplitudes at the 3rd harmonic, shown in Figure 11 (c1) increases with the clearance values, which is consistent with the analysis made in Section 2 in that the higher loads can cause more dynamic forces. Therefore, this consistent feature can be a useful indicator for making differences between bearing clearances.

Comparatively, the amplitudes at the first four harmonics, shown Figure 11 (a2) to (d2) show little differences between different tests, which confirms that the experimental study is accurate and reliable.

5.0 Conclusion

This study focuses on the influence of different bearing clearances on vibration characteristics of gear transmission system. Both analytic analysis and experimental study have shown that vibration increases when the bearing clearances become too large as a results of progress wear during gear lifetime. In particular, TSA analysis of vibration signals obtained based on a general purpose two stage helical gearbox shows that:

- 1) Improper bearing clearance could affect the gear mesh process, like large bearing clearance could induce extra impact due to the tangential component projected from the mesh force and friction force. Meanwhile, too small bearing clearance could also cause more vibration due to high frictional forces of more the metal-to-metal contact and over-sensitive to gear errors.
- 2) According to the variation of $3f_{m3}$, when gearbox is working at low load, the small bearing clearance generates more vibration due to the metal-to metal contact and gear errors and the influence become smaller with the increase of clearances. When working at high load, the impact induced by bearing clearance will be enhanced due to the radial fluctuation effect. A clear increase of $3f_{m3}$ can be noticed in the TSA spectrum which can be used for monitoring the increase of bearings clearance.
- 3) The variation of $4f_{m3}$ also implies that with the increase of bearing clearance, the amplitude of $4f_{m3}$ reduce gradually. This illustrates that the $4f_{m3}$ is mainly influenced by the friction of bearing components, and the friction excitation induced by small bearing clearance could transmit to the mating gears, thereby influence the mesh frequency.

6.0 Acknowledge






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A Study of Diagnosing Reciprocating Compressor Faults using EMD-entropy of the Airborne Acoustic Signals

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Abstract For more effectively and less-costly monitoring of reciprocating compressors, this paper focuses on the developing of a new monitoring method based on airborne sounds which can be easily obtained in and remote way and contains richer information of an entire machine. Possible sound sources of the compressor have been examined according to the working process of mechanical motions and fluid dynamics in order to understand the sound characteristics under different operating conditions. Especially, the sound signal from the compressor is highly non-stationary due to the periodic excitation resulted by the combined effect of gas dynamics and the mechanical forces acting on the compressor associated with the random disturbances of valve motions and flow turbulence and the variations of discharge pressures. In addition, the acoustic signals are also veritably influenced by background noises which often are of unsteady. To characterise such signals for fault detection and diagnosis, Empirical Mode Decomposition (EMD), an effective tool for non-stationary signal analysis, is used to find and enhance the inherent information that correlates more to the various acoustic events involved in compressor operations. Experimental studies, carried out based on a two-stage reciprocating compressor, have shown that Intrinsic Mode Functions (IMF) from EMD can depict more of the signals to indicate the conditions of the machine. In particular, using EMD- entropy as a diagnostic parameter allows common faults such as inter-cooler leakage (ICL) and discharge valve leakage (DVL) to be discriminated and separated from the baseline operation over a wider range of discharge pressures, demonstrating that the proposed EMD acoustic signatures can be an effective approach for monitoring reciprocating machines.

Key words Condition monitoring, Reciprocating compressor, Airborne acoustic, EMD-entropy.

1.0 Introduction

Condition monitoring of a compressor based on airborne sound analysis is difficult to perform due to its high level of noise associated with it. There are many traditional approaches including cylinder pressure monitoring, valve temperature monitoring, and vibration measuring for crosshead cylinders to diagnose any abnormal behaviour of the compressor. But all these techniques are depended on installing the respective sensors to the compressor body. Acoustic measurement can be useful in this case as it can remotely record airborne sound from the compressor and cost effective as well due to its use of minimum numbers of transducer microphones compared to the other sensors. There are many approaches to look into the airborne signal for its characteristic behaviour like time domain analysis, statistical parameter estimation, frequency domain analysis, time frequency domain analysis and advanced signal processing technique.

Elhaj *et al.* [1] used instantaneous angular speed (IAS signal) in order to find out the faults from a two-stage reciprocating compressor and validated their model with the test results obtained from the analysis. Toprak and Iftar [2] placed several microphones at different places of a virtual hemi-sphere and used sound power level as a raw data input for their analysis. Analysis shows that the obtained results from the artificial neural network and multilayer perception model is capable of finding faults from the compressor. Elhaj *et al.* [3] proposed a new method for diagnosing of valve faults in a reciprocating compressor by using time domain, frequency domain and continuous wavelet transform (CWT) of the acoustic sound signals. Lowson [4] presented a theoretical analysis of the noise from axial-flow fans and compressor. Ball *et al.* [5] analysed the acoustic signals from a diesel engine using the smoothed pseudo-Wigner-Ville distribution (SPWVD) and continuous wavelet transform (CWT) and successfully detected the faults from their analysis.

Huang *et al.* [6] introduced a new signal processing technique called Empirical Mode Decomposition (EMD), a noise assisted data analysis method, completely dependent on the local characteristics of a signal. This made the analysis of the non-stationary and no-linear signals very easy and can be successfully diagnose the faults in rotating machineries [7-9]

Information entropy can be used as a successful tool in the signal processing point of view. Huang *et al.* [10] developed an intelligent fault diagnosis method of high voltage circuit breaker using improved EMD energy entropy and multiclass support vector machine. Cui *et al.* [11] used information entropy and support vector machine to diagnose the valve faults from a reciprocating compressor.

From the literature review it is found that the EMD method is very effective for the analysis of non-stationary signal and entropy can be a good choice as an effective feature tool in the diagnosing of the faults in a machine. Thus, combining these two methods might be effective for diagnosing the compressor faults by analysing the airborne sound signal recorded from the compressor.

Initially this paper focuses on the finding the noise sources generated from the compressor with clear understanding of the fluid dynamic interaction with the mechanical components and keeping in mind the non-stationarity behaviour of the

compressor noise signal, the developing of a robust fault feature extraction method based on EMD entropy to diagnose the different health conditions of the double stage single acting reciprocating compressor.

2.0 Acoustic sources associated with the compressor

To utilise acoustic signals for monitoring and diagnosis, it is necessary to understand the possible sound sources of a reciprocating compressor and their primary characteristics associating with common faults.

2.1 Basics of Sources

According to the working process of a reciprocating compressor, the acoustics can be broadly caused by aerodynamic and mechanical forces. The piston moving back and forth in a cylinder forms zones of compression and rarefaction, which formalises acoustic periodic pulsation waves that propagate through the system at the speed of sound of the gas [12]. In addition, the mass flow through the discharge or suction is further modulated to cause the pulsations and produces turbulent noise. These acoustic waves propagate through the system and are reflected due to the impedance inequality. This incident and reflected waves correspond to not only one cylinder but the other cylinder as well, which often cause acoustic resonances. The pulsation is a function of speed of sound of the gas and the frequency of the pulsation [13].

$$c = f \times \lambda \quad (1)$$

where c = speed of the sound; f = frequency and λ is the wavelength.

From more study, it can be found that there is a linear relationship between the velocity of the face of the piston and the resultant pressure. As the motion of the piston is nearly sinusoidal, the pressure wave also follows the same trend. In general, the pulsating flow responsible for the results in the increment of sound level of the compressor.

The inertia forces produced by the motion of the pistons and related part give rise to the level of vibration and noise in the RC. Imbalance of con-rod and crank mechanism is also another cause to produce vibration in compressor. Static and dynamic unbalances produced by the unbalance masses accumulated in the rotating parts of the machine is also considered as a major exciting factor that causes the vibration hence noises from the compressor body. Another major source of noise from the cylinder is the knocking sound produced by the pistons and crank con-rod system during crossover. The gap between the piston and cylinder liner permits the piston to move with a certain velocity in the transverse direction, impacting against the wall of the cylinder. These contribute to an intense vibration of the cylinder walls at their resonant frequency.

One other important acoustic source in a reciprocating compressor is its suction and discharge valves. The valve noise has oscillatory energy transmitted to the

outside through pipes and the housing shell. The compressor valve produces flow oscillations, even if it does not flutter. The suction and discharge valve system of the air compressor consist of a stainless-steel ring plate of high tensile strength riveted to a valve assembly block. During the compression and expansion cycle air is forced through a set of ports located in the valve assembly block and directed against the valve element. The valves open, dump mass into the discharge system or take it from the suction system, close, and after one cycle, open again. As a result a valve knocking sound is produced.

Although these mechanical and aerodynamic forces are dominant, the driving motors and transmission system also contribute to the overall acoustics of a compressor.

2.2 The effect of faults on acoustics

One of common faults in compressors is the air leakage, which usually happen on various valves and pipeline joints. In this study, intercooler leakage (ICL) and discharge valve leakage (DVL), which are more typical due to the high vibration and thermal shocks, are examined for the evaluation of acoustic based condition monitoring.

Influence of ICL:

If there is a leakage in intercooler, the pressure drops in the system. The intercooler leakage causes a significant pressure drop in the first stage cylinder and reduces the force to keep the discharge valve closed. As a result, the discharge valve opens earlier for the first stage and causes delay in the opening of discharge and suction valves for the second stage. Insufficient pressure causes the second stage suction valve improper lifting and results in valve fluttering. The insufficient gas flow pressure causes the valve descending back to its closed position very late compared to its rise time and Flutter occurs. This phenomenon creates an audible noise which can be heard as a clattering sound generated from the compressor. Moreover, the leakage flow streams also create broad band sound due to turbulences.

Influence of DVL:

In case of discharge valve leakage, the mass flow takes place across the cylinder through the leakage because of the constant area of opening in the form of leaking area. Hence this leaking mass flow rate depends on the pressure difference across the valve. Until the valve is closed this area remains constant. During this time the pulsating pressure increases as the compressed pressure passes through the discharge valve and increases the air pressure in the pipe resulting an increasing pressure difference between reservoir and pipe. The fluid flows in the opposite direction to its regular state. The back flow in this case can contribute to the turbulence of the gas flow resulting in pulsation. Valve also generates pressure pulsation because of its vibration and the resulting pressure will mainly be in the natural frequency range of the valve. As a result, resonance of the valve occurs. Due to the pulsation the impact velocity of the valve plate against the seat increases. Short

pulsation can cause high valve impact. These resonating sound and valve impacts have a rich influence for the radiation of noise through the compressor shell.

The acoustic signal from the compressor is highly non-stationary due to the periodic excitation resulted by the combined effect of the gas dynamics and the mechanical forces acting on the compressor associated with the random disturbances of valve motions, flow turbulences and the variations of discharge pressures. This phenomenon gives rise in the randomness or complexity in the airborne signal recorded from the compressor.

3.0 Experimental set up

The experiment is carried out on a two-stage single acting reciprocating compressor identified as the Broom Wade TS9 and is represented in Figure 1 below. This machine has proven suitable for condition monitoring purposes over the years. The V-shaped reciprocating compressor chamber is made up of two cylinders positioned at an angle of 90° to each other giving it the V-shape. These cylinders are tailored to deliver compressed air between 5.5 bar (0.55Mpa) to 8.3 bar (0.8Mpa) to a horizontally positioned receiver tank with a maximum capacity of 13.8 bar (1.38Mpa). Also included in the compressor chamber is an intercooler coil connected from the first stage cylinder (after discharge) to the second stage cylinder (before suction). The compressor chamber is powered by a 2.5KW three-phase induction motor, which transfers electrical current to the compressor pulley to mechanical move the crankshaft.

Two different faults have been simulated: inter-cooler leakage fault and discharge valve leakage fault. One microphone sensor has been used to record the airborne signals placed at 60 cm distant from the main compressor body.

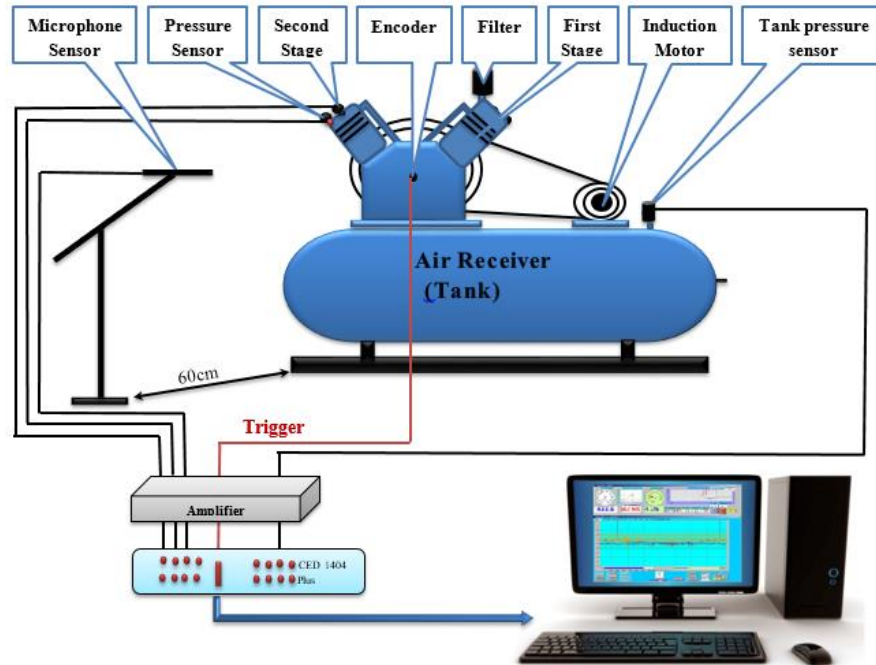


Figure 12 Schematic diagram of the compressor test rig.

The noise from the compressor propagates as longitudinal waves through the elastic air medium. The sound waves cause changes in the air pressure and can be recorded with pressure sensitive instrument like microphone. The sound pressure that we heard is dependent on the distance from the source and the acoustic environment in which sound propagates [12]. If the sound comes contact with a surface some portion of the sound is reflected and some is absorbed. Hence the measured sound pressure is partly consisting of sound that generates from source and partly of the sound that is reflected by surrounding surfaces. As sound propagates outwards from the source its' energy get dissipated and becomes weaker the further it travels from the source. The shape of the sound wave with no obstacles in its way is approximately spherical. This condition is often termed as 'free field' condition where the energy emitted at a given time will diffuse in all directions and, one second later, will be distributed over the surface of a sphere of 340 m radius [13].

A simple point source radiates uniformly in all directions. In general, however, the radiation of sound from a typical source is directional, being greater in some directions than in others. The directional properties of a sound source may be quantified by the introduction of a directivity factor describing the angular dependence of the sound intensity. To avoid the near field effect the sound measurements are made at a sufficient distance from the source which is usually greater than 1m [13].

Whenever sound waves encounter an obstacle, such as when a noise source is placed within boundaries, part of the acoustic energy is reflected, part is absorbed

and part is transmitted. The relative amounts of acoustic energy reflected, absorbed and transmitted greatly depend on the nature of the obstacle. Different surfaces have different ways of reflecting, absorbing and transmitting an incident sound wave. The higher the proportion of the incident sound reflected, the higher the contribution of the reflected sound to the total sound in the closed space. As the surfaces become less reflective, and more absorbing of noise, the reflected noise becomes less and the situation tends to a "free field" condition where the only significant sound is the direct sound. In practice, there is always some absorption at each reflection and therefore most work spaces may be considered as semi-reverberant. The phenomenon of reverberation has little effect in the area very close to the source, where the direct sound dominates [13].

Due to the physics behind the propagation of sound it is very important to place the microphone sensor in a proper position. Keeping in the mind, the reverberation, directional propagation property of the sound, the microphone sensor has to be placed at some position where the direct sound dominates and nearly free field property exists. As well as from a study of the proper placement of microphone sensors for identification of RC noise it has been found, that there are three locations where noise response found to be good: first is over the cylinder head, second is at NRV (Non-Return Valve) side, third one is at opposite of NRV side and fourth one is at the opposite side of the flywheel [14].

In this present investigation one microphone sensor was placed at a distance of 60cm from the compressor body at the side opposite to the flywheel minimising the effect of directional propagation and reverberation property of the sound.

4.0 Methodology

In this study, EMD based entropy method has been used to find out the difference between the health conditions of the compressor under a range of operating discharge pressures like 60 psi, 70 psi, 80 psi, 90 psi, 100 psi, 110 psi and 120 psi.

An adaptive signal processing method Empirical Mode Decomposition has been used in this investigation. EMD decomposes a time domain signal into several intrinsic mode functions preserving the frequency components from the original signal in each mode of oscillatory function. As the name suggests the process is empirical which implies that the decomposition is based on the local characteristics of the signal. Thus, it can be effective for non-stationary signals like the airborne signal from the compressor body. The method is found to be superior and different from the traditional techniques like Short Time Fourier Transform (STFT) and Wavelet transform (WT) used for non-stationary signal analysis. The STFT process assumes some portion of the signal as stationary and performs FFT for the windowed segments of the signal and in Wavelet transform there are different types of wavelets available that are used to match the signal behaviour. The WT method is based on the basis functions. Therefore, prior knowledge about the acquired signal is necessary to apply this method, whereas EMD does not require any basis function and is purely adaptive in nature. This kind of data driven tech-

nique makes it easier to analyse any kind of signal whether it is non-stationary or non-linear.

EMD splits a raw signal into several subsets of IFMs. More details can be investigated with these IFMs, which allows key features to be extracted for discriminating different scenarios for fault diagnosis.

Step 1: If $C_1, C_2, \dots, C_b, \dots, C_N$ be the IMF components obtained by the EMD method for different datasets, then the energy and energy ratio of these IMF components are calculated as follows:

$$E_i = \sum_{n=1}^{N_i} C_i(n)^2 \quad (2)$$

$$P_{Ei} = \frac{E_i}{\sum_{i=1}^N E_i} \quad (3)$$

where E_i is the energy of the i^{th} IMF component; N_i is the number of sample points present in the IMF; P_{Ei} is the energy ratio for i^{th} IMF component; N is the total number of IFMs generated by the EMD process.

Step 2: Form the energy ratio vector P_E by putting all the energy ratios for individual IFMs.

$$P_E = [P_{E1}, P_{E2}, P_{E3}, \dots, P_{EN}] \quad (4)$$

Step 3: Find the entropy of the energy ratio vector $E_{entropy}$.

$$E_{entropy} = -\sum_{i=1}^N P_{Ei} \log_2 P_{Ei} \quad (5)$$

Step 4: Consider four different datasets for each machine condition and determine the average entropy value for respective tank pressure.

5.0 Results and Discussion

5.1 Change of cylinder pressure

The effect of the simulated faults on in-cylinder pressure at 120 psi is shown in Figure 2. The intercooler and discharge valve leakage faults cause a change in the pressure waveform in both stages.

When the intercooler leakage occurs the pressure inside the 1st stage cylinder is lower than the baseline one. This causes a reduction of force to keep the 1st stage discharge valve closed. Thus, the discharge valve opens earlier in 1st stage cylinder with intercooler leakage fault.

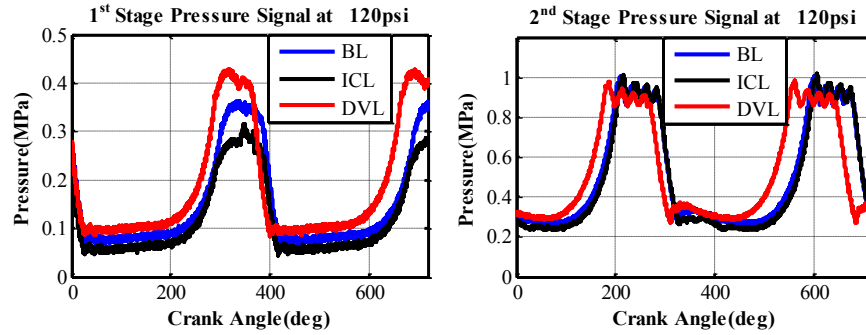


Figure 13 1st stage and 2nd stage pressure comparison for different compressor health conditions at 120 psi.

As for the 2nd stage, the intercooler leakage causes a small change in the cylinder pressure; the pressure inside the cylinder is lower than in healthy operation. This will result in reduction in discharge efficiency. The drop in the cylinder pressure causes a delay in the opening of both suction and discharge valves.

On the other hand, discharge valve leakage leads to a slight but significant increase in the pressure of the first stage cylinder compared to the leaky valve (intercooler leakage) and healthy operations. This increase in the cylinder pressure causes the first stage suction and discharge valves to open early due to the higher pressure in the cylinder. The second stage discharge valve leakage causes the both valves open and close earlier than for the healthy operation. The discharge valve leakage fault causes the second stage cylinder pressure to build-up earlier than the healthy operation; thus, the process of discharge occurs earlier.

5.2 Acoustic waveform analysis

The airborne sound signal from the compressor with different health conditions at different pressures has been acquired by the microphone installed at 60 cm distant from the compressor body. The comparison of the time domain acoustical waveform for different health conditions at the pressure of 120 psi has been shown in Figure 3.

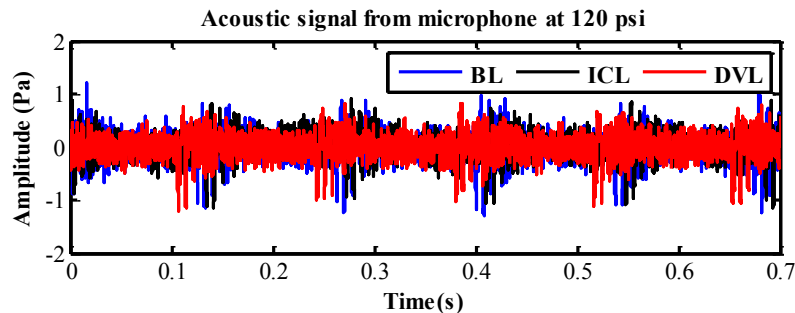


Figure 14 Time domain acoustic waveform comparison at 120 psi.

From the analysis of the above figure it can be shown that the waveforms of the baseline (BL), intercooler leakage (ICL) and discharge valve leakage (DVL) has some differences with each other. The time differences between the excitation of the signals shows a clear difference between the machine conditions. These excitations are caused by the opening and closing of the valves. From the time domain waveform representation, it can be seen that opening of the valves with different machine conditions follows the same trend obtained from the pressure analysis in the previous subsection. Result shows that the opening of the valve in case of discharge valve leakage is the earliest whereas, for intercooler leakage the delay time for opening the valve is maximum. Though it is hard to reach a conclusion about the machine conditions because the opening and closing of the valves also depend on other factors, the time domain waveform analysis is not sufficient to differentiate between the compressor conditions. Further advanced signal processing method is required to diagnose the faults in a compressor.

5.3 EMD of the acoustic signal

As the compressor sound signal is highly non-stationary due to the periodic excitation resulted by the combined effect of gas dynamics and the mechanical forces acting on the compressor associated with the random disturbances of valve motions and flow turbulences and the variations of discharge pressures, from the literature review it has been found that the data driven technique EMD is very effective for non-stationary and non-linear application hence the proposed method based on EMD has been applied to find out the faults from the compressor. Figure 4 shows the first five intrinsic mode functions (IMFs) obtained from the EMD process for different machine conditions at the pressure of 120 psi.

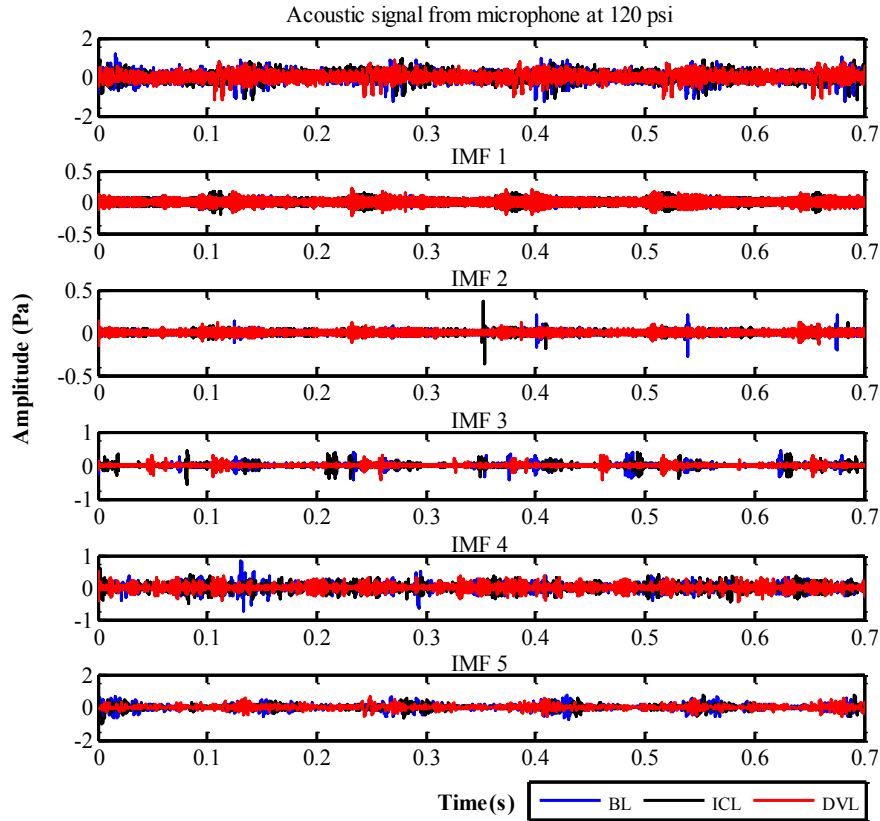


Figure 15 Decomposed IMF signals for three different compressor conditions at the pressure of 120 psi

From the Figure 4 it has been seen that the decomposed IMFs from EMD show the randomness of the signals whereas, normal time domain signals fail to show the property. Randomness is a phenomenon which gives an indication of how randomly a signal changes over the time. Generally, the sound signal from the compressor has a periodic behaviour due to the steady rotational motion of the mechanical systems. This periodic phenomenon can be seen in Figure 3. Due to the instable and turbulent fluid force the sound signals contain some sort of randomness which cannot be identified from the time domain analysis, whereas, EMD analysis makes it possible to identify that property in the IMFs generated by the process (Figure 4). In both occasion, the baseline and the faulty conditions with ICL and DVL show some sort of randomness in signal information obtained from the decomposed IMFs by EMD process. Especially if the 5th IMF for different machine conditions are plotted separately with less time duration the randomness of the signals are clearly visible in Figure 5.

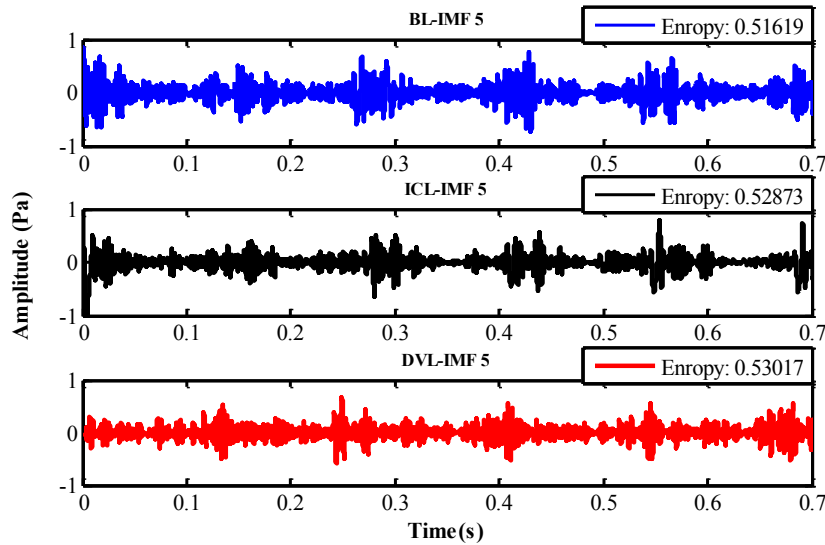


Figure 16 Decomposed third IMF at 120 psi show its randomness property for different compressor conditions.

5.4 EMD-Entropy calculation

Entropy is a parameter which measures the randomness of the signal. More randomness means less information, less organized which results in an increase of entropy values in this case. Provided that a faulty compressor can cause more randomness in acoustic signals due to turbulence flows, the entropy of the decomposed IMFs has been chosen as a feature parameter in this analysis. Though the concept of entropy and RMS looks like same, but there is an obvious difference between the two. The statistical parameter RMS of an acoustic signal provides an average loudness. This describes the strength of a signal. The RMS value is only related to the signal amplitude. The root-mean-square pressure is most often used to characterize a sound wave because it is directly related to the energy carried by the sound wave, which is called the [intensity](#). The intensity of a sound wave is the average amount of energy transmitted per unit time through a unit area in a specified direction. The RMS pressure is most often used to characterize sound waves that have the simple shape. Not all sound waves have such simple shapes, which contain only one [frequency](#). Especially in compressor the non-stationary behaviour of the sound signal and its change in amplitudes over time gives an overall energy content of the signals while measure the RMS value. The results obtained from the RMS and entropy values are compared and shown in Figure 6.

Four sets of data for each condition have been considered in the analysis. Finally, the average RMS and entropy values from the four datasets for baseline, inter-cooler leakage and discharge valve leakage faults have been calculated for a broad range of pressures from 60 psi to 120 psi and are shown in Figure 6. From the re-

sults it has been shown that there is a clear separation of the compressor machine conditions while analysing entropy values whereas, RMS value does not give the clear indication of the machine conditions as it's not reliable.

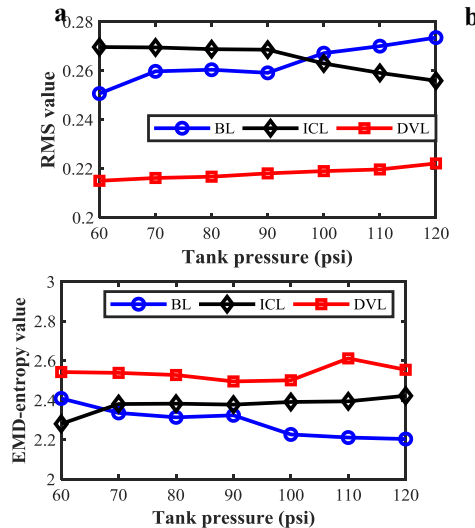


Figure 17 (a) RMS values with changing tank pressure, (b) Entropy values correspond to the tank pressure for different conditions.

From the Figure 6(b), the physics behind the noise generation for different machine conditions can be explained by the change of energy entropy with the increasing tank pressure.

At low pressure, the performance of the compressor is not stable and this is reflected in the pressure range of 60-70 psi. The energy entropy in the particular low pressure zone for different machine conditions is inconsistent. At the intermediate pressure zone (70-90 psi), the working of the compressor system is normal and the energy entropies for the respective machine conditions almost follow a straight line path. There are no abrupt changes of the entropy values in this pressure region. At high pressure (>90 psi), the severity increases and it is noticeable that the entropy values for ICL and DVL are much higher compared to the baseline and an increasing trend in entropies for both the fault conditions is recorded with the corresponding pressure whereas, when the compressor works in a normal condition the sound generated from it is more organized and as the pressure increases it works more smoothly. That indicates the decreasing of entropy values with the pressure in case of baseline condition.

The sound mechanism in the presence of ICL and DVL can also be explained from the results obtained from the analysis.

Presence of ICL fault: The presence of this kind of fault causes a significant pressure drop in the first stage cylinder and can be shown in Figure 2. As a result, a delay is caused in the opening of the suction valve and can be shown in the time

domain waveform of the acoustic signal (Figure 3). Any presence of fault increases the randomness of the signal and the entropy values go up. The same thing is noticeable in Figure 6(b), where the ICL fault has the higher entropy values than the normal baseline condition.

Presence of DVL fault: The presence of this kind of fault increases the pulsating pressure as the compressed pressure passes through the discharge valve. This increases the air pressure in the pipe resulting an increasing pressure difference between reservoir and pipe. The back flow in this case can contribute to the turbulence of the gas flow resulting in pulsation and produces noise. This turbulence results in the increase of entropy values for the airborne signal recorded with this seeded fault and from Figure 6(b) it can be found that this kind of fault has the highest entropy values due to the pulsation occurred.

From the analysis, it is confirmed that the entropy values change with the increase of pressure conditions. The increasing value of the entropy with the increase of tank pressure indicates the severity of the simulated faults with the pressure change. The entropy values for three conditions of the compressor show a clear separation among them. From the analysis result, the proposed method based on EMD-entropy is found to be effective for diagnosing faults in the reciprocating compressor.

6.0 Conclusion

This paper focuses on the study of airborne sound signal characteristics for the diagnosis of faults in a reciprocating compressor. The experimental results have shown that the acoustic signal contains rich information reflecting the differences of simulated fault cases but it is highly non-stationary due to a combination of different sources including various noises. An effective signal processing method, EMD, is used to detail the insight of the signal where the randomness is clearly identified, and therefore EMD-entropy is used to quantify the amount of randomness present in the signals for three different cases. The diagnostic results show that the entropy values provide a better separation between the faulty cases, compared with the conventional RMS analysis, demonstrating acoustic based condition monitoring can be more efficient, along with its simplicity of signal acquisition.

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Educational building technical system retrofitting - IAQ and maintenance considerations

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Abstract Specially since the beginning of the century, buildings, their systems and equipment have evolved becoming progressively complex, which stresses the importance of buildings infrastructures maintenance and its role in cost control, savings in materials, and lifetime enlarging of equipment and facilities.

Concurrently, much of our time is spent inside buildings, and over the last years users became more demanding and aware on issues related to Health, Safety and Comfort. Subsequently, Indoor Air Quality (IAQ) have become increasingly important, not only when considering the existence and concentration of pollutants but also by taking into account the level of comfort and the perception of users about the quality of the air one breathes. The effects of a poor IAQ are usually translated with complaints or symptoms such as headaches, fatigue, nose and throat irritation, eye inflammation, allergies or concentration difficulties.

For the particular case of educational buildings, both for new buildings and for school facilities framed in some retrofitting state programs, active systems for indoor air-conditioning play an important role promoting the right conditions for IAQ and thermal comfort. The indoor air conditions can have a significant impact on health, student learning as well as on staff members' performance, and therefore the adequate management of spaces, installations and equipment has a significant contribute for the educational and scholar success of each student.

In this context, holistic retrofit solutions must always take into account the promotion of IAQ, energy efficiency and energy-savings opportunities as well as maintainability or restrictions related to assets management.

This paper presents some results of an IAQ analysis carried out following requests from a local administration, as well as some of the corrective measures suggested for a school building.

The full version of this paper presents a comparison between the IAQ conditions before and after the implementation of some proposed corrective measures, considering the comparative discussion between the measured values and the legal framework, namely the Decree Law n°. 118/2013, concerning the System for Energy and Indoor Air Quality Certification. It is also presented a study regarding the passive performance of some spaces with respect to the air renewal passively achieved.

Key words Asset Management, Health, Safety & Environment, Indoor Air Quality, Maintenance Organisation, Maintainability.

1.0 Introduction

According to the Portuguese law for the Educational System, the dimensions of educational buildings must provide the possibility to receive a reasonable number of students, in order to guaranty the necessary conditions for a good pedagogical practice and to promote a true scholar community. Simultaneously, the management of spaces, installations and equipment, human and material resources, as well as financial and administrative management, should contribute to the education and scholarly success of each student. To accomplish that, fundamental areas such as Fixed Equipment, Building Structure, Safety, Technology and Maintenance must be considered in a well-balanced way. [1,2].

Portuguese educational system has changed significantly over the last decades, and for preparatory and primary schools the Portuguese policy led to a major transfer of responsibilities to municipalities or townships. Such responsibilities are related, not only to educational planning and financing of constructions, but also to maintenance and material operation of educational buildings, their technical systems and equipment [3].

Economic factors often tend to regulate options, but it must be undertaken that public expenditure control measures do not stand only in financial ones. Without an effective coordination regarding planning and administration, and without the necessary investments in school preservation, keeping them in good state of conservation, their progressive degradation will inevitably lead to assets precociously degradation and the need for their substitution [2]. Even when considering new edifications, it must be considered the evident need for an adequate budget for maintaining schools in good state of conservation, preventing deferred work, which results in a progressive deterioration of existing school buildings and equipment, and in some cases precocious degradation, until a state that requires their substitution [2, 3].

An equipment failure, bad dimensioning or bad operation conditions may interfere directly in the organisation economics. Moreover, in addition to reducing the overall availability of buildings installations and technical systems and equipment,

it may simultaneously interfere with occupants' safety (students, teachers and other personnel), as well as occasional users (for example students' guardians). Concurrently, in our days much of our time is spent inside buildings, and over the last years users became more demanding and aware on issues related to Health, Safety and Comfort. The effects of a poor IAQ are usually translated with complaints or symptoms such as [4]:

- Sleepiness or fatigue,
- Headaches, dizziness,
- Irritation of mucous membranes,
- Irritation and/or inflammation of the eyes,
- Irritation of nose and/or throat,
- Coughing or sneezing,
- Rhinitis or nasal congestion,
- Nausea,
- Lack of concentration,
- Poor physical and psychological disposition.

Subsequently, Indoor Air Quality (IAQ) have become increasingly important, not only when considering the existence and concentration of pollutants but also by taking into account the level of thermal comfort and the perception of users about the quality of the air one breathes.

An adequate dimensioning of both passive and active systems, their operation, but also the user's behavior when using them, is critical to guaranty the proper IAQ, reason why the maintenance of such systems pay such an important role. Simultaneously, since the beginning of the century, buildings, their systems and equipment have evolved becoming progressively complex, which stresses the importance of buildings infrastructures maintenance and its role in cost control, savings in materials, and lifetime enlarging of equipment and facilities.

All physical assets, namely equipment, go over several phases during their life cycle, as referred in Table 1. To be implemented in an ideal way, the maintenance should therefore be taken into account from the initial phase of any project or installation, being thus possible to study and analyze the assets previously, ensuring their proper functioning during the operational phase.

Table 1. Stages in the life cycle of an asset [3] [5][6]

Life cycle Stages	Preparatory	Idea, Conception and Designing Manufacturing and Assembly Procurement and Installation Test Acceptance and Commissioning
	Operational	Service / Use Maintenance Promotion Planning Closure Disposal

It is important for managers to improve maintenance performance of educational facilities, focusing on areas such as maintenance, building systems, safety improvements and technology, if possible anticipating problems and opportunities in time. To accomplish all these goals, educational and teaching organisations must be determined to manage their available resources effectively, and to seek improvements for increased efficiency. At the same time, it's vital that they implement a regularly scheduled detailed maintenance plan for all assets [7].

For the case of educational buildings, both for new buildings and for school facilities framed in some retrofitting state programs, active systems for indoor air-conditioning play an important role promoting the right conditions for IAQ and thermal comfort. The indoor air conditions can have a significant impact on health, student learning as well as on staff members' performance, and therefore the adequate management of spaces, installations and equipment has a significant contribute for the educational and scholar success of each student.

Considering the complexity of the Educational System, there is an obvious need to review management and administration models, applying the principles of the Educational System Foundation Law published in 1986, particularly the principle of institutional autonomy [3, 7-12].

In this context, holistic retrofit solutions must always take into account the promotion of IAQ, energy efficiency and energy-savings opportunities as well as maintainability or restrictions related to assets management.

The information presented here refers to a study developed following the request of a local administration, which requested an IAQ study in one of its buildings, after receiving complaints from the occupants, referring to two distinct spaces: library and free time activities room (ATL room).

This paper presents some results of the IAQ analysis carried out, as well as some of the corrective measures suggested for a school building.

The full version of this paper presents a comparison between the IAQ conditions before and after the implementation of some proposed corrective measures, considering the comparative discussion between the measured values and the legal framework, namely the Decree Law n°. 118/2013, concerning the System for Energy and Indoor Air Quality Certification. It is also presented a study regarding the passive performance of some spaces with respect to the air renewal passively achieved.

2.0 Technical Conditions and Legal Framework for IAQ

When contaminated, the air inside buildings is responsible for a high percentage of respiratory problems, skin allergies and infectious diseases. There may be specific and non-specific symptoms but usually the signs and symptoms involved in poor Indoor Air Quality (IAQ) are usually translated with complaints or symptoms such as headaches, fatigue, nose and throat irritation, eye inflammation, allergies or concentration difficulties, as aforementioned. Although these symptoms and complaints may often be attributed to colds, noise, overcrowding,

improper lighting, ergonomic conditions and professional stress, it is important to note that in most cases the symptoms are due to poor indoor air quality.

The protection thresholds and reference conditions are set out in tables I.08 and I.09 of the Ordinance 353-A/2013 [13, 14]. The methodology used for the analysis of Indoor Air Quality is described as follows [4]:

1. Definition of measuring points;
2. Measurement of the following parameters:
 - Suspended particles in the air: PM10 - Limit value 50 $\mu\text{g}/\text{m}^3$; PM2,5 - Limit value 25 $\mu\text{g}/\text{m}^3$. Tolerance Margin (TM) of 100%.
 - Carbon Dioxide (CO₂) - Limit Value 2250 mg/m^3 ; 1250 ppm. TM of 30%
 - Carbon Monoxide (CO) - Limit Value 10 mg/m^3 ; 9 ppmv.
 - Total Volatile Organic Compounds (TVOC's) - Limit Value 600 $\mu\text{g}/\text{m}^3$; TM of 100%.

The assessment of the conditions for Thermal Comfort (TC) and IAQ was based on the Portuguese legal framework [4, 13-19]:

- Article 273° of Law 99/2003 of 27 August, which establishes the general obligations of the employer [15];
- Decree Law n°. 118/2013 of 20 August, which approves the Buildings Energy Certification System, the Energy Performance Regulations for Housing and Buildings Regulation of Energy Performance of Buildings Trade and Services [13].
- The evaluation of IAQ focused on the parameters set by the abovementioned Ordinance 353-A/2013[14];
- Decree-Law 243/86 of 20 August, approving the General Regulation of Health and Safety at Work in Commercial Establishments, Offices and Services [16];
- ISO 7730, which establishes an objective criterion for evaluation of thermal comfort using calculation of the PMV and PPD indices [17];
- NT-SCE-02, which presents a Methodology for periodic audits of IAQ in existing services buildings, within the RSECE [18];
- ISO 8995-1: 2002 (CIE S 008/E:2001), which establishes the regulation on lighting of indoor work places [19].

3.0 Case Study

The requested audit to the IAQ was preceded by a third-party evaluation. Based on their former results it was decided to adjust the methodology proposed by law [13, 18]. Although it was technically possible to follow this methodology, the present study was carried out in a complementary way to the one that would be drawn without this information [20].

The overall study was conducted in three distinct periods as resumed in Table 2:

Table 2. Data collection periods [4][20][21]

Year	month	days
2016	March	14, 15 and 16
2018	April	10, 11, 12, 13 and 14
2018	June	26 and 27

3.1 The Educational Building and the study approach

Figure 1 shows the top view of the school (satellite photography) with indication of the cardinal points for a better perception of the orientation of the school [4, 20, 21].

Continuous and punctual measurements were carried out inside the school:

- Continuous Measurements: Library and 2nd ATL Room;
- Spot measurements: Corridor, rainwater box, 1st floor room, sanitary facilities, cafeteria, gymnasium.

Complementary measures were taken outside, in the spot metering locations presents in Figure 1, namely in: Stormwater boxes around the school grounds (next to the library and ATL rooms, next to the stairs and gymnasium, access ramp to the back of the school, playground next to the orange room, school management site), roof drop tubes and boiler chimney.

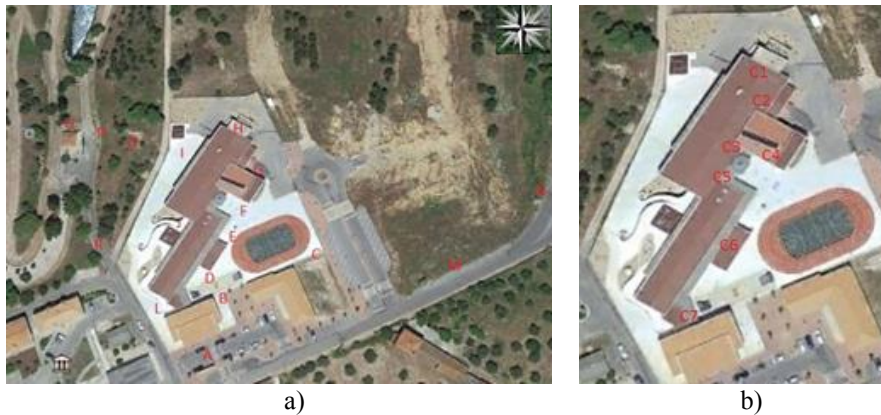


Figure 1. School Center under analysis: a) Spot metering locations; b) Measuring sites (Spot metering locations) in coverage.

3.3 Some suggested Retrofitting and some Results

The corrective measures recommended and implemented, however, are:

- Ventilation of the Pluvial Net with the installation of secondary ventilation tube next to the pluvial box next to the gas tank, as illustrated in Figure 2.
- Siphon installation in the sewage of the fan coils. According to information provided, all the fancoil units in the building were submitted to this correction.
- Sealing covers rainwater boxes. All boxes were sealed with a mastic type solution.
- Two drop tubes were identified as the preferred inputs of the pollutant, on the roof near the entrance door / access to the playground and above the multipurpose window. The option in this case was to cut the discharge pipe, shown in Figure 3. The implementation of the above corrective measures proved to be effective in improving indoor air quality, minimizing the effect of previously identified external contamination.



Figure 2. Secondary ventilation tube of the rainwater network.



Figure 3. Polyvalent drop tubes.

Although the results obtained are encouraging in relation to the infiltration of pollutants inside the school space, the tests carried out here should be repeated at the time of the rains, as well as in a school period with normal functioning of the establishment, suggesting in this case that the scope of be extended to thermal comfort [20, 21].

To achieve sustainable results, it is essential to ensure that behavioral and preventive measures are taken: the involvement, participation and effort of all stakeholders will be crucial [4, 20, 21].

In order for the results to be achieved over time, special attention should be paid to the following recommendations: [20, 21]:

- The recommendation to create a suitable maintenance record system and a suitable preventive maintenance plan;
- The renovation of air (through the opening of doors and windows), whenever possible in order to ensure good air quality - this measure was identified as a rule meanwhile implemented in the school center and recommended to be maintained.

- To study the need to implement a mechanical system in order to make air renewals viable, considering the ideal minimum airflow rates, according to the Annex to Administrative Rule no. 353-A / 2013;
- Adopt procedures to ensure the minimisation of paper storage, as well as selecting "ecologically clean" furniture and decoration materials
- Periodic checks of indoor air quality, taking into account the characteristics of the building. Such checks shall include at least: i) measuring the concentrations of the pollutants covered I.08 and I.09 tables Order No. 353-A / 13 of December 4, as well as, where appropriate, additional measurements from other hazardous pollutants; (ii) assessment of HVAC cleaning conditions, including maintenance actions such as checking the condition / effectiveness of the filters and visual inspection / measurement of dirt (dust).

4.0 Conclusion

The list of health problems and symptomatology associated with poor indoor air quality are important factors that justify inspections and analyzes to measure compliance with the air quality indexes we breathe inside buildings. In order to meet the legal requirements for the reduction of possible risks to public health, there is a need to control sources of pollution, to take appropriate preventative measures, both at the design and rehabilitation of buildings, and that preventive measures are taken in the operation of buildings and technical installations during their operation.

Therefore, it is important to focus on areas such as maintenance, technology, safety improvements, infrastructure and building systems, leading managers to improve maintenance performance of these organisations, if possible anticipating in time problems and opportunities.

This paper presents the results of a study regarding an Educational Buildings, specifically the ones concerning retrofitting actions to improve the IAQ. It identifies some areas needing improvements, as well as the suggestions made to improve maintainability, regarding technical solutions but also management, decision making and strategies employed in maintenance management, among others.

For the particular under analysis, the correct functioning of the air conditioning units of the space is fundamental to guarantee the thermal comfort of its occupants, to maintain acceptable levels of energy efficiency of the air conditioning systems and, in addition, to allow the interior spaces are not contaminated by the rainwater network.

5.0 Acknowledgement

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Authors' Biography

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An iterative process to extract value from maintenance projects

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Abstract Research and development projects are producing novel maintenance strategies and techniques. Anyway, it is not straightforward to transfer results from the lab to the real world, and thus many projects, both internal to a company and in cooperation between the members of a consortium, speculate how to perform this feat, called “exploitation” in the context of European projects. This paper discusses the necessity of novel techniques in modern maintenance, and then introduces a novel approach to the problem of transferring innovation from the lab to the market. The novel approach spawns from the “spiral software development” process and proceeds as a set of iterations that bring together different stakeholders to increase the number of products, techniques and results in general that can survive the end of a research and development project. The approach was applied to a large European project, which is described as use case, and the paper reports on the encouraging results that were attained.

Key words Exploitation, Research Projects, Machine Maintenance, Case Study; Advanced Maintenance.

1.0 Introduction

Maintenance came to prominence, in the last few year, as an important activity that can benefit companies, instead of a “necessary evil”. In fact, novel approaches such as maintenance-as-a-service (MaaS) and condition based maintenance (CBM) can provide new sources of income and save a great deal of time and money respectively.

Many research activities are currently active all over the world to advance current techniques for maintenance, and are advancing state-of-the-art by great lengths. On the other hand, there is an intrinsic gap between the lab and the real world, since the acceptance by the industry of new techniques depends on the existence of real-world applications of the techniques, which on its part requires the stakeholders to commit to creating applications and thus investing in them. Finally, to invest in a novel technique, the stakeholders must have accepted it, which creates a vicious circle. The problem appears in both research and development projects internal to a company, and to collaboration between multiple stakeholders.

To break this vicious circle, one solution is implemented by the Ecsel Agency of the Horizon 2020 program for European international research projects. Its approach is to finance collaboration between different international partners that end up being stakeholders to the project, with the financing depending on the creation of applications of the techniques in real environments. Anyway, in many cases the lifespan of a research project is not enough to ensure the creation of products, and there is no assurance that a company will provide continuity to the innovation created by a project. Therefore, most research and development project have, among their activities, the study of the potential exploitation of the project’s results.

Current processes to identify exploitable results are either ad-hoc, or based on a very rigid structure, and sub-optimal, since the number and extent of identified exploitable results end up being limited.

Inspired by modern software development processes, this paper proposes a novel approach to the problem of identifying exploitable results in a research and development project. The proposed approach is iterative, and considers to repeat a number of steps for multiple iterations, to grow and refine the list of potential exploitable results periodically, and measure their potential, until reaching convergence over further iterations. In each iteration, different stakeholders are brought together to analyze the exploitation list, with the goal of maximizing the number of products, techniques and results that can survive the end of a research and development project. The approach was applied to a large European project on maintenance called MANTIS (Albano, Papa, Jantunen, & Zurutuza, 2018), and the paper reports on the results from the exploitation point of view.

The rest of the paper provides background information in section 2 on the potential for advanced maintenance. Section 3 describes the MANTIS project, which aims at pushing forward the state-of-the-art of collaborative and proactive maintenance, and advanced maintenance in general. Section 4 describes and provides

motivation for the proposed iterative process, and Section 5 describes how it was applied to the MANTIS project, and the results it provided. Finally, Section 6 discusses the results and provides a preliminary comparison to different approaches applied in similar projects, and concludes the paper.

2.0 Applying Maintenance advances in the Real World

This section discusses the importance of maintenance, and in particular starts from an analysis of current maintenance practices and their importance for the industry. Thus, it motivates the execution of research and development projects to push forward innovations in maintenance that can provide value.

Later on, the section delves into details regarding advanced maintenance practices. It turns out that many activities are pushing forward the state-of-the-art, and thus we can be on a turning point for maintenance.

Anyway, extracting exploitable results from research and development projects is not trivial. The last subsection considers software development life cycles, which are used as inspiration to study novel processes to bring novel products, strategies, and techniques for advanced maintenance from the lab to real-world pilots, to production environments such as the shop floor, up to the market.

2.1. The Value of Advanced Maintenance Practices

The Operation and Maintenance (O&M) phase in a machine's life cycle requires large expenses and more efforts than the installation (construction) phase, because in its long useful life, any accident of an asset can result in catastrophic damage to the entire company. Maintenance has gained lot of importance as the technical complexity of the machines has increased. Maintenance is defined as all technical and managerial actions taken during usage period to maintain or restore the required functionality of a product or an asset (Shin and Jun, 2015). Maintenance has been classified by various researchers and practitioners in the past. Most widely acknowledged classification defines maintenance as per the instant that it is executed, i.e., whether after the breakdown (corrective maintenance) or before the breakdown (predictive maintenance). Predictive maintenance concerns with the prediction of degradation process of the product, which is based on the assumption that most abnormalities do not occur suddenly, and usually there are some kinds of degradation process from normal states to abnormalities (Fu et al., 2004). This degradation process is characterized by certain responses that the machine provides to the sensors. These changes in the measured parameters can indicate that the machine is moving towards a possible failure in the future. The method can be used to reduce the uncertainty of maintenance activities and is carried out accord-

ing to the requirements indicated by the equipment condition (Peng et al., 2010). A large number of advanced maintenance methods are being used today as the cost of failure is becoming increasingly prohibitive or simply catastrophic.

The need for implementing advanced maintenance strategies is no more a choice. Companies have no option but to implement them in order to remain competitive. These advanced maintenance strategies like CBM give prior warning of impending failure and increase the probability of accurately predicting the kind of failure. Some other machines, where the personnel safety is at stake, have CBM as the only viable option. Modern maintenance practices also enable the maintenance providers to better plan their resources. Resources like skilled manpower, spare parts, specialized tools, etc. can be placed at pre-planned locations to both optimize their usage as well as make them available in the shortest possible time to reduce administrative delays.

Implementation of modern maintenance methods was a costly exercise a few decades back. However, the reducing costs of sensors and computational resources, coupled with increase in computational power and decrease in the size of the sensors has made it a more technically and economically viable approach. It can lead to a decrease in the maintenance budget (Bengtsson, 2004). Modern advanced maintenance practices have the capability to optimize the production process and improve its productivity. It provides the ability for the system to continue operating as long as it is performing within predefined performance limits (Prajapati et al., 2012).

2.2. Advanced maintenance in real-world scenarios

Application of modern maintenance methods in real-world scenarios is not a very easy process. There are a number of technical issues that inhibit the free use of such advanced maintenance practices. First and foremost, the organizations must select the assets that require condition monitoring. CBM is supposed to be applied where appropriate, not as an overall policy as some techniques are expensive and it would not be cost effective to implement them everywhere (Starr, 1997). This selection should be based on technical and economic feasibility analysis. The machine should be critical enough to warrant large investments in a CBM system. Also, the selected asset must be such that it has parameters that matter for its functioning and that can be monitored with sensors. Most CBM implementations fail because the organisations start to measure ‘what can be measured’ rather than ‘what should be measured’. The first challenge is to obtain effective features from many candidate features to reflect health degradation propagation in the whole life of machines (Yu, 2012). In machine-learning-based defect detection, the accuracy of prognostics and diagnostics models subsequently depends on the sensitivity of the features used to estimate the condition and propagation of the defects. Therefore, it is critical to devise a systematic scheme that is capable of selecting

the most representative features for current machine health states (Yu, 2012; Malhi et al., 2004). The complexity of selecting a suitable measure can be gauged from an example. Some research shows that the use of acoustic signal is better than vibration signal due to its sensitivity and accuracy (Al-Ghamd & Mba, 2006; Baydar & Ball, 2001; Tandon et al., 2007). However, in practice, the application of acoustic signal may not be appropriate due to the significant effects of noise (unwanted signals) from other equipment. In addition, alternative sources of information are important contributors to health monitoring. These sources include the OEM, ISO standards, experience of the workers, etc. The new challenge is to find ways to use these alternative sources of information in order to achieve better monitoring of assets and correct decision making (Ahmad and Kamaruddin, 2012).

Choice of a correct sensor with appropriate sensitivity is an important step. Selecting a costlier sensor when it is not required will make the CBM system unnecessarily expensive which will not be able to justify the cost-benefit argument. On the other hand, selecting a cheaper non-sensitive sensor when the data being measured has minute variations that require high quality sensor can also upset the cost-benefit balance as the diagnosis of the fault may not be correct. Other ICT challenges include sensor data quality related to gathering frequency, noise, and level of details of sensor data, data availability, wireless communication problem, frequency of diagnostics and prognostics, and so on (Shin and Jun, 2015). In addition, the technologies and technical methods for the CBM approach are still in their infancy. It means that there are some limitations in ensuring the accuracy of diagnostics and prognostics (Shin and Jun, 2015). Numerous different techniques and technologies exist but choosing the correct one, or even remembering to make the decision in due time can be a troublesome activity which can put an entire implementation effort at risk (Bengtsson, 2007).

The condition monitoring practice is based on the fact that a sensor is used to measure a parameter. When the value of the measured parameter crosses a predetermined threshold, suitable maintenance actions are initiated. In practice however, deciding on the threshold is a complex process. The failure of each equipment may be defined and classified in different ways. Some organisations consider failure as the physical event such as a breakage that stops production. The machine stops to function as a result of such a failure. In some other cases, a functional failure may occur which results in the final product of the machine to have quality flaws but the machine may continue to work. It is necessary for the organisations to determine threshold based on their requirements. The definition and determination of failure limits should be considered from both the entire machining process perspective (system/sub-system) and the overall output of the system (e.g., product quality characteristics) (Ahmad and Kamaruddin, 2012).

Analysing waveform data is an intricate process because of noise effects, which are unwanted signals generated by other equipment. Noise must be minimised or eliminated from the data (Ahmad and Kamaruddin, 2012). Some noise also gets generated due to the transmission medium. It is necessary to identify which data

transmission type (wire or wireless) is effective in terms of cost and reliability with least noise (Shin and Jun, 2015). Large data sets are required for effective data analysis and modelling. This collected data needs to be cleaned before any analysis. This is a complex task, especially for waveform-type data. Newly commissioned systems have no historical data. Even the OEM is not aware of the failure patterns or failure rates. In such cases, it is not possible to identify the trends or failure thresholds. Such situations are no-data situations (Si et al., 2011). The quantity and completeness of data are insufficient to fit the full statistical models. Hence, it may be a better choice to develop physics-based models with the help of subjective expert knowledge from design and manufacturing (Si et al., 2011).

2.3. Software Development Life Cycles

In the Information and communication technology (ICTs) projects, there is a need to have an information technology approach for its project management phases, i.e. the use of a software development life cycle (SDLC). Brewer and Dittman, (2013) highlight different project variances between disciplines, such as requirement changes, sources of changes, requirements specification, etc., where requirements changes are slow and incremental for engineering while rapid and unplanned for information technology projects, for instance. The sources of changes are for engineering known and predictable while for ICTs projects many times unknown. Requirements are other factors that are different, namely for engineering it is an explicit plan while for ICTs projects normally ambiguous (Brewer & Dittman, 2013).

The SDLC approaches, such as the waterfall model, highlight the processes, namely the different phases of a system development process. Some reports highlight the death of the Waterfall Life-cycle Model, which are greatly exaggerated (Laplante and Neill, 2004), since it forms essential practices and might be seen as the pillars of the area of the methodologies in the area of system development. Hence, a methodology is defined as a system of methods used in a particular area of study or activity (Kuosa, 2016). The waterfall model is a sequential progressive process, whose development is a steadily downwards, i.e. resembling a waterfall through its stages. In the waterfall model, the requirements are evident before the next step of design is started. The testing of the code is done when the application is completely developed (Leau et al. 2012). This can be compared with the so-called V- model, which characterises a different SDLC process can be reflected as an extension of the waterfall model. The difference is that as an alternative of progressing linearly in its process paces, it is curved upwards after the programming phases and is, namely, the reason it is called the V – model, i.e. because it forms a V shape. Another well-known approach is the Agile methodology that emphasises adaptive teams that are capable of reacting quickly to the changing requirements' specifications. In addition, it also accepts requirements update late in

development phases. Hence, the software is typically delivered frequently, i.e. within weeks instead of months. The key principle of the approach is customer satisfaction by providing rapid and constant delivery of its software applications. However, to design and develop ICT applications for the domain of interest there is a need for a detailed and comprehensive understanding of the different algorithms suitable for analysing the different parts of the equipment. In other words, there is a need for an approach that considers the key aspects of the domain.

Still, organisations that are developing software applications are challenged with the difficulties of choosing the relevant SDLC or methodology and included methods (Balaji and Murugaiyan, 2012). The different aspects of the SDLC models among other are documented in Ruparelia (2010). New development life cycles have been suggested with the aim to increase the customer satisfaction (Kumar et al. 2013). In the suggested model such features as the understanding of requirements, costs, risk involvement, etc., are highlighted. The proposed SDLC plan attempts to achieve the objectives of an ICT project through the illustration of the requirements in a prototype to the clients to discover deviations from the planned order as well as to estimate the costs, schedule and work time invested more precisely, among other aspects. Another work that discusses improvements of the existent agile developments methods and traditional SDLC is (Leau et al., 2012). The different aspects of SDLC, such as the Waterfall model on large projects, are discussed in Petersen et al. (2009). A comparison between different SDLC methods in different scenarios are presented in Mishra and Dubey (2013). In brief, there is a need of a SDLC or project management methodology that contemplates the important aspects of the specific domain it intends to be implemented in, i.e. that is flexible enough to fit into the required aspects of the particular domain.

It is, however, recommended that before deciding the model to be used it is essential to understand certain crucial aspects, namely how stable the requirements are, who are the end users of the system, the size of the project, and where the project teams are located, etc (Balaji and Murugaiyan, 2012). In the case that the requirements are volatile, i.e. that they frequently change, and it is about a smaller projects where there is a need to deliver the product in short time which includes skilled resources, then the Agile methods are of preference. In the case that the requirements are stable as well as precise, and it involves a larger project, then it is proper to choose approaches similar to the Waterfall model. In addition, in the case that the requirement specifications changes in a larger project where proper validation needs to be taken at each stage, as well as to have testers to be part of the project in early phases of the development process, then the approaches alike the V-model are proper.

In addition, aspects of the Rational unified process (RUP) and the Spiral methodology are discussed in (Mateen et al., 2016). The authors propose a new methodology for the development of software applications that overcomes the weakness of the waterfall, agile, spiral, RUP and RAD development life cycle. The life cycle models are complex because they involves rigorous processes and there is no “sil-

ver bullet” in software development methodologies (Zykov, 2016). In addition, the Agile methodologies entail distinct methods and a high level of discipline; else, they can end in a low-quality software application.

Consequently, the business analysis, as well as other aspects of the development life cycle, becomes crucial to evaluate in any ICT project. It results in a need of a project methodology or SDLC that consider among other aspects the essential aspects of the specific domain to understand and develop project management processes in order to be successful in the ICTs implementation of the industrial maintenance area.

3.0 The MANTIS project

The MANTIS Project (Albano, Papa, Jantunen, & Zurutuza, 2018) was a European initiative focused on innovation on advanced maintenance practices. The project was alive in the period 2015-2018, and studied many sides of maintenance, spanning from sensors and Cyber Physical Systems to collect data on the machines and the shop floor, to the communication middleware (Albano, Sharma, Campos, & Jantunen, 2018) to transport the data to the cloud in an efficient and secure manner, to the machine learning techniques that can be used to provide CBM to the machines using the collected data, to advanced data visualisation systems to help the technicians make sense of the high volume of information that is collected in the machines and produced by the machine learning algorithms.

The MANTIS Project was driven by its real-life pilots. All studied techniques were applied to machines, and had to be validated as integrated in production environments. Many important industrial fields were tackled by the project, such as automotive, energy production and manufacturing. In this sense, the pilots are the testing ground for the innovative functionalities of the proactive maintenance service platform architecture and for its future exploitation in the industrial world.

Among the results of the project, there is the reference architecture for advanced maintenance techniques. This is the underlying architecture of the service platforms that were implemented in the different pilots, and is based on three tiers. The Edge Tier is on the production floors, and close to the machines in general, and its goals are to collect data from the environment and the machines; to preprocess the data; to transport the data to the cloud. The Enterprise Tier is close to the customer and/or to the personnel that operates and maintain the machines, and it allows for the visualisation of the data, analyze it from a technical and economic points of view. It is also able to issue control commands to the other tiers. Finally, between these two tiers there is the Platform tier, which receives the streams of telemetry data from the Edge tier, and the control commands coming from the Enterprise tier. This tier consolidates the data flows by means of external data; analyzes the data by means of machine learning techniques; offers non-domain specific services such as data query and analytics.

The MANTIS Project was able to investigate a large number of matters related to maintenance. Anyway, the benefits in the real world depend on a process to extract the best results, corroborate them by integration in different scenarios, and package them for future usage. This process is called exploitation, and it was of the utmost importance to maximize the benefits of the MANTIS Project to the industry. Given the large size of the MANTIS Project, the exploitation process was target to innovation to be able to cope with the task at hand.

4.0 An Iterative process for defining exploitable results

Exploitation activities are characterized by identification, experimentation, characterisation and investigation, which can result in new knowledge. This new knowledge or exploitable results, can be applied as an internal institution asset for new research projects, as such for the creation of new goods (products or services). The speed, cost efficiency and successfulness in the market of the exploitable results development depend on the extent to which the exploitation activities are completed in the project (Lantos, 2006).

The usual approach to exploitation is based on the creation of a list of potential results at some time in the project, and a refining at the end of the project. This traditional approach is similar to the waterfall SDLC, but it can be sub-optimal for large projects whose complexity does not allow for a clear vision of the whole project at once.

A novel approach can be based on an adaptive exploration/exploitation tradeoff that helps to identify and get the exploitable results to the market in an iterative and retrofitting approach.

The methodology follows a planned process of transferring the successful results of the project to useful exploitable results, based on diverse innovation processes and management tools such as Effectuation, Exploit, FoF-Impact, Value Chain, Innovation Radar, etc., giving a constant interaction and feedback all over the course of the project.



Figure 18 Iterative Exploitation Methodology

The methodology, represented in Figure 1, benefits from constant external interaction, getting assistance and feedback redefining the means and goals of the project. Corporations must identify continuously new opportunities, while devising strategies for their outcomes in diverse industries, helping on the definition or redefinition of the strategic vision, the needs of the market and the exploitable results configuration. The identification of the opportunity precedes to the necessity of acting on the opportunity through an iterative and heuristic process.

The methodology proposed (Figure 1) is a structured process formed by diverse phases and divided into three main blocks or processes:

1. Idea generation. Recognition of objectives, capacities, external threats and possible exploitable results.
2. Conversion contrasting a set of means and possible exploitable results within the project's partners, identifying who would own the outcomes and how they would be further exploit.
3. Evaluation of the exploitable results, reconfiguring the means and goals of the project, examining the best ways to protect the outcomes, and designing guidelines to face the risk market hazards.

The proposed methodology considers to repeat a number and specific stages to strength and redefine the exploitable results as well as the way to protect and further exploit them. For each iteration a number of stakeholders are involved, bringing together diverse market and businesses perspectives, encouraging their interaction, and maximizing the project's novel products and services. For example, Figure 2 represent the process when we consider two stages, where novel inputs from the industry forces to repeat the prioritisation and evaluation, and leaves it open to further iterations.

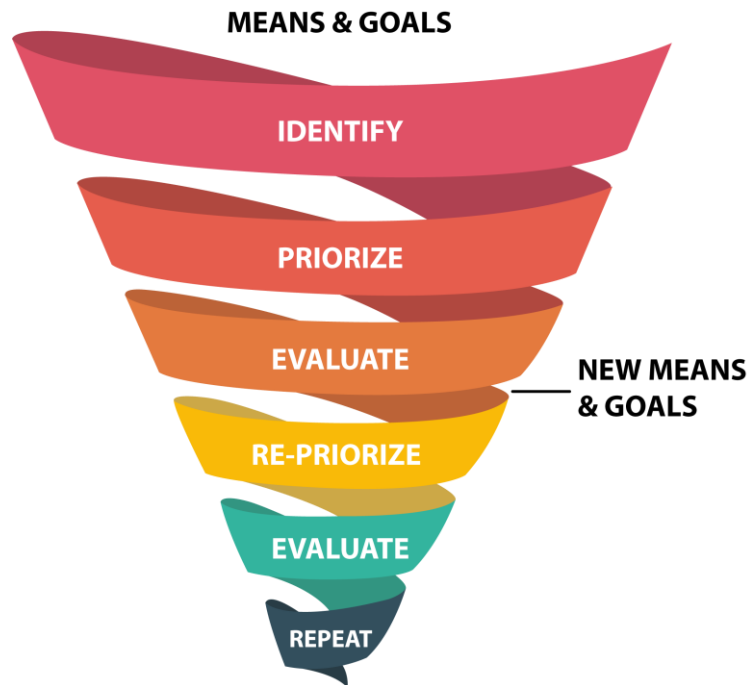


Figure 19 Repetition of stages in defining exploitable results

5. Results of the iterative process in a case study

The approach presented in Section 4 was applied in an ECSEL predictive maintenance project called MANTIS (see Section 3), whose implementation is represented in Figure 3 and comprised the execution of six main workshops in a three-years period:

- 1st and 2nd workshop had the goal to advance in the search of servitisation business models around predictive/proactive maintenance solutions. The ultimate goal was to establish a baseline for consortium members to start an early definition of their new business model and start identifying the possible exploitable results.
- 3rd and 4th workshop had the objective of characterizing the potential exploitable results, analyzing the possible ownership and exploitation claims.
- 5th workshop first exploitable results prioritisation, identifying the most relevant outcomes for each institution.
- 6th workshop aim to identify, evaluate and respond to the critical market entry hazards of the exploitable results.

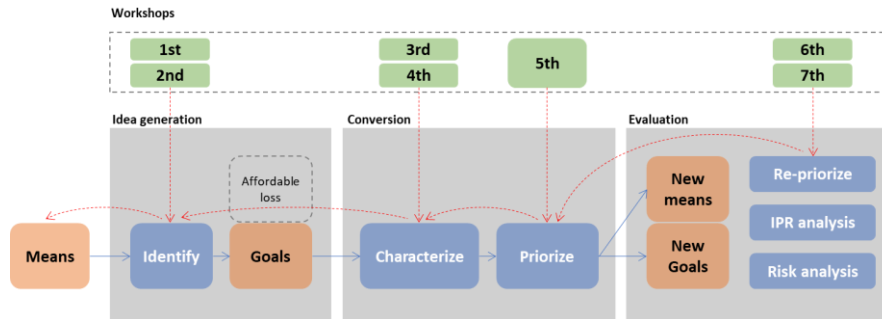


Figure 20 Iterative process for the exploitable results definition

- 7th workshop aim to recheck the exploitability, ownership, prioritisation and intellectual property protection status of each of the reconfigured results.

The characterisation of the iterative process for the exploitable results definition improved the consortium commitment in the exploitation process, providing constant interaction and feedback all over the project course. The workshop method revealed its effectiveness since it is easier to transmit a message with the goals and purpose of the survey, together with the data collection of the answers provided by the participating partners.

As part of the evolution and the iterative process, the MANTIS consortium identified 97 exploitable results at the middle of the project, readjusting to 76 in the last months. Some of the eliminated items couldn't been tested due to the lack of base line data, they need to be verified in other uses in order that the entities are entirely sure to exploit them or they don't fulfil the criteria for specific exploitation.

6.0 Discussion and conclusions

The outputs generated during a project can create an important impact during and after the project's lifecycle. The further exploitation of the results, such as creating and marketing a product or process, or creating and providing a service, or even for internal usage activities, reveal the external impact of the project.

On preliminary industry 4.0 projects, the exploitable results were identified at the beginning of the project, and weren't exploit/used by the partners after the project's lifecycle. The number of identified exploitable results differ from type of project and kind of products, MANTIS had a high number of exploitable results (estimated at 76) that can be transferred into 13 successful business cases taking into account the industrial and software partners. In previous projects of size comparable to MANTIS, a mean of 12 exploitable results were identified, and they had less impact in the entities' business cases or could not be used afterwards.

In other projects, the exploitation process relied on a theoretical approach from the first months, and did not take into account the industrial process feedback to identify new exploitable results or to eliminate the ones that will not be exploited. Future work will perform a final inventory of exploited results one year after the end of the MANTIS project, to provide a final evaluation. Anyway, the current number (76) is already the result of multiple iterations and refinement, and most exploitable results are already employed in production environment, thus there will probably be no surprises. Moreover, we plan to perform a thorough comparison between older projects that had no specific and explicit exploitation activities (work packages), traditional projects with a waterfall/ad-hoc exploitation process, and MANTIS and future project that adopt our proposed iterative process.

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Poly-Coherent Composite Bispectrum Analysis for fault diagnosis in Rotating Machines

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Abstract The poly-coherent composite higher order spectra (*p*CCHOS) were used earlier for faults diagnosis in the rotating machine. Earlier research studies have also suggested the unified multi-speeds approach for identical machines but with different operating speeds. However the studies were only tested at several machine speeds but below the first critical speed. In the present study, the same unified method using the poly-coherent composite bispectrum (*p*CCB) is further tested when the experimental rig runs below and above the machine's first critical speed. The results and observations are presented here.

Key words Rotating Machines, Bispectrum Analysis, Data Fusion, Fault Diagnosis

1.0 Introduction

Fault diagnosis in rotating machine using vibration-based condition monitoring (VCM) techniques is well accepted. In order to meet production demand through availability and reliability, various techniques to diagnose and predict machine conditions are being developed [1-2]. Recent research studies show increasing interest in the use of higher order spectra (HOS) in the VCM approach for fault diagnosis (FD) in rotating machines [3-10]. These studies has shown the complexity of HOS [6] but also presented proof of its usefulness in fault diagnosis especially on non-linear signals as expressed by Sinha [5] A justification for using HOS is the ability to retain both amplitude and phase in its analysis and also the potential of combining various frequency components of measured vibration signals as

against the traditional power spectrum density (PSD) which contains only harmonic component with the phase information lost [5-6].

The poly-coherent composite higher order spectra (*pCCHOS*) were used in earlier studies for diagnosing faults in the rotating machines [8-9], thus reducing the rigor of analyzing large vibration data due from individual bearings. The studies focused on vibration data measured below first critical speed. However, most large machines function in such a way that they run above their critical speeds [11]. In the present study, the use of the poly-coherent composite bispectrum (*pCCB*) in machine fault diagnosis is further tested when the experimental rig runs below and above the machine's first critical speed. The results and observations are presented here.

2.0 poly-Coherent Composite Bispectrum (pCCB)

The poly-coherent composite bispectrum **B** is represented mathematically as [8-9]

$$\mathbf{B}(f_l f_m) = \frac{\sum_{r=1}^{n_s} (X_{pCCS}^r(f_l) X_{pCCS}^r(f_m) X_{pCCS}^{r*}(f_l + f_m))}{n_s} \quad (1)$$

where X_{pCCS}^r in equation (1) is the poly-coherent composite Fourier Transform (FT) for the *r*th segment of the measured vibration data from 'b' bearing location at frequency f_k and n_s is the number of equal segment used for the FT computation. Hence X_{pCCS}^r is computed as [8-9]

$$X_{pCCS}^r(f_k) = \left(\sum_{r=1}^{n_s} X_1^r(f_k) \gamma_{12}^2 X_2^r(f_k) \gamma_{23}^2 X_3^r(f_k) \gamma_{34}^2 X_4^r(f_k) \dots X_{(b-1)}^r(f_k) \gamma_{(b-1)b}^2 X_b^r(f_k) \right)^{\frac{1}{b}} \quad (2)$$

where $X_1^r(f_k), X_2^r(f_k), X_3^r(f_k), X_4^r(f_k), \dots, X_{b-1}^r(f_k)$ and $X_b^r(f_k)$ respectively represents the FT of the *r*th segment at frequency f_k of the vibration responses at bearings 1, 2, 3, 4, ..., (b-1) and b [8]. Also, $\gamma_{12}^2, \gamma_{23}^2, \dots, \gamma_{(b-1)b}^2$, respectively represents the coherence between bearing 1-2, 2-3, ..., (b-1)b (where b = 1, 2, ..., b), and the $S_{pCCS}(f_k)$ is the pCCS at frequency f_k [8-9].

The measure of the combination of the frequencies at f_l, f_m , and $f_l + f_m$ explains the characteristics of the bispectrum. The correlation of various harmonic components in bispectrum of found to be useful for robust and effective diagnosis especially in rotating machines [9].

3.0 Experimental Rig and Test Conditions

The experimental rig for this study is represented pictorially in Figure 1 and is located in the Dynamic laboratory at the University of Manchester. The rig support

structure has been redesigned for this study to accommodate a more flexible system. It consists of a motor, two shaft (1000 mm and 500 mm long respectively) joined by a rigid coupler. The long shaft is connected to the motor by a flexible coupler. Four anti-friction bearing is connected to the bearing pedestal using four spring per bearing (Figure 2) with each spring having a stiffness of 4.69 N/mm. Three balance disc (125 mm diameter x 14 mm thickness) hangs on the shaft with two of the disc on the long shaft and one on the shorter shaft. All of these are bolted to a lathe bed placed on dampers. Modal testing carried out on the experimental rig to determine its dynamic characteristics presented a number of natural frequencies. The first few identified are 11.52 Hz, 18.62 Hz, 30.75 Hz, 49.13 Hz and 85.83 Hz. Details of the experimental rig and dynamic characterisation are presented in previous work [12].

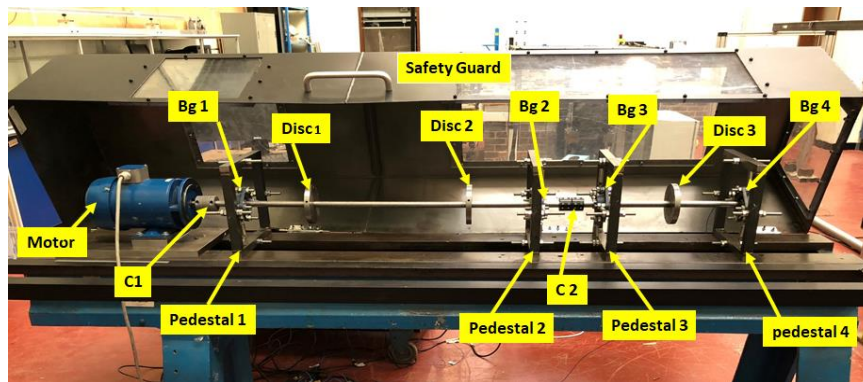


Figure 1 Picture of Experimental Rig.

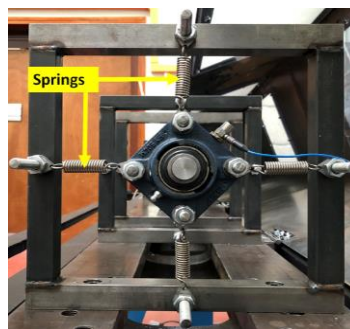


Figure 2 Picture showing bearing pedestal of experimental rig with spring connection (flexible).

3.1 Test condition and data acquisition

In this experiment, 10 sets of data were collected at a sampling frequency of 10,000 Hz for each condition at three different speeds i.e. 450 rpm (7.5 Hz), 900 rpm (15 Hz) and 1350 rpm (22.5 Hz) which were selected based on the machine's natural frequencies. The first speed is below machine's first critical speed and the two other speeds are above the machine's first critical speed. Table one below gives clear description of the simulated conditions. The pCCB analysis plots, observation and discussion is presented in section 4.0.

Table 1 Showing description of test conditions

No	Condition	Code	Description
1	Healthy	RMRU	Residual Misalignment Residual Unbalance.
2	Crack near Bearing1	CBg1	0.34mm wide x 4mm deep notch with 0.33mm shim glued (on rotor near Bg1).
3	Crack near Bearing2	CBg2	0.34mm wide x 4mm deep notch with 0.33mm shim glued (on rotor near Bg2).
4	Rub near Disc1	RubD1	Perspex blade on rotor near Disc1.

4.0 Observation and Discussion

Figure 3 shows the pCCB plots at 900 rpm (15 Hz). In the plots signals from all four bearings are fused into a single analysis. Observation of the pCCB plots showed the presence of \mathbf{B}_{11} , $\mathbf{B}_{12} = \mathbf{B}_{21}$, $\mathbf{B}_{13} = \mathbf{B}_{31}$ at all speeds and all conditions. The RMRU had very little \mathbf{B}_{12} . All other faults had the presence of \mathbf{B}_{22} , $\mathbf{B}_{23} = \mathbf{B}_{32}$, and \mathbf{B}_{33} . Similarly, the 450 rpm has its features with lower components. However, the 1350 rpm analysis showed higher peaks in all conditions. Therefore it is difficult to do the diagnosis based on visual observations on the pCCB plots.

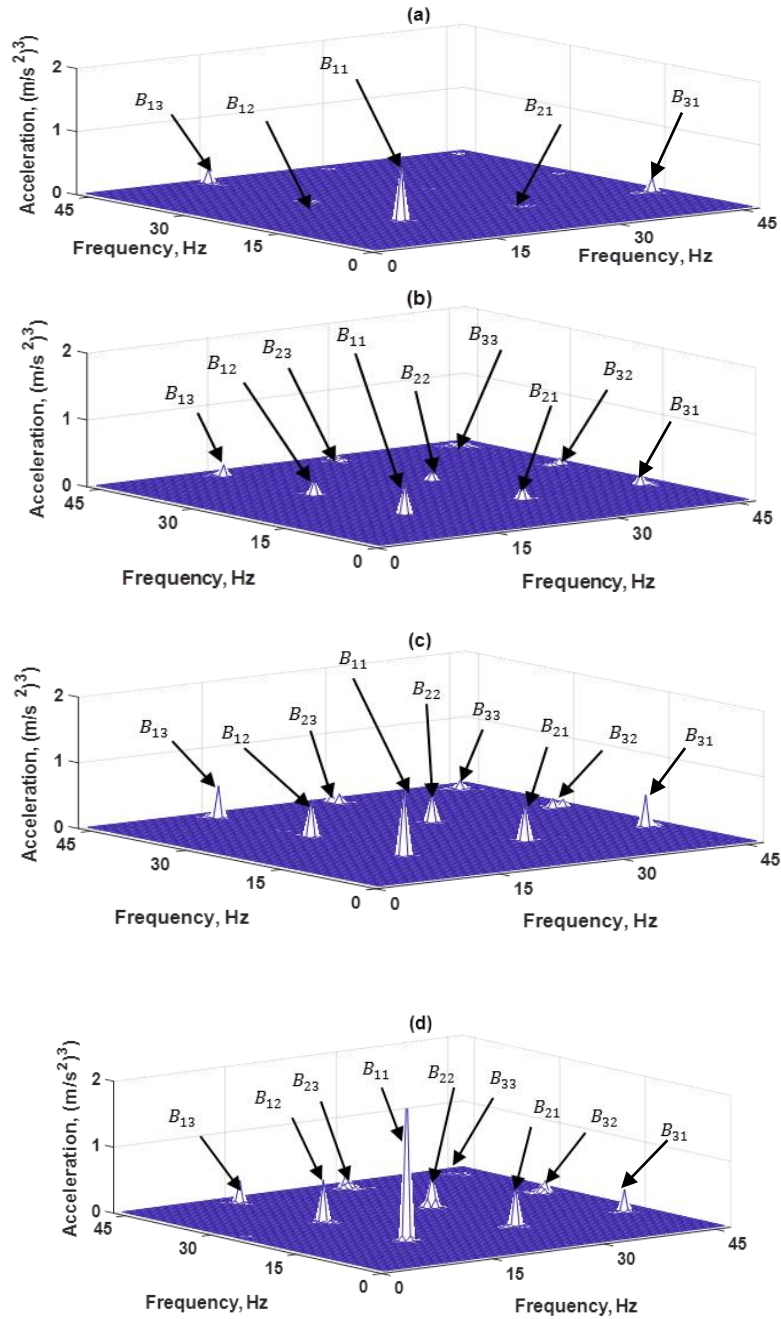


Figure 3 Typical pCCB plots at 900 rpm (15 Hz) for (a) RMRU (b) CBg1 (c) CBg2 (d) RubD1

5.0 Faults classification

Since it is difficult to do the diagnosis manually, hence the mathematical approach is used based on the pattern recognition method. In this study, three pCCB components i.e \mathbf{B}_{11} , $\mathbf{B}_{12} = \mathbf{B}_{21}$, $\mathbf{B}_{13} = \mathbf{B}_{31}$ at all the 3 speeds were selected and then a data matrix was built. Equations (3) and (4) provide the details of the data matrix construction.

$$B_{C_1 S_1} = \begin{bmatrix} b_{11D_1} & \cdots & b_{13D_1} \\ \vdots & \ddots & \vdots \\ b_{11D_{10}} & \cdots & b_{13D_{10}} \end{bmatrix}_{C_1 S_1} \quad (3)$$

$$\mathbf{B} = \begin{bmatrix} B_{C_1 S_1} & \cdots & B_{C_1 S_3} \\ \vdots & \ddots & \vdots \\ B_{C_4 S_1} & \cdots & B_{C_4 S_3} \end{bmatrix} \quad (4)$$

where C is the machine condition, S is the operating speed and D is the number of data set. The matrix was built in such a way that at a particular condition and speed, say $B_{C_1 S_1}$, a 10 x 3 data matrix is formed. Therefore the data matrix of 40 x 9 is developed for all 4 conditions and 3 speeds. The principal component analysis (PCA) [13] is then applied to this data matrix as the pattern recognition tool for classification of the different fault conditions of the rotor in the rig.

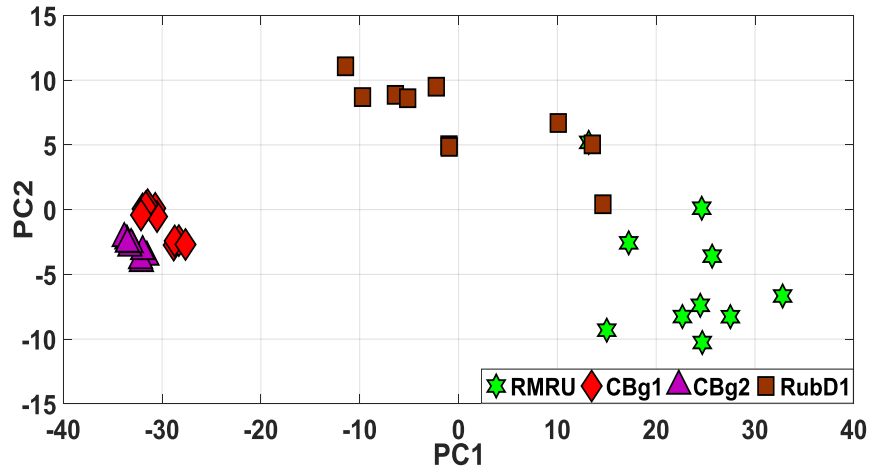


Figure 4 Classification of experimental rig fault conditions at multiple speeds

The result presented in this section shows data fusion of multiple speeds from components of pCCB analysis. Figure 4 showed good clusters of data set between

PC1 and PC2, each cluster represents one fault condition of the rotor. However it has also been observed that 2 crack conditions CBg1 and CBg2 shows separation between their clusters but they are close to each other. Hence it is good indication that clusters of the similar faults may appear close by but their fault locations may be different.

6.0 Conclusion

The use of the pCCB once again is found to be a useful tool for the classification of different rotor faults even when the machine is running above or below the critical speed. Currently only 3 rotor fault conditions are used together with a healthy condition. However the results are encouraging but it needs to be tested further with more different fault conditions.

7.0 Acknowledgement


First author likes to acknowledge Dr Keri Elbhah for his support during set up and modal testing of the experimental rig and also his contribution at various stages of the study.



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ME2018_1052: New Maximo configuration for Marine Fleet Maintenance

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Abstract In an oil major like Kuwait Oil Company (KOC), the maintenance management system is a centralized process for all company's operations like drilling, production, export and marine. All processes have stationary assets at shore and maintenance is performed by the shore team, except marine. In marine the assets (ships) are operating (moving) from one place to another, whereas the maintenance is performed by shore based maintenance team.

Designing a maintenance management system for marine fleet was a challenging task, as it has to meet with marine industry requirements and yet communicate with other maintenance management processes of the company outside marine like procuring materials through a centralized system, sending internal service requests to different departments, processing service orders for contractors and third parties etc.

This paper presents various modules (Vessel Logsheet, Service Bulletins, Cost Benefit Analysis, Risk Assessment, Class Survey & Certification etc.) developed in the new marine maintenance management system to cater the need of marine at KOC and ensured that the communication with company maintenance management system (IBM Maximo) is carried out smoothly..

Key words Marine Maintenance, IBM Maximo, Maintenance system customization

1.0 Introduction

Kuwait is situated at the Gulf of Hormuz, through which more than a third of world's oil is exported. Kuwait Oil Company (KOC) is a State Oil Company established in 1934 for upstream oil and gas business including exploration, drilling, production, operations and export. KOC is world's 7th largest crude oil producer. Export & Marine Operation is an integral part of KOC and was undergoing expansion and modernization to replace ageing fleet and to meet up with the growing oil export of the company.

KOC is using IBM Maximo Oil & Gas Module for all its facilities. However, marine group has different challenges. Other facilities have stationary assets at land, whereas marine assets (ships & equipment) are moving at sea. Yet, the maintenance system has to communicate with other facilities processes like procuring materials, contract orders, service orders for third parties, service requests for internal teams etc. The team designed a holistic maintenance management system, which fulfilled needs of marine and at the same time communicated with other teams in the organization.

2.0 Maintenance Management System at KOC

In Kuwait Oil Company, IBM Maximo was used as Computerized Maintenance Management System (CMMS) for handling short term/long term maintenance activities and planning. Being an upstream oil company with versatile operations at various locations and different model of performing/reporting work, it was very difficult to have a uniform CMMS throughout Company's operation.

Oil rigs generally have different approach towards maintenance of machines as the machines are very large & critical, most of the routine maintenance is outsourced to Original Equipment Manufacturer (OEM). On the other hand, maintenance of offshore vessels (operation is in sea but maintenance is performed on land) is performed in house with skilled workforce. Hierarchy for location and asset in drilling rigs is based on ISO 14224, whereas hierarchy for location/asset in marine is based on SFI (Skipsteknisk Forsknings Institutt: A Norwegian company) coding and IMPA (International Marine Purchasing Association) coding. Also, the usual work order approval process is also different in marine as compared to oil rigs. This has prompted the team to reconfigure IBM Maximo to meet marine requirements. The maintenance management system (IBM Maximo) at KOC has following business aspects:

2.1 Types of Assets

Following are the assets which KOC has across the teams. Except Marine Team & Transport Team assets, all other assets are stationary.

- Sub surface facilities: Reservoir, Wells
- Surface facilities: Gathering centers, Booster stations, Water treatment and Injection Plants
- Export facilities: Tank farms, Export terminals
- Infrastructure: Pipe line, cables, Roads, Facilities, Office Buildings, Staff Accommodation
- Workshop: Machining, Welding, Fabrication, Repairs

- Transports: Heavy Equipment, Light Vehicles, Mobile Cranes
- Information Technology (IT): Communication, Servers, Workstations, Accessories, Software
- Medical: Assets of Hospital
- Marine: Tug boats, Crane Workboats, Pilot Boats, Dry-Dock facilities, Catenary Anchor Leg Mooring (CALM) Buoys, Mooring Boats

2.2 Business Processes

Different business processes work synchronously to produce the end result. Some of the processes are discussed here.

- Horizontally: From capital project to Asset write off.
- Vertically: Work Management, Inventory, Purchasing, Contracts, eBusiness, Financials.

3. New Maximo Approach

The project was taken as a novel idea. This means that the team has to unlearn of whatever Maximo and Marine standards knowledge they had and start from the scratch by building blocks step by step. The objective of the project was to achieve Computerized Maintenance Management System for marine vessels, whose operation is at sea and maintenance is done at land. Marine Maintenance Process is shown in Figure 1, which covers all the activities of the team.

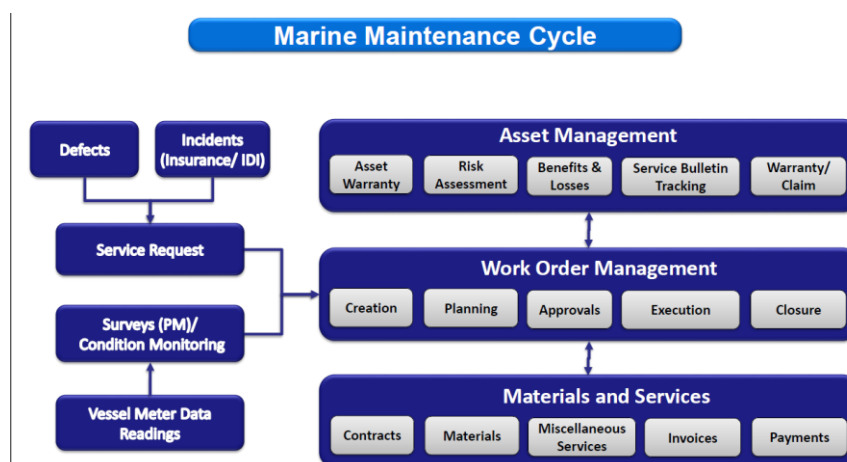


Figure 1: Marine Maintenance Process Cycle

3.1 Evaluate

A team was formed using Maximo experts, IT experts and Marine Experts. A consultant (with experience in Marine & Maximo) was engaged with in-depth expertise in configuring and support Maximo for Marine Industry to carry out the project.

3.2 Initiate & Plan

The project was divided into eight (8) stages and in two phases. First phase was to implement the system data/procedures on a pilot vessel and phase two was to implement the data on all other vessels.

Project was divided into 8 stages viz. Initiation and Planning, Analysis and Configuration, Data Templates, Data Model and Data Load – Phase I, Testing and User Acceptance, Training and Procedures, Cutover, Go Live and error free period and Data Load – Phase II.

Initiation and Planning

A kick off meeting conducted among all parties involved. Project plan was developed by the Contractor and presented to the Company. After minor modification, project plan was accepted. Time line to complete the project was nine (9) months. Roles and responsibilities were discussed and agreed upon.

3.3 Analyze

There were numerous workshops with the consultant to understand how IBM Maximo can be modified to match marine requirements. During workshops, there was a lot of discussion about how the current process is and how can it be improved.

Data Templates

First job was to understand IBM Maximo Oil & Gas Module. There were series of brainstorming workshops with the Contractor to discuss the “As-Is processes”. “To-Be Processes” were developed based upon discussions during workshops.

Locations-assets hierarchy were defined as per technical taxonomy i.e. systematic classification of items into generic groups based on factors possibly common to several of the items using by consulting ISO 14224, SFI Coding and IMPA standard codes for marine. We defined the Locations-Assets based

on their physical presence and on common system. For example, first level was the type of boat, second level was 50TBP Tug Boats, third level was Port Propulsion System, fourth level was the Port Main Engine, fifth level was unit number and so on. The team grouped all system under one reference, like all components related to lube oil system were under one group viz. lube oil pump, lube oil cooler, lube oil filter etc.

3.4 Configure & Test

Data Model and Data Load – Phase I

The first step in any maintenance system is to report defects through various teams/groups. This was established by process shown in figure 2.

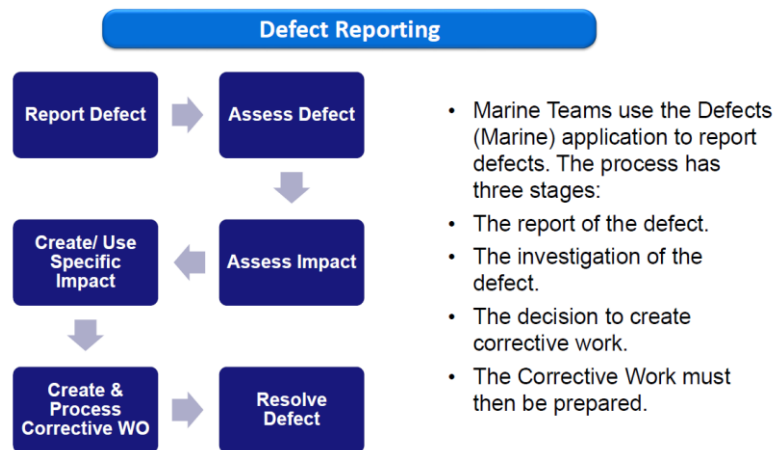


Figure 2: Defect Reporting

Work order type was defined as “Planned”, “Corrective” and “Emergency”. Planned work order generates automatically, corrective work orders can be created by user for corrective maintenance work and emergency work order is for emergency use only, which will by-pass the regular approval process and can also be generated retrospectively.

Further work order was divided in sub work type of “Warranty”, “Condition Monitoring”, “Insurance”, “Standard Work”, “Survey” and “Service Bulletin”. Warranty WO is for machinery under warranty and the cost for manpower/spares will be paid by third party. Condition monitoring WO is for carrying out work before the equipment fails by analyzing its condition by vibration monitoring or thermal inspection or pressure monitoring etc. Insurance WO is for insurance claims raised by the user and the cost would be re-

covered through insurance in recoverable account. Survey WO is for any classification society or flag state survey and inspection work. Service Bulletin WO is for the work carried out as per the modification suggested by OEM. Standard WO is for any standard work which is not any of above. Service Bulletin Work flow is explained in Figure 3

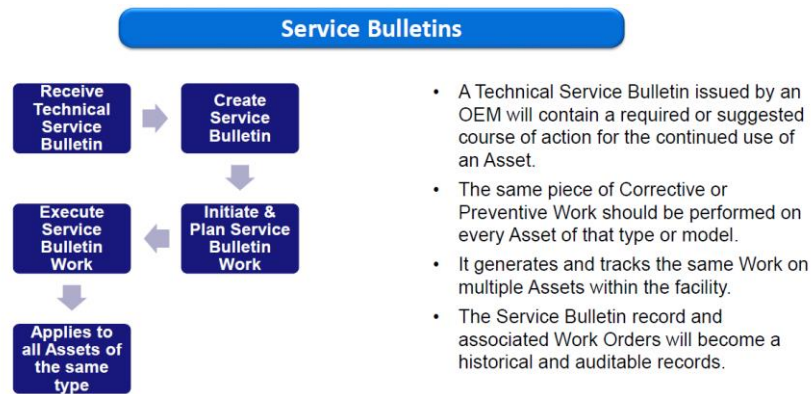


Figure 3: Service Bulletin

Survey & Certification process of Marine Assets was achieved as shown in Figure 4.

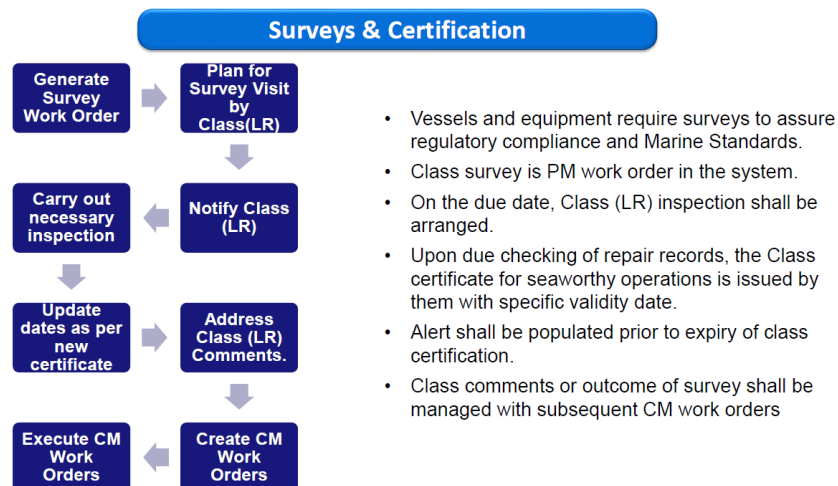


Figure 4: Survey & Certification Process

Each marine vessel has its own log sheet, which records all the parameters (temperature, pressure, tank levels etc.) for each operation or every four hours. During workshops, the idea of setting up log sheet application in the Maximo was coined and accepted widely. The order of readings sat up exactly as in ship's computer. On ship's computer readings are automatically logged on to Propulsion Control Monitoring System (PCMS) in the excel sheet. Readings were copied from the excel sheet and sent to office via email. These readings were entered into the system via macros in the excel sheet. The historical trend analysis for each of the log sheet reading were set up. This feature allows to perform Root Cause Analysis (RCA) of any problem with the machine.

Insurance process was set up as shown in figure 5

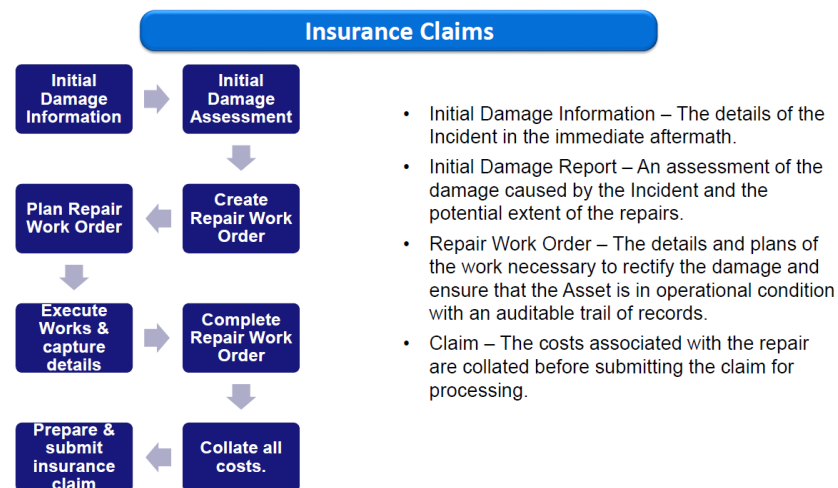


Figure 5: Insurance Claim Process

Risk Assessment module was build up using our company's Health Safety Environment Maintenance (HSEMS) Procedures and marine best practices. There were 3 categories of hazards, Health, Safety and Environment. Each hazard has it's precautions as listed in the marine standards. With these precautions, Risk category is defined. If the risk category is in unacceptable region of the matrix then additional control measures have to be taken, based on our group's risk register, till the time risk comes down to acceptable region. The application is made user friendly. The user has to select a Hazard and the precautions pops up automatically. Any Material Safety Data Sheet (MSDS) is populated automatically as per the hazard selection. Instead of doing manual tedious Risk Assessment, with this application user can perform

Risk assessment just by knowing hazards and few control measures as per the requirements. This application has saved a lot of man-hours.

Marine assets goes for Dry-Dock to repair any underwater area repair or any other major repair which can be repaired only when ship is out of water. Figure 6 depicts the Dry Dock process.

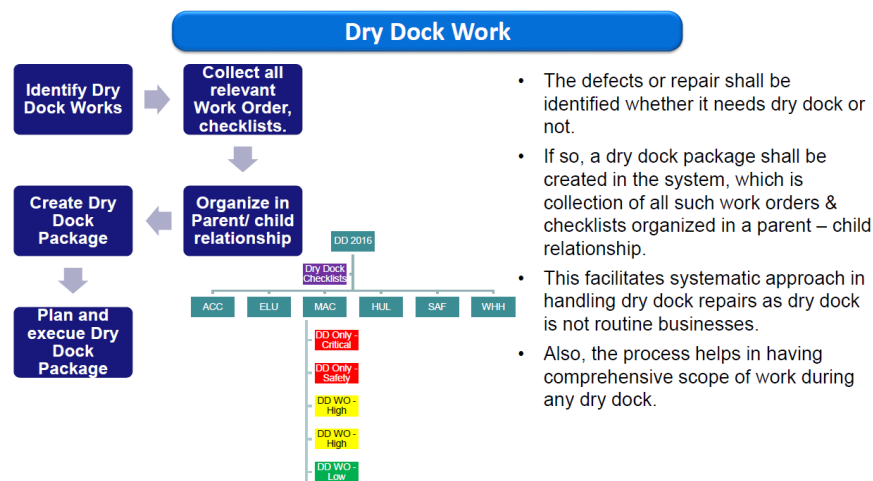


Figure 6: Dry Dock Process

Testing and User Acceptance, Training and Procedures

After establishing data and processes, system was tested and necessary training was provided to the end user team. Any minor adjustments were done at this stage.

3.5 Training & Deployment

Employees were imparted with training to use New Maximo Marine Module. There were many doubts raised by the operations and maintenance team members, which were incorporated in the system.

3.6 Certification

The reconfigured Maximo Marine Maintenance Module was tested and certified by International Classification Society Lloyd's Register UK.



3.7 Maintain

The challenge ahead is to maintain the system and build good data base to generate reports, which eventually will ameliorate the Marine Maintenance Business Processes.

4.0 Key Benefits

- Automation of manual maintenance process for marine operations
- Streamlined marine operations processes in accordance with ship classification society standards and ensuring regulatory compliance.
- Improved productivity, enhanced performance, timely management reporting and informed decision making.
- The use of standard IBM Maximo with Marine configuration without affecting company core Maximo processes.

Authors' Biography

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ME2018_11053: Investigation of explosion on scavenge airline of a 4 stroke Marine Engine

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Abstract This study is about the explosion on scavenge airline of a 4-stroke marine engine on ship during operation. The maximum scavenge airline pressure is 2.5 bar at full load of the engine. The exploded pipe/elbow was made of Aluminum alloy metal with significant thickness, which has almost zero probability of failure at such low pressure. The explosion has caused metal pipe/elbow to break down into tiny metal particles of varying dimensions.

The impact of the explosion was so strong that anyone in the vicinity could have been killed by the flying debris of metal. Metal particles were found all over in the machinery room. During operation nobody was in the machinery space and hence there was no casualty.

Various possibilities were explored during investigation of the cause of the explosion. Metal debris (varying dimensions), reverse engineering, process cycle etc. were investigated in deep. The paper is about exploring individual cause and rule out based on the process logic and/or metal particle analysis and arrive at the root cause of problem.

Key words 4 Stroke Engines, Explosion Scavenge Air, Fatigue in metal

1.0 Introduction

Kuwait is situated at the Gulf of Hormuz, through which more than a third of world's oil is exported. To facilitate the oil export operation, Kuwait Oil Company (KOC) has a fleet of 52 vessels consisting of Tugboats, Workboats, Mooring boats, Crew/Pilot boats, Oil Spill Recovery Vessels, Barges etc.

One of such Tugs, Tug Sabahi built in year 1990, was doing her regular offshore operation when the Turbocharger blower side elbow exploded and metal pieces were thrown all around machinery spaces. Fortunately, no one was hurt. The elbow was part of Main Engine Caterpillar 4 stroke Engine 3608, which had 54,314 operating hours on it. The elbow was between Turbocharger (blower side) and the air cooler. There was an emergency shut down valve just after the elbow.

The emergency shut down valve rod was found bent under closed condition. The valve was broken into pieces. This suggest that the emergency shut down must have activated accidentally, as there was no alarm during the incident. The broken elbow was 8 mm thick, 7" diameter, was made of Aluminum alloy and the medium was compressed air. The operating pressure of the line was 1.0 Bar and maximum air temperature was 80°C. It was hard to understand how the elbow can be broken into pieces at such low pressure and temperature. Investigations were performed and all possibilities were considered. After further investigation, different possibilities were ruled out to reach the conclusion.

2.0 Investigation

Explosion of 7 inch diameter, 8mm Aluminum Alloy elbow is highly unlikely on a compressed air medium with pressure 1.8 Bar & temperature 80°C.

Figure 1 shows the location of the incidence on the Turbocharger blower side elbow.



Figure 1: Elbow (7.5"), 8mm thickness Exploded

Turbocharger, all cylinder heads, pistons, connecting rods were removed. No visual fault could be found from all components.

2.1 Immediate Cause Analysis:

Following unsafe conditions were observed:

- Oil in inlet manifold: Came from inlet valves lubrication lines.
Corrective Action: Pump flow to be adjusted after boxing back the Engine.
- Bent rod of Emergency Shut Down valve, suggesting explosion occurred from Turbocharger side.
- 7" Elbow of 8mm thickness made of Aluminum alloy (which is ductile) broken into pieces.
Elbow pieces became very fragile & weak.
Possible causes: Fatigue failure, Fire/Explosion in the line, High Pressure, High Temperature.

2.2 Root Cause Analysis:

In order to find out root cause of the explosion, Fire Triangle of Oxygen, Fuel & Ignition Source were explored independently.

1. Oxygen:
There's lot of Oxygen available as air is compressed in the Turbocharger & travels through air cooler, inlet manifold & then through inlet valves into the combustion space, where fuel is burn.
We cannot eliminate Oxygen from entering the Engine.
2. Fuel:
There are two possibilities of Fuel entering the scavenge air system:
 - i) Lub oil passing through seals of Turbocharger.
Seals of Turbocharger checked, found OK. So, this option is ruled out.
 - ii) Lub oil through Inlet valve lubrication, which comes in the inlet manifold directly.
But the flash point of Lub oil is between 160°C to 180°C.
This is quite unlikely that temperature of this magnitude might have reached in the elbow.
Suspect Diesel oil contamination in the lub oil. Flash point of diesel oil is 60°C to 100°C.
Air is compressed in the turbocharger blower & if it doesn't find way out, air temperature might have reached up to 90-100°C. This could have caused the explosion.

We will individually take reasons for obstruction of air flow:

- (a) Dirty Air Cooler:

Air cooler was removed & found moderately dirty with lub oil. This is not enough to cause compression & temperature of that sort.

- (b) Inlet valves not operating:
All Cylinder Heads were removed & function of all inlet/exhaust valves tested: Found satisfactory. This option is ruled out.
- (c) Emergency Shut off Valve Operated:
Emergency Shut off valve is operated by Air, which comes from solenoid valve (Figure 3) on activation of any shut down alarm such as Lube Oil pressure low-low, jacket water temperature high-high etc. but at the time of incident no alarm was observed.
Other possibility of operation of the valve is malfunction of solenoid: Solenoid function tested & found satisfactory.

Malfunction of the valve itself: This is probable cause as we can see that the rod holding the flap is bent in direction of air flow, as shown in Figure 2.

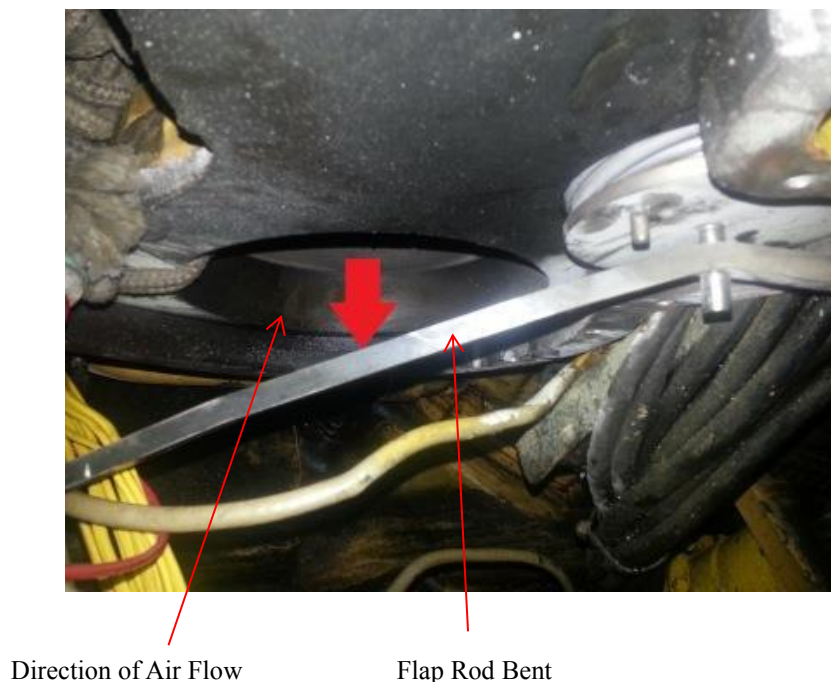
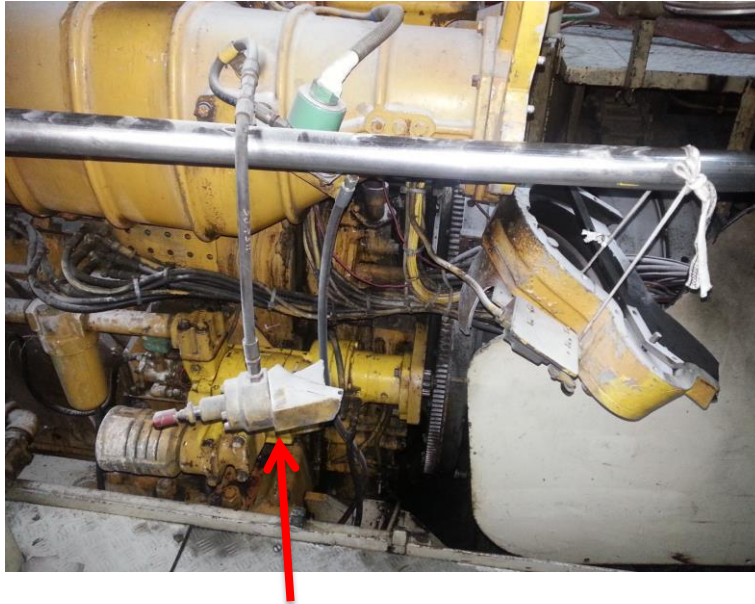


Figure 2: Emergency Shut Off Valve Bent



Emergency Shut off Device (Expecting Flap Operated)
Figure 3: Emergency Shut-Off Valve Activation Device

3. Ignition Source:
Three possible causes of ignition source are
 - i) Leak of combustion gases through Inlet valve
All cylinder heads were removed & inlet valves were checked.
There was Carbon deposits on #4 & #5 unit valves but not enough to let exhaust gas pass through, as depicted in Figure 4 and 5.



Figure 4: #4 Cylinder Head



Figure 5: #5 Cylinder Head

- ii) Leak of exhaust gases through Turbocharger
 Turbocharger was removed in workshop & end deflection found within range.
 End Play: 0.12 mm (Range 0.1 to 0.3 mm)
 Radial Play: 0.35 mm (Range 0.44 to 0.87 mm)
 Turbocharger seal were found intact. So, possibility of exhaust gases leaking through the seal is ruled out.
- iii) High compression of air causing temperature to rise.
 High compression can be caused by obstruction in the air flow & Turbocharger continuously pumping air into the system.
 As explained above, possibly Emergency Shut off valve might have operated & obstructed the air flow & hence temperature of the air rose up to the flash point of mixture of lube oil mixture.
 During normal operation, the charge air pressure is 1.8 Bar, maximum air temperature in the elbow was 80°C (approximately as there was no means to measure it in the elbow) but in case of any obstruction (like activation of emergency shut down) could have resulted in to pressure near to fatigue failure. Also, as the blower was running continuously this could have caused high temperature inside the elbow, which had diesel-lube oil mixture & would have reached near the auto ignition point.

Broken metal particles were sent to metallurgy lab test to determine composition of the metal. Following were the results.

Elbow	%Al	% Si	% Cu	% Zn	% Fe	% Ni	Aluminium Die -Cast A-380
	86.2	7.52	2.86	0.52	0.82	0.37	
	% Ti	% Mn	% Mg				
	0.21	0.32	0.13				

Endurance limit of Aluminum decreases with the number of cycles as shown in figure 6.

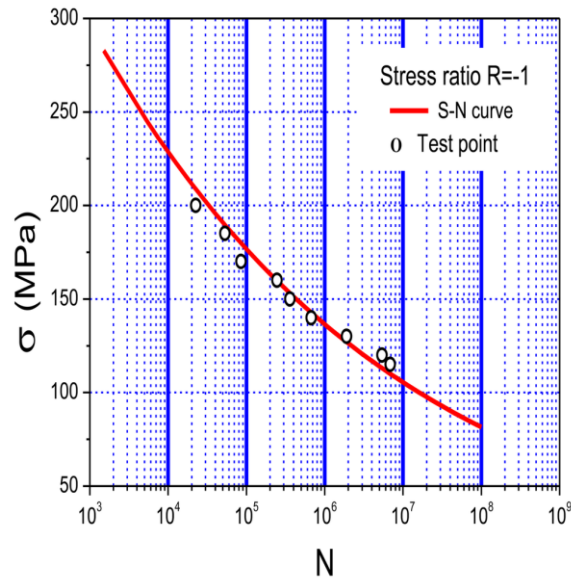


Figure 6: Aluminum Fatigue Life

Based on above the Kuwait has huge temperature difference between summers and winters. Highest temperature recorded was 54°C and the lowest was -6°C . The elbow was under constant reversal cycles of compression and tension as per the frequent operations of engine and also as per the frequent load change in the extreme weather conditions. This has exaggerated the extremities of fatigue life of the material (high stress ratio).

3.0 Conclusion

Critical Factors Analysis:


Fatigue of the material: Material was more than 23 years old under continuous load reversal cycles ($>1 \times 10^8$). This along with emergency shut down valve activation has caused the air temperature inside charge airline to rise above the auto ignition point of Diesel-Lube oil mixture.

The combination of both of these events has resulted into explosion of 7" diameter 8mm thick Aluminum alloy elbow of the charge air side of turbocharger.

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