Publication of the MIRCE Akademy

2016 Annals of MIRCE Science

> *"The goal of a scientist is to uncover new ideas, concepts and tools, practical or theoretical, that extend our understanding of the world around us and enable us to do new things. One must believe in what one is doing and stay the course. Now of course, in science one can ultimately prove the correctness of one's work by appeal to experiment and established theory. But even with this buttressing of one's ideas, acceptance can be a long and difficult road."*
>
> **Richard F.W. Bader (1931 – 2012)**
> **Grand Fellow of the MIRCE Akademy**

Publication Date: 31 December 2016

Publisher:
MIRCE Science Limited
Woodbury Park
Exeter
EX5 1JJ
United Kingdom

Phone: +44 (0) 1395 233 856
Email: quest@mirceakademy.com
Website; www.mirce.com

Editor: Dr J. Knezevic, President of the MIRCE Akademy

Editorial Board: Fellows of the MIRCE Akademy

All Rights Reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or any means, electronic, mechanical, photocopying, recording, scanning or otherwise, except under the terms of Copyright, Designs and Patents Act 1998 or under the terms of a license issued by the Copyright Licensing Agency, 90 Tottenham Court Road, London W1P 9HE, UK, without the permission in writing of the Publisher.

Mirce Science Limited has asserted his rights under the Copyright, Design and Patents Act, 1988, to be identified as the author of this book.

Neither the author nor MIRCE Science Ltd. accept any responsibility or liability for loss or damage occasioned to any person or property through using the material, instructions, methods or ideas contained herein, or acting or refraining from acting as a result of such use. The author and publisher expressly disclaim all implied warranties, including merchantability or fitness for any particular purpose.

Designations used by companies to distinguish their products are often claimed as trademarks. In all instances where MIRCE Science is aware of a claim, the product names appear in initial capital or all capital letters. Readers, however, should contact the appropriate companies for more complete information regarding trademarks and registration.

Price:	**General Public:**	**£95.00**
	MIRCE Akademy Fellows:	**£75.00**
	MIRCE Akademy Members:	**Free of charge**

For any questions regarding the Annals of Mirce-mechanics, please send an email to: quest@mirceakademy.com

Order Form: http://www.mirceakademy.com/uploads/Order%20Form-%20MA%287%29.pdf

To become a Member of the MIRCE Akademy please follow the link:
http://www.mirceakademy.com/index.php?page=Membership

Content

---

[1] Paper was presented at the 22 International Conference “Maintenance 2016”, in Sibenik, 16-18 May 2016, Croatia, organised by the Croatian Maintenance Society, www.hdo.hr

Mirce-mechanics

The philosophy of Mirce-mechanics is based on premises that the purpose of existence of machines is to do a work by delivering intended function(s) thought time, like transporting, communicating, cooling, informing, computing and others with measurable performance, like speed, capacity, frequency, power and similar physical quantities. However, experience teaches us that in-service life of machines is dominated by complex interactions between their consisting parts on one hand and their interactions with natural environment and human actions, on the other. As result a variety of mechanical, electrical, chemical, thermal, radiant and other types of energy are generated, some of which causing failures of machines to deliver intended function(s). Actions like servicing, repairing, testing, replacing, changing the mode of operation and similar that are required to regain functionability[2] of machine. Hence, in Mirce-mechanics a machine with associated in-service tasks, resources, constraints and environmental conditions constitute a maintainable system, which is ultimately and uniquely responsible for delivering functionability performance of a machine.

As all physical phenomena associated with the functionality of machines are characterised by certainty, reversibility and independence of time, location and human influences, their functionality performance can be accurately predicted by making use of well understood laws of natural sciences, such as: Newton's laws of motion, Maxwell's law of electrodynamics, Coulomb's law of solid friction, Boltzmann's law of thermodynamics, Hook's law of stress and strength, to name a few. However, the information regarding functionability performance of a machine within a given Mirce-system is almost non-existent at the beginning of in-service life. The reason being, all associated functionability phenomena are characterised by uncertainty, discontinuity, irreversibility, inseparability, and are dependent on time, location and human influences, Hence, the laws of natural sciences cannot be used to predict functionability performance of a maintainable systems in Mirce-mechanics.

To address rationally essential questions of the accurate predictions of functionability performance of machines in 1999 Dr Jezdimir Knezevic resigned from Exeter University, UK, and established the MIRCE Akademy at Woodbury Park, Exeter, UK. Staff, Fellows, Members and students of the Akademy have endeavoured to subject in-service behaviour of a maintainable systems to the proven methods of science and mathematics to:

1. Experimentally observe and measure their functionability performance of maintainable systems that are quantified through the work done by a system and the work done on a system throughout in-service life, together with the resources consumed in these processes[3], and prevailing environmental conditions, to determine their patterns in respect to time.
2. Scientifically understand physical phenomena that govern occurrences of functionability events[4] through life of a given maintainable system to the level of the dimensional fidelity ranging from the atom (10^{-10} metres) to the Solar System (10^{10} metres).

---

[2] Functionability, n. ability to deliver intended function, Knezevic, J., Reliability, Maintainability and Supportability – A probabilistic Approach, Text and Software package, pp. 291, McGraw Hill, London 1993. ISBN 0-07-707691-5

[3] Boeing 747, registration number N747PA, been air born 80,000 flying hours, transported 4,000,000 passengers, burned 271,000,000 gallons of fuel while receiving 806,000 maintenance man-hours and consuming: 2,100 tyres, 350 brake systems, 125 engines, among other parts, during the 22 years of in-service life, at Pan Am airlines.

[4] Any event, natural or induced, that impacts the functionability performance of maintainable systems.

3. Mathematically define a scheme for calculating expected functionability performance for a given maintainable system (uniquely determined by the physical properties of consisting parts and their configurations) within a given operational scenario, environmental conditions, maintenance policies, support strategy and in-service constraints.

Decades of research has generated new, science-based, body knowledge, named Mirce-mechanics. It comprises of axioms, laws, mathematical equations and calculation methods that enable accurate descriptions of functionability phenomena that are characterised by uncertainty, discontinuity, irreversibility, inseparability, and dependence on time, location and humans. Thus, Mirce-mechanics enables accurate predictions of the expected functionability performance of a given maintainability system, at the time when it is possible to achieve the best compromise between all feasible solutions and stake holders.

Volcanic Ash as a Mechanism of a Motion in Mirce-mechanics

Dr Jezdimir Knezevic,
MIRCE Akademy, Woodbury Park, Exeter, EX5 1 JJ, UK

Abstract

Mirce-mechanics is a scientific theory of the motion of in-service systems through Mirce Spacetime that enables prediction of the work done by them to be made by using Mirce Equations. Practical applications of Mirce-mechanics are possible only, when the physical mechanisms that generate the motion of systems through positive and negative states of Mirce Spacetime are understood. The mechanism of motion addressed in this paper is the impact that volcanic ashes made on the trajectory of maintainable systems through Mirce Spacetime. Volcanic ash fall is physically, socially and economically disruptive. It can affect both proximal areas and areas many hundreds of kilometres from the source, and causes disruptions and losses in a wide variety of different infrastructure sectors. Impacts are dependent on: ash fall thickness; the duration of the ash fall; the grain size and chemistry of the ash; whether the ash is wet or dry; and any preparedness, management and prevention measures employed to reduce effects from the ash fall. Specific emphasis is this paper is given to the analysis how different sectors of infrastructure and society are affected in different ways and are vulnerable to a range of impacts or consequences.

1. Introduction

Infrastructure is critical to supporting modern societies, particularly in urban areas, where high population densities create high demand for services. These infrastructure networks and systems support urban living, and provide lifeline services upon which human race depends for health, education, transport, communication, security and defence.

Among many natural phenomena that impact human lives, volcanic ash fall events can disrupt and or damage the infrastructure upon which society depends. Several recent eruptions have illustrated the vulnerability of urban areas that received only a few millimetres or centimetres of volcanic ash. This has been sufficient to cause disruption of transportation, electricity, water, sewage and storm water systems. Costs have been incurred from business disruption, replacement of damaged parts and insured losses. Ash fall impacts on critical infrastructure can also cause multiple knock-on effects, which may disrupt many different sectors and services.

Volcanic ash fall is physically, socially and economically disruptive. Volcanic ash can affect both proximal areas and areas many hundreds of kilometres from the source, and causes disruptions and losses in a wide variety of different infrastructure sectors. Impacts are dependent on: ash fall thickness; the duration of the ash fall; the grain size and chemistry of the ash; whether the ash is wet or dry; and any preparedness, management and prevention measures employed to reduce effects from the ash fall. Different sectors of infrastructure and society are affected in different ways and are vulnerable to a range of impacts or consequences.

The impacts on lifelines may also be inter-dependent. The vulnerability of each lifeline may depend on: the type of hazard, the spatial density of its critical linkages, the dependency on critical linkages, susceptibility to damage and speed of service restoration, state of repair or age, and institutional characteristics or ownership.

Recent, the most obvious example of the impact of volcanic ash on the human life was the 2010 eruption of Eyjafjallajokull in Iceland. It clearly highlighted the impacts of volcanic ash fall in modern society and our dependence on the functionality of infrastructure services. During this event the airline industry suffered business interruption losses of €1.5-2.5 billion from the closure of European airspace for six days in April 2010 and subsequent closures into May 2010[5]. It is necessary to stress that ash fall from this event is also known to have caused local crop losses in agricultural industries, losses in the tourism industry, destruction of roads and bridges in Iceland, in combination with glacial melt water. At the same time, across Europe there were further losses associated with travel disruption, the insurance industry, the postal service, and imports and exports across Europe and worldwide.

Consequently, the main objective of this paper is to address the volcanic ashes as a mechanism that generates physical actions which cause the motion of maintainable systems from the positive to negative functionability state. The impact of volcanic ash on diverse systems are presented here together with the consequences on the operational processes affected by it.

2. Mirce-mechanics Overview

Human needs for transportation, education, ventilation, communication, refrigeration, information, computation and many other functions are continuously satisfied through human created and managed products or constructions, commonly called systems. Their functionality performance, measured by speed, capacity, frequency, power and similar physical quantities, can be accurately predicted during the design process and tested at the delivery, as they are functioning in accordance to linear chains of cause and effect, well understood by laws of natural sciences, such as: Newton’s laws of motion, Maxwell’s law of electrodynamics, Coulomb’s law of solid friction, Hook’s law of stress and strain, Boltzmann’s law of thermodynamics, to name a few. All of them are characterised by certainty, reversibility and independence of time, location and humans.

Experience teaches us that due to complex internal interactions within the system, external impacts from environment and human actions, variety of mechanical, electrical, chemical, thermal, radiant and other types of energy are generated, some of which cause the failure of systems to deliver a function. To maintain f**unctionability**[6] actions like servicing, repairs, inspections, replacements and similar, are undertaken by humans, which make them maintainable systems. Thus, the life of a system could be considered as a motion through positive and negative functionability states through time, which is physically, manifested by occurrences of corresponding functionability events. Unlike accurate quantitative information regarding the design-in performance of systems that is available on the delivery

---

[5] 1."Volcanic ash crisis cost airlines £2.2 billion". The Daily Telegraph. UK, 27 April 2010.

[6] Functionability, n. ability to function, Knezevic, J., Reliability, Maintainability and Supportability – A probabilistic Approach, Text and Software package, pp. 291, McGraw Hill, London 1993. ISBN 0-07-707691-5

day, the in-service performance is not. Instead, years later the statistics for various functionability measures become available. The reason for this is the fact that they are characterised by uncertainty, discontinuity, irreversibility, inseparability, and dependence of time, location and humans, and as such non predictable by existing laws of science.

To rationally address questions of the accurate predictions of functionability performance of maintainable systems, prior to entry into service Dr Knezevic has established the MIRCE Akademy at Woodbury Park, Exeter, UK, in 1999. Staff, Fellows, Members and students of the Akademy have endeavoured to subject in-service behaviour of systems to the laws of science and mathematics to:

- Determine the trajectory of the motion of a system through functionability states through time, which is uniquely defined by the sequence of occurrences of positive and negative events, together with the statistics of the work done by the systems and on the system[7]
- Understanding mechanisms that lead to the occurrence of functionability events like fatigue, operator errors, corrosion, creep, foreign object damage, a faulty weld, carburettor icing, shelf life, perished rubber, to name just a few, which are manifested within physical scale from the atom to the Solar System (from 10^{-10} to 10^{10} metre).
- Define a mathematical scheme for predicting expected functionability performance of systems for a given operational scenario, maintenance policies and support strategy, which is vital for the calculation of the work done by the systems and on the system.

While in classical mechanics a force is said to do work if, when acting on a body, there is a displacement of the point of application in the direction of the force, in Mirce-mechanics a given system is said to do work, if there is a provision of measurable functions in the direction of time.

In summary, the body of knowledge comprising of axioms, mathematical equations and methods that enable engineering, predicting and managing the functionability performance of maintainable systems through time, based on the scientific understanding of the mechanisms that cause occurrences of observable positive and negative functionability events through the life of maintainable systems constitutes Mirce-mechanics.[3]

3. Impact of Volcanic Ashes on Functionability

3.1 Infrastructure sectors

During ash fall events large demands are commonly placed on water resources for cleanup and shortages can result. Shortages compromise key services such as fire fighting and can lead to a lack of water for hygiene, sanitation and drinking. Municipal authorities need to monitor and manage this water demand carefully, and may need to advise the public to utilise cleanup methods that do not use water (e.g., cleaning with brooms rather than hoses).

Wastewater networks may sustain damage similar to water supply networks. It is very difficult to exclude ash from the sewerage system. Systems with combined storm

---

[7] Boeing 747, registration number N747PA, been air born 80,000 flying hours, transported 4,000,000 passengers, burned 271,000,000 gallons of fuel while receiving 806,000 maintenance man-hours and consuming: 2,100 tyres, 350 brake systems, 125 engines, among other parts, during the 22 years of in-service life, at Pan Am airlines.

water/sewer lines are most at risk. Ash will enter sewer lines where there is inflow/infiltration by storm water through illegal connections like from roof downpipes, cross connections, around manhole covers or through holes and cracks in sewer pipes.

Ash-laden sewage entering a treatment plant is likely to cause failure of mechanical pre-screening equipment such as step screens or rotating screens. Ash that penetrates further into the system will settle and reduce the capacity of biological reactors as well as increasing the volume of sludge and changing its composition.

3.1.1 Drinking water supplies

Following an eruption, one of biggest fear for humans is a chemical contamination of water supplies. Generally speaking, the physical impacts of an ash fall tend to overwhelm problems caused by the release of chemical contaminants from fresh volcanic ash. However, impacts vary according to the type of treatment system.

Groundwater-fed systems are resilient to impacts from ash fall, although airborne ash can interferes with the operation of well-head pumps. Electricity outages caused by ash fall can also disrupt electrically powered pumps if there is no backup generation.
For surface water sources such as lakes and reservoirs, the volume available for dilution of ionic species leached from ash is generally large. The most abundant components of ash leachates are Ca, Na, Mg, K, Cl, F and SO_4 which occur naturally at significant concentrations in most surface waters and therefore are not affected greatly by inputs from volcanic ash fall, and are also of low concern in drinking water, with the possible exception of fluorine. The elements F, Mg and Al are commonly enriched over background levels by volcanic ash fall. These elements may impart a metallic taste to water, and may produce red, brown or black staining of white ware, but are not considered a health risk. Volcanic ash falls are not known to have caused problems in water supplies for toxic trace elements such as H and Pb, which occur at very low levels in ash leachates.

The physical impacts of ash fall can affect the operation of water treatment plants. Ash can block intake structures, cause severe abrasion damage to pump impellers and overload pump motors. Many water treatment plants have an initial coagulation or flocculation step that is automatically adjusted to turbidity, the level of suspended solids, measured in nephelometric turbidity units, in the incoming water. In most cases, changes in turbidity caused by suspended ash particles will be within the normal operating range of the plant and can be managed satisfactorily by adjusting the addition of coagulant. Ash falls will be more likely to cause problems for plants that are not designed for high levels of turbidity and which may omit coagulation or flocculation treatment. Ash can enter filtration systems such as open sand filters both by direct fallout and via intake waters. In most cases, increased maintenance will be required to manage the effects of an ash fall, but there will not be interruptions of functionability flow.

The final step of drinking water treatment is disinfection to ensure that final drinking water is free from infectious microorganisms. As suspended particles can provide a growth substrate for microorganisms and can protect them from disinfection treatment, it is extremely important that the water treatment process achieves a good level of removal of suspended particles.

Many small communities obtain their drinking water from diverse sources, like lakes, streams, springs and groundwater wells. Levels of treatment vary widely, from rudimentary systems with coarse screening or settling followed by disinfection, usually achieved by chlorination, to more sophisticated systems using a filtration step. It is necessary to stress that unless a high quality source is used, such as secure groundwater, disinfection alone is unlikely to guarantee that drinking water is safe from protozoa such as Giardia and Cryptosporidium, which are relatively resistant to standard disinfectants and which require additional removal steps such as filtration.

Volcanic ash fall is likely to have major effects on these systems. Ash will clog intake structures, cause abrasion damage to pumps and block pipes, settling ponds and open filters. High levels of turbidity are very likely to interfere with disinfection treatment and doses may have to be adjusted to compensate. It is essential to monitor chlorine residuals in the distribution system.

3.1.2 Rainwater-fed supplies

Many households, and some small communities, rely on rainwater for their drinking water supplies. Roof-fed systems are highly vulnerable to contamination by ash fall, as they have a large surface area relative to the storage tank volume. In these cases, leaching of chemical contaminants from the ash fall can become a health risk and drinking of water is not recommended. To deal with this situation prior to an ash fall, downpipes should be disconnected so that water in the tank is protected.

A further problem is that the surface coating of fresh volcanic ash can be acidic. Unlike most surface waters, rainwater generally has a very low alkalinity, acid-neutralising capacity, and thus ash fall may acidify tank waters. This may lead to problems with plumbo-solvency, whereby the water is more aggressive towards materials that it comes into contact with. This can be a particular problem if there are lead-head nails or lead flashing used on the roof, and for copper pipes and other metallic plumbing fittings.

3.2 Aviation Industry

The principal damage sustained by aircraft flying into a volcanic ash cloud is abrasion to forward-facing surfaces, such as the windshield and leading edges of the wings, and accumulation of ash into surface openings, including engines. Abrasion of windshields and landing lights will reduce visibility forcing pilots to rely on their instruments. However, some instruments, like pitot tubes, may provide incorrect readings as sensors can become blocked with ash. Ingestion of ash into engines causes abrasion damage to compressor fan blades. The ash erodes sharp blades in the compressor, reducing its efficiency. The ash melts in the combustion chamber to form molten glass. The ash then solidifies on turbine blades, blocking air flow and causing the engine to stall.

The composition of most ash is such that its melting temperature is within the operating temperature above 1000°C of modern large jet engines[8]. The degree of impact depends upon the concentration of ash in the plume, the length of time the aircraft spends within the plume and the actions taken by the pilots. Critically, melting of ash, particularly volcanic glass, can

---

4 Sammonds, P.; McGuire, B.; Edwards, S. Volcanic hazard from Iceland: analysis and implications of the Eyjafjallajökull eruption. UCL Institute for Risk and Disaster Reduction Report, UK, 2010.

result in accumulation of re-solidified ash on turbine nozzle guide vanes, resulting in compressor stall and complete loss of engine thrust. The standard procedure of the engine control system when it detects a possible stall is to increase power which would exacerbate the problem. It is recommended that pilots reduce engine power and quickly exit the cloud by performing a descending 180° turn[9]. Volcanic gases, which are present within ash clouds, can also cause damage to engines and acrylic windshields, although this damage may not surface for many years.

3.2.1 Recent Occurrence

There are many instances of damage to jet aircraft as a result of an ash encounter, some of which are presented below:

- On 24 June 1982 a British Airways Boeing 747-236B (Flight 9) flew through the ash cloud from the eruption of Mount Galunggung, Indonesia resulting in the failure of all four engines. The plane descended 24,000 feet (7,300 m) in 16 minutes before the engines restarted, allowing the aircraft to make an emergency landing.
- On 15 December 1989 a KLM Boeing 747-400 (Flight 867) also lost power to all four engines after flying into an ash cloud from Mount Redoubt, Alaska. After dropping 14,700 feet (4,500 m) in four minutes, the engines were started just 1–2 minutes before impact. Total damage was US$80 million and it took 3 months' work to return the plane into functionable state.
- In the 1991 a further US$100 million of damage was sustained by commercial aircraft, some in the air, others on the ground, as a consequence of the eruption of Mount Pinatubo in the Philippines.
- In April 2010 airspace all over Europe was affected, with many flights cancelled-which was unprecedented-due to the presence of volcanic ash in the upper atmosphere from the eruption of the Icelandic volcano Eyjafjallajökull.
- On 15 April 2010 the Finnish Air Force halted training flights when damage was found from volcanic dust ingestion by the engines of one of its Boeing F-18 Hornet fighters.
- On 22 April 2010 UK RAF Typhoon training flights were also temporarily suspended after deposits of volcanic ash were found in a jet's engines. In June 2011 there were similar closures of airspace in Chile, Argentina, Brazil, Australia and New Zealand, following the eruption of Puyehue-Cordón Caulle, Chile.

3.2.2 Detection

Volcanic ash clouds are very difficult to detect from aircraft as no onboard cockpit instruments exist to detect them. However, a new system called Airborne Volcanic Object Infrared Detector, AVOID, has recently been developed by Nicarnica Aviation, a daughter company of the Norwegian Institute for Air Research, which will allow pilots to detect ash plumes up to 100 km ahead and fly safely around them[10]. The system uses two fast-sampling infrared cameras, mounted on a forward-facing surface, that are tuned to detect volcanic ash. This system can detect ash concentrations of less than 1 mg/m^3 up to 50 mg/m^3, giving pilots approximately 10 minutes warning.

---

[9] Miller, T.P.; Casadevall, T.J., . "Volcanic ash hazards to aviation". In H., Sigurdsson; B.F., Houghton; S.R., McNutt; H., Rymer; J., Stix. Encyclopedia of Volcanoes. San Diego, USA: Elsevier Inc. p. 1417, 2000.

[10] "No more volcanic ash plane chaos?". Norwegian Institute for Air Research. 4 December 2011

In addition, ground and satellite based imagery, radar, and lidar can be used to detect ash clouds. This information is passed between meteorological agencies, volcanic observatories and airline companies through Volcanic Ash Advisory Centers, VAAC. There is one VAAC for each of the nine regions of the world and each can issue advisories describing the current and future extent of the ash cloud.

3.2.3 Airport systems

Volcanic ash not only affects in-flight operations but can affect ground-based airport operations as well. Small accumulations of ash can reduce visibility, create slippery runways and taxiways, infiltrate communication and electrical systems, interrupt ground services, damage buildings and parked aircraft.

Ash accumulation of more than a few millimetres requires removal before airports can resume full operations. Unlike snowfalls that disappear, ash fall must be disposed of in a manner that prevents it from being remobilised by wind and aircraft.

3.3 Other Transport

Ash may disrupt transportation systems over large areas for hours to days, including roads and vehicles, railways and ports and shipping.

Falling ash will reduce the visibility which can make driving difficult and dangerous. In addition, fast travelling cars will stir up ash, creating billowing clouds which perpetuate ongoing visibility hazards. Ash accumulations will decrease traction, especially when wet, and cover road markings. Fine-grained ash can infiltrate openings in cars and abrade most surfaces, especially between moving parts. Air and oil filters will become blocked requiring frequent replacement.

Rail transport is less vulnerable, with disruptions mainly caused by reduction in visibility.

Marine transport can also be impacted by volcanic ash. Ash fall will block air and oil filters and abrade any moving parts if ingested into engines. Navigation will be impacted by a reduction in visibility during ash fall. Vesiculated ash, pumice and scoria, will float on the water surface in ‘pumice rafts’ which can clog water intakes quickly, leading to over heating of machinery.

3.4 Communication Systems

Telecommunication and broadcast networks can be affected by volcanic ash in the following ways: attenuation and reduction of signal strength; damage to equipment and overloading of network through user demand.

Signal attenuation due to volcanic ash is not well documented. However, there have been reports of disrupted communications following the 1969 Surtsey eruption and 1991 Mount Pinatubo eruption. Research by the New Zealand-based Auckland Engineering Lifelines Group determined theoretically that impacts on telecommunications signals from ash would be limited to low frequency services such as satellite communication[11]. Signal interference may also be caused by lightning, as this is frequently generated within volcanic eruption plumes[12].

Telecommunication equipment may become damaged due to direct ash fall. Most modern equipment requires constant cooling from air conditioning units. These are susceptible to blockage by ash which reduces their cooling efficiency. Heavy ash falls may cause telecommunication lines, masts, cables, aerials, antennae dishes and towers to collapse due to ash loading. Moist ash may also cause accelerated corrosion of metal components[5].

Reports from recent eruptions suggest that the largest disruption to communication networks is overloading due to high user demand, which is common phenomenon in many natural disasters.

3.5 Electricity Supply Systems

Volcanic ash can cause disruption to electric power supply systems at all levels of power generation, transformation, transmission and distribution.

There are four main impacts arising from ash-contamination of apparatus used in the power delivery process:

- Wet deposits of ash on high voltage insulators can initiate a leakage of a small amount of current flow across the insulator surface that, if sufficient current is achieved, can cause the unintended electrical discharge around or over the surface of an insulating material.

- If the resulting short-circuits current is high enough to trip the circuit breaker then disruption of service will occur. Ash-induced flashover across transformer insulation can burn, etch or crack the insulation irreparably and will likely result in the disruption of power supply

- Volcanic ash can erode, pit and scour metallic apparatus, particularly moving parts such as water and wind turbines and cooling fans on transformers or thermal power plants.

- The high bulk density of some ash deposits can cause line breakage and damage to steel towers and wooden poles due to ash loading. This is most hazardous when the ash and/or the lines and structures are wet and there has been over 10 mm of ash fall. Fine-grained ash (less than 0.5 mm in diameter) adheres to lines and structures most readily. Volcanic ash may also load overhanging vegetation, causing it to fall onto lines. Snow and ice accumulation on lines and overhanging vegetation further increases the risk of breakage and or collapse of lines and other hardware.

3.6 Computers

---

[11] Wilson, T.M., Vulnerability of Pastoral Farming Systems to Volcanic Ash fall Hazard, 2009.

[12] McNutt, S.R.; Williams, E.R. (2010). "Volcanic lightning: global observations and constraints on source mechanisms". Bulletin of Volcanology. Bibcode:2010BVol...72.1153M. doi:10.1007/s00445-010-0393-4.

Computers may be impacted by volcanic ash, with their functionality and usability decreasing during ash fall, but it is unlikely they will completely fail. The most vulnerable components are the mechanical components, such as cooling fans, CD drives, keyboard, mice and touch pads. These components can become jammed with fine grained ash causing them to cease working; however, most can be restored to working order by cleaning with compressed air.

Moist ash may cause electrical short circuits within desktop computers; however, will not affect laptop computers[13].

3.7 Buildings and Structures

Damage to buildings and structures can range from complete or partial roof collapse to less catastrophic damage of exterior and internal materials.

Impacts depend on the thickness of ash, whether it is wet or dry, the roof and building design and how much ash gets inside a building. The specific weight of ash can vary significantly and rain can increase this by 50-100%. Problems associated with ash loading are similar to that of snow. However, ash is more severe as:

1) the load from ash is generally much greater
2) ash does not melt
3) ash can clog and damage gutters, especially after rain fall.

Impacts for ash loading depend on building design and construction, including roof slope, construction materials, roof span and support system, and age and maintenance of the building.

Generally flat roofs are more susceptible to damage and collapse than steeply pitched roofs. Roofs made of smooth materials, like sheet metal or glass are more likely to shed ash than roofs made with rough materials like thatch, asphalt or wood shingles.
Roof collapse can lead to widespread injuries and deaths and property damage. For example, the collapse of roofs from ash during the 15 June 1991 Mount Pinatubo eruption killed about 300 people.

3.8 Environment and agriculture

Volcanic ash can have a detrimental impact on the environment which can be difficult to predict due to the large variety of environmental conditions that exist within the ash fall zone. Natural waterways can be impacted in the same way as urban water supply networks. Ash will increase water turbidity which can reduce the amount of light reaching lower depths, which can inhibit growth of submerged aquatic plants and consequently affect species which are dependent on them such as fish and shellfish. High turbidity can also affect the ability of fish gills to absorb dissolved oxygen. Acidification will also occur, which will reduce the pH of the water and impact the fauna and flora living in the environment. Fluoride contamination will occur if the ash contains high concentrations of fluoride.

---

[13] Wilson, G.; Wilson, T.M.; Cole, J.W.; Oze, C. (2012). "Vulnerability of laptop computers to volcanic ash and gas". Natural Hazards. doi:10.1007/s11069-012-0176-7.

Ash accumulation will also affect pasture, plants and trees which are part of the horticulture and agriculture industries. Thin ash falls (<20 mm) may put livestock off eating, and can inhibit transpiration and photosynthesis and alter growth. There may be an increase in pasture production due to a mulching effect and slight fertilizing effect, such as occurred following the 1980 Mount St. Helens and 1995/96 Mt Ruapehu eruptions. Heavier falls will completely bury pastures and soil leading to death of pasture and sterilization of the soil due to oxygen deprivation. Plant survival is dependent on ash thickness, ash chemistry, compaction of ash, amount of rainfall, duration of burial and the length of plant stalks at the time of ash fall. The acidic nature of ash will lead to elevated soil sulfur levels and lowered soil pH, which can reduce the availability of essential minerals and alter the soil’s characteristics so that crops and plants will not survive. Ash will also impact upon arable crops, such as fruit, vegetables and grain. Ash can burn plant and crop tissue reducing quality, contaminate crops during harvest and damage plants from ash loading.

Young forests, trees less than 2 years old, are most at risk from ash falls and are likely to be destroyed by ash deposits beyond 100 mm. Ash fall is unlikely to kill mature trees, but ash loading may break large branches during heavy ash falls, with deposits above 500 mm. Defoliation of trees may also occur, especially if there is a coarse ash component within the ash fall.

Land rehabilitation after ash fall may be possible depending on the ash deposit thickness. Rehabilitation treatment may include: direct seeding of deposit; mixing of deposit with buried soil; scraping of ash deposit from land surface; and application of new topsoil over the ash deposit.

4 Conclusions

Mirce-mechanics is a scientific theory of the motion of in-service systems through Mirce Spacetime that enables prediction of the work done by them to be made by using Mirce Equations. Practical applications of Mirce-mechanics are possible only, when the physical mechanisms that generate the motion of systems through positive and negative states of Mirce Spacetime are understood. The mechanism of motion addressed in this paper is the impact that volcanic ashes made on the trajectory of maintainable systems through Mirce Spacetime.

Volcanic ash fall is physically, socially and economically disruptive. It can affect both proximal areas and areas many hundreds of kilometres from the source, and causes disruptions and losses in a wide variety of different infrastructure sectors. Impacts are dependent on: ash fall thickness; the duration of the ash fall; the grain size and chemistry of the ash; whether the ash is wet or dry; and any preparedness, management and prevention measures employed to reduce effects from the ash fall.

It is important to stress volcanic ashes cause the motion of many systems into negative functionability state as well as it requires actions to cause the move of a system into positive functionability state.

Specific emphasis is this paper is given to the analysis how different sectors of infrastructure and society are affected in different ways and are vulnerable to a range of impacts or consequences.

5. References

1. Warwick, G., NASA’s Ash Trials: Engine Survives, Provides Insight, Aviation Week & Space Technology, Oct 26, 2015
2. Fruchter, J.S.; Robertson, D.E.; Evans, J.C.; Olsen, K.B.; Lepel, E.A.; et al. (1980). "Mount St. Helens ash from the 18 May 1980 eruption: chemical, physical, mineralogical, and biological properties". Science 209 (4461): 1116–1125.
3. Jones, M.T.; Gíslason, S.R. (2008). "Rapid releases of metal salts and nutrients following the deposition of volcanic ash into aqueous environments". Geochimica et Cosmochimica Acta **72**: 3661–3680.
4. Nellis, C.A.; Hendrix, K.W. (1980). "Progress report on the investigation of volcanic ash fallout from Mount St Helens". Bonneville Power Administration, Laboratory Report ERJ-80-47
5. Sarkinen, C.F.; Wiitala, J.T. (1981). "Investigation of volcanic ash in transmission facilities in the Pacific Northwest". IEEE Transactions on Power Apparatus and Systems 100: 2278–2286.
6. Shipley, S.; Sarna-Wojcicki, A.M. (1982). "Distribution, thickness, and mass of late pleistocene and holocene tephra from major volcanoes in the northwestern United States: a preliminary assessment of hazards from volcanic ejecta to nuclear reactors in the Pacific Northwest". US Geological Survey Miscellaneous Field Studies Map MF-1435.
7. Johnston, D.M.; Stewart, C.; Leonard, G.S.; Hoverd, J.; Thordarsson, T.; Cronin, S. (2004). "Impacts of volcanic ash on water supplies in Auckland: part I". Institute of Geological and Nuclear Sciences Science Report: 25.
8. Leonard, G.S.; Johnston, D.M.; Williams, S.; Cole, J.W.; Finnis, K.; Barnard, S. (2005). "Impacts and management of recent volcanic eruptions in Ecuador: lessons for New Zealand". Institute of Geological and Nuclear Sciences Science Report: 51.

Maintainability Design Principles for Aircraft Maintenance Error Avoidance

Clive Nicholas
Mirce Engineering, Woodbury Park, Woodbury, Exeter EX5 1JJ, UK

Abstract

There has long been a philosophy in aircraft design that errors by maintainers are not the concern of the designer – maintainers should be trained not to make errors. That philosophy is rapidly changing. There is an increasing awareness by regulators, designer/manufacturers, operators and other organisations in the aircraft industry of the impact that the design characteristics of aircraft can have on safe and effective maintenance performance and, in particular, on the avoidance of maintenance error and the mitigation of its consequences.

Designers of aircraft, systems and components cannot influence all of the many factors that might influence maintenance performance and maintenance error. However, designers have an important role to play because design characteristics have a significant impact on the form, frequency and duration of the maintenance task and have important implications for the possible occurrence of maintenance error.

From a design perspective, there are a number of complementary and integrated strategies that can be adopted to effectively address the relationship between design characteristics and maintenance error including – i) to specify design requirements for aircraft, system and component design that directly address the possibility of maintenance error, ii) to integrate into design general principles that can be applied by the aircraft, system or component designer to assist in them in designing to prevent maintenance error or, if this is not practicable, to reduce its negative effects, and iii) to analyse design solutions for maintenance error through formal evaluation processes such as human hazard or human error analyses.

This paper examines the second of these strategies. It identifies and discusses the rationale of general design principles that can be adopted by designers as part of an overall design effort for maintenance performance.

It is based on the author's experience in developing design principles for maintenance performance and in developing and delivering practical training for designers of commercial aircraft.

Key Words:

Maintainability, Maintenance Performance, Maintenance Error, Human Error, Design Principles

1. Maintenance Error

The aircraft maintenance process consists of a flow of tasks designed to maintain the safe and effective operation of the aircraft in service. Maintenance tasks typically include removal, installation, servicing, rigging, inspection, cleaning and other maintenance activities.

The execution of any maintenance task involves the possibility of error. Error in aircraft maintenance is the consequence of a complex interaction of many factors including system and maintenance task design, maintenance personnel and other resources, maintenance organisation, and the physical environment in which the maintenance occurs.

Maintenance error can be formally defined as the unintentional act of performing a maintenance task incorrectly that can potentially degrade the performance of the aircraft. For example, if a maintainer working in limited conditions of visual access fails to connect a component correctly the resulting maintenance error could be an incorrect installation leading to potential failure of the component.

Human behaviour is variable and is determined by a considerable range of factors that can vary significantly in different conditions and environments. Common factors can produce different responses and effects. Individual behaviours do not display uniformity and the designer would find it difficult to generate a design solution that would be applicable to the individual behaviours of maintainers. However, when designing an aircraft system or component the designer can address common patterns of behaviour manifest in reasonably foreseeable maintenance errors.

Empirical evidence indicates that there are common maintenance errors that tend to reoccur. Frequently occurring maintenance errors include –

- Wrong part installed
- Fault not found by inspection
- Incomplete installation
- Cross connection
- Fault not detected
- Wrong orientation
- Access not closed
- Wrong fluid
- Servicing not performed
- Fault not found by test
- System not deactivated
- Material left in aircraft

Most errors in aircraft maintenance are the result of unintentional or inappropriate actions that lead to maintenance error in a particular set of circumstances. There are also intentional actions on the part of the maintainer when, for some reason, it is either considered to be the correct action or a better way of performing a maintenance task. It should be recognised that maintenance error does not necessarily result in degradation of the aircraft.

An error can be recovered or corrected, before it results in consequential degradation. The consequence of maintenance error may be relatively insignificant or largely economic and recoverable. However, maintenance error can potentially lead to catastrophic consequences with loss of both aircraft and of life.

2. Design Impact

The correct completion of an aircraft maintenance task depends upon the interaction and interrelationships of the design characteristics of the aircraft and its operation in a particular environment. Design characteristics of the aircraft include technical systems and components. They also include the consequent design of maintenance tasks, procedures, manuals, tools, equipment and initial training of maintainers. Operation will include the characteristics of maintenance personnel, the maintenance organisation and the physical environment within which they work.

The potential for maintenance error arises where the maintainer and the aircraft interact through the maintenance task. The purpose of the aircraft is to provide a set of functions that enable its operation to deliver a safe flight that departs and arrives on schedule. The aircraft's ability to deliver safe and effective flights is sustained through maintenance to ensure that it functions as and when required.

The operation, maintenance and support of an aircraft are made up of related processes, which consist of tasks carried out by humans using physical resources.

A maintenance task can be described in the following terms –

- A maintenance task is any specified set of maintenance actions that is performed to maintain the required function of an aircraft component or system.
- The set of maintenance actions is related by their task requirement and their sequential occurrence in time.
- The execution of maintenance tasks involves human actions that comprise of some combination of cognitive ("thinking") and physical action ("doing").
- Each task requires an expected level of maintenance performance to be complete each action and the task as a whole.

The successful completion of a maintenance task as specified therefore involves –

- The human – performance and limitations (e.g. vision, hearing, physique, perception, memory, fatigue, etc.).
- System and process design – the demands placed on human performance that are the result of design (e.g. operation, maintenance and support task and resource demands).
- System and process operation – the demands placed on human performance that are a result of operation (e.g. organisation, procedures, etc.).
- Physical environment – the demands placed on human performance that are a result of the physical environment in which the task is performed (e.g. climate, temperature, noise, illumination, etc.).

Aircraft designers are not in a position to control or directly influence all these factors. Nevertheless, the design of aircraft systems and components can have a significant impact on maintenance performance. System and component design characteristics can promote correct performance of the maintenance task. Importantly, design characteristics can potentially reduce the likelihood and consequences of maintenance errors and hazards to the maintainer safeguarding both the aircraft and the maintainer.

As previously stated, the maintainer and the aircraft interact through the maintenance task. It is through the maintenance task that the aircraft affects the performance of the maintainer and the maintainer affects the performance of the aircraft. The design of the system or component will influence the type, frequency and duration of maintenance tasks carried out in operation.

Key questions for the designer to consider are –

- what types maintenance tasks does the design generate and what actions do they involve?
- how often is the maintenance task needed and how long will it take?
- what demands does the design place upon the capabilities of the maintainer to complete maintenance task?
- can the demands of the task exceed the possible limitations of the maintainer?

The complexity of design configuration, physical form, weight, location, access, method of installation, visual information and similar factors play an important part in determining the demands placed upon the level of maintenance performance required to successfully complete a maintenance task. Different designs will have different effects on maintenance performance. For example, the use of fewer parts may influence how easy it is to do the task – improving maintenance performance and reducing the likelihood of maintenance error.

Aircraft maintenance often involves complex processes that place considerable demands upon the maintainer to perform at the level required by the maintenance task. Maintenance often occurs in environments that also often place considerable demands upon the maintainer.

It is important to recognise the human capabilities and limitations of the maintainer and the capabilities and limitations that are inherent in any aircraft design. It involves the design of aircraft so that the relationship between the aircraft design and the maintainer effected through the maintenance task will result in optimal maintenance performance that minimises demands on maintainers that could lead to maintenance error.

The design of aircraft systems and components and the operational environment in which that design functions will influence the behaviour of the maintainer – for example, how easy it is to complete the task. Design characteristics can generate tasks that are within the capabilities and limitations of the maintainer that have a potentially positive effect on maintenance performance. Equally, design characteristics can challenge the capabilities and limitations of the maintainer and have a potentially negative effect on maintenance performance. Amongst other consequences, such as decreased maintenance efficiency, this could lead to error or personal injury during maintenance.

Design can therefore affect the vulnerability of an aircraft to maintenance error and the consequences of that error. By actively integrating general principles that address maintenance error into the design process, it is possible to create design characteristics that can possibly prevent or reduce maintenance error (e.g. sealed units or colour coding), or, eliminate or mitigate the consequences of maintenance error (e.g. isolation or partial operation).

3. General Design Principles

In developing design strategies and principles that enable the practical realization of these strategies through physical design characteristics, it is important to recognize that error is an integral and important part of fundamental human behaviour – it is part of the normal cognitive and learning processes of the human. Indeed, error in itself is not inherently problematic. It is only problematic when its consequences bring about unwanted or negative consequences. Design strategies should therefore attempt to avoid errors or to contain the consequences before they become negative. Error in maintenance is a normal part of maintenance operations that can be addressed during the design process.

Design strategies may revolve around two basic approaches. The first is avoidance of error. Here the error may be completely avoided by prevention. Examples of this type of strategy include designing out operation significant maintenance tasks, the design of components that are physically impossible to assemble or install incorrectly and the use of staggered part positions that require a specific configuration or sealed units that do not require intervention.

It is also possible to reduce the frequency of occurrence of error. Examples of error frequency reduction include the use of different part numbers, colour coding, shaped switch tops, locking switches, standard display formats, standard direction of operation, convenient access panels, reduction of servicing frequency, protection against accidental damage, or lubrication points that do not require disassembly.

The second is tolerance of error. Here mechanisms to detect error, to reduce the impact of error, and to recover error may be employed. Mechanisms to detect error may include built-in tests, functional tests, illuminated test points, functionally grouped tests or warning lights. Detection error can also include initial training of the maintainer for system state recognition. Reduction of the impact of error can be achieved through strategies such as isolation of the consequences of error, the ability for partial operation or the use of redundancy in systems or components. Recovery of error may be achieved through self-correction, the development of recovery procedures or specific training for error recovery.

Specific design objectives can be summarised as follows –

- Design that absolutely eliminates any possibility of an identified maintenance error or eliminates its consequences.
- Design that reduces the size of an identified maintenance error or reduces the extent of its consequences.
- Design that reduces how often an identified maintenance error, or how often its consequences, are likely to occur.
- Design that ensures that the maintenance error or its consequences is evident under all maintenance conditions, easy and rapid to detect, and is detected before flight.

- Design that ensures that following a maintenance error the means to return a system to its correct state are evident, easy, and timely.

In practice, the strategies of avoidance and tolerance are complementary and it may be felt necessary to design using a combination. An error tolerant design may be combined with error avoidance mechanisms to produce a robust design. Total avoidance of error may be considered to be an ideal given the nature and variability of human performance – error tolerance will capture and contain errors that fail avoidance mechanisms.

The general design principles discussed below provide practical means by which these strategies can be realised.

3.1 Appreciate the maintainer's perspective of the aircraft

Designers design systems or components to deliver their required functionality. Maintainers are responsible for maintaining that functionality over the life of the aircraft whilst ensuring safety standards and operational requirements are met.

As a consequence, maintainers have a very specific perspective of an aircraft that will focus on the efficiency and safety of maintenance. Maintainers look for '*maintainer friendly aircraft*' whose design characteristics enable them to achieve good maintenance performance that deliver the aircraft back into service when required by the operator and that will complete the flight in safety.

From the maintainer's perspective therefore questions such as those below are of critical importance in achieving the necessary standards of maintenance performance to achieve these objectives. Hence,

- How long will the task take?Is the task complicated?How often is the task required?
- Do I need special training?
- Do I need special tools or equipment?Could I make an error?
- How will I know if things go wrong?Where is the item located on the aircraft?
- Is there enough space to work in?Can I see the item?
- Can I reach the item?Where will I carry out the maintenance?

It is particularly important that the design of a system or component does not infringe normal maintenance practices and the reasonable expectations of the maintainer based on training and experience. Maintainers might reasonably expect, for example, that on a dial values will increase clockwise.

3.2 Understand and design for the aircraft maintenance environment

To fully appreciate the impact of design on maintenance performance it is important to understand the environment in which aircraft maintainers work. Aircraft maintenance generally takes place under conditions that are complex and very demanding.

Line maintenance, for example, is generally performed outside the hanger working on the airport ramp or apron area in all types of weather and climate, often at night with limited visibility. The environment is extremely busy with aircraft loading and servicing vehicles moving around. There is considerable noise and there are fumes from aircraft engines and

APUs (auxiliary power units) running. Above all there is constant pressure to complete maintenance activities as quickly as possible to turn the aircraft around on time for departure. Operators are in the business of transporting passengers. Aircraft on the ground cost money and loose revenue for the operator.

Similarly, base maintenance that is generally carried out in the hanger involves an environment where there is a considerable amount of activity and pressure to get the job done. Having to meet exacting work schedules while still observing standard procedures and safety standards can be stressful. The hangar is generally noisy from the use of power tools and there are many fluids and substances (hydraulic fluids, cleaning compounds, fuel, paints, etc.) that are potentially dangerous. Maintenance is often carried out at night when the aircraft are not in use. This means the work requires regular shift working. Requirements for overtime working and call-outs are common. Maintenance tasks can be physically demanding involving lifting, working in uncomfortable positions or working at height on scaffolds or cherry pickers (lifts).

The aircraft maintenance environment places considerable demands upon the maintainer and upon maintenance performance. The physical environment has an impact on maintenance performance through –

- lighting
- climate (dry or humid climates)
- temperature (hot or cold temperatures)
- weather (rain, wind, ice, snow, etc.)
- fumes and toxic substances
- noise
- motion
- vibration

Clearly designers cannot directly influence the many factors present in the working environment that will affect maintenance performance. However, they can have an impact on maintenance performance by taking them into consideration during the design process and reflecting this in design solutions. For example, where maintenance tasks are carried out in extremely low temperatures it is important to consider whether a maintenance task generated by a particular design could be carried out whilst wearing gloves or other protective clothing. On aircraft lighting can be used where there are light limitations for critical tasks such as inspection.

Design solutions that consider the physical environment in which maintenance is conducted can reduce the potentially negative impact that it can have on maintenance performance.

3.3 Protect the aircraft and protect the maintainer

Design solutions can actively influence both the impact that the maintainer has on the aircraft (e.g. through maintenance error or routine violation of procedures) and the impact that the aircraft has on the maintainer (e.g. through the health and safety effects of aircraft design).

Examples of design features that are tolerant to the consequences of maintenance error or resistant to the effects of maintenance activity and maintenance environment include –

- Designing out safety critical maintenance tasks
- Items physically impossible to assemble or install incorrectly
- Staggered part positions
- Partial operation or redundancyShaped switch tops, display formats, direction of operation, etc.
- Warning lights and illuminated test points

Examples of design considerations to protect maintenance personnel from risks, hazards, incidents, injuries or illnesses include –

- electrical isolation and protection from high voltages
- adequate circuit breakers and fuses
- rounded corners and edges
- warning labels
- hot areas shielded and labelled
- hazardous substances and radiation not emitted

Protecting the maintainer is important not only from a health and safety perspective – demands placed on the maintainer that can be potentially injurious can also lead to the occurrence of maintenance error. Design can place undue physical stresses on the maintainer. The maintainer may be required to wear cumbersome protective equipment to work in particular areas of the aircraft such as fuel tanks. The fatigue that can result could generate error. Other stressing design characteristics are those that, for example, involve inadequate lighting, vibration or noise, undue strength requirements for maintenance activities, unusual positions in which to carry out maintenance, or proximity of hot surfaces. A maintainer who must work close to heat generating components in a humid environment may rapidly loose body fluid, through perspiration as a result of increasing body temperature, which will seriously affect the ability to function correctly. If working close to a hot component, the maintainer must continuously avoid being burned whilst undertaking the maintenance task. The presence of such psychological and physical stressors can potentially lead to error.

Example – The Boeing 777 Refuelling Panel

> *Boeing didn't think of the fact that existing fuel stands only reached a certain height to fuel under the wings of the airplane. The 747 was about as high as the fuel stands could go to reach that fuelling panel, and the panel designed on the 777 was thirty-one inches higher than the 747.*

Refuellers got very upset. "Have you ever fuelled an airplane in a high wind at O'Hare?" they said – "it's really uncomfortable."

To go any higher without additional stability would be a safety issue. Unless the operators hired personnel who are eight feet tall it wouldn't work. Boeing agreed to move the panel down the wing, closer to the fuselage, and, because the wing is slanted up, by moving it inboard it also came closer to the ground - within six inches of reaching the panel. Safety specialists allowed a stool to be put on the top of the fuelling platform to reach the panel. Adapted from Sabbagh K. (1996) 21st Century Jet – The Making of the Boeing 777, Pan Books, pp. 73-74.

3.4 Avoid complexity of maintenance tasks

The design of a system or component will impact upon both the cognitive (thinking) and physical (doing) demands of the maintenance task. Complexity in design can generate complex maintenance tasks that are difficult to understand and difficult to do.

However, the avoidance of complexity in design need not compromise or constrain the technical design solution. The design principle is concerned with the effect that the design on the maintenance task – an advanced design solution does not necessarily generate complexity in maintenance.

Example – Airbus A320 Flap Rotary Actuator

There are four rotary actuators on each wing of the A320. The function of these actuators is to translate the rotary motion of the flap drive shaft into movement of the flaps. Following flap lock events, it was reported in several cases that the flap rotary actuators had recently been removed for re-greasing.

Investigation revealed that during accomplishment of removal or installation slight mis-rigging in the flap transmission had been induced. This was found as a contributing actor factor in the reported flap locks.

Existing flap rotary actuators filled with grease needed removal for re-greasing approximately every 5 years. A new type of actuator introduced is filled with semi fluid and is serviceable on the wing.

The design solution simplified the maintenance task by eliminating the need for removal/installation of the actuators and thereby removing the opportunity for miss-rigging.

Adapted from Airbus FAST Technical Magazine A320 Special May 2005.

3.5 Enable adequate maintenance access

Accessibility means having adequate visual and physical access to perform maintenance safely and effectively. Adequate physical and visual access is needed not only for repair, replacement, servicing, and lubrication but also for troubleshooting, checking and inspection.

Examples of physical access considerations include –

- adequate access to frequent maintenance areas
- openings of adequate size
- avoidance of the need to remove or large numbers of components, fittings, etc. to reach a component
- replacement of components with the least amount of handling
- workspace for manipulative tasks, body and tools positions and movements

Examples of visual access considerations include –

- avoidance of unnecessary obstructions to the maintainer’s line of sight

- lighting level and direction

Some components by their function or requirements have to be located in poorly accessible areas – a design solution in such cases might be the use of integrated access platforms or other aids to access.

Example – B-1B Engine Visual Access

Each engine on the B-1B bomber has an accessory drive gearbox (ADG). A hinged access door with four thumb latches is provided on each compartment panel for servicing. The access door permits checking of the ADG oil without having to remove the compartment panel. However, the oil level sight gauge requires line-of-sight reading. The way it is installed, the gauge cannot be read through the access door, even with an inspection mirror. The entire compartment panel, secured with 63 fasteners, must be removed just to see if oil servicing is needed.Adapted from Worm CM. (1997) The Real World – A Maintainer's View, Proceedings IEEE Reliability and Maintainability Symposium, IEEE.

3.6 Positively standardise and positively differentiate

Aircraft maintenance tasks are largely repetitive and standardised. Maintainers rely on pattern recognitions that are determined by their training and experience to identify system and component type properties and the form of the maintenance tasks that are required.

Commonality in design enables such pattern recognition and enhances maintenance performance. If, for example, a part has commonality in function and properties (and, of course, fully meets all requirements of the design specification) then it makes sense from the maintenance perspective to use common parts.

Similar systems or components with variations in configuration can reduce the effectiveness of maintenance and can be a cause of maintenance error. Re-enforcement of pattern recognition can also be applied to commonality in maintenance activities.

If a part does not have commonality with the function and properties of other parts then it makes sense from the maintenance perspective to make the differences obvious. This will provide a clear and unambiguous signal to the maintainer that there are differences in maintenance actions.

Example – Boeing 777 Door Hinges

Early in the design process it was realized that there were three separate hinges that are complex parts. In addition, if the hinge came into the door at a different place on each door all the mating, parts would be different. It was recognized early on that the key to make all the parts common was to make the hinge common, notwithstanding the fact that the shape of the body was different.

As a result, not only is the hinge common but also all the mechanism is common. Indeed, 98 per cent of all the mechanism of the door is common. Adapted from Sabbagh K. (1996) 21st Century Jet – The Making of the Boeing 777, Pan Books, p. 89.

3.7 Build error detection into the maintenance process

Design solutions can assist in the detection of maintenance error before aircraft dispatch. Design can determine how maintenance error is detected and by whom. Ideally, maintenance error should be detected before the aircraft is handed back to service after maintenance has been completed. In practice, however, the flight crew often detects error either before take off or, worse, in flight.

Mechanisms to detect error may include built-in tests, functional tests, illuminated test points, functionally grouped tests or warning lights but equally they can be very simple such as the use of physical indicators.

Ambiguous, difficult, complex or lengthy means to detect a maintenance error can affect the likelihood of detection being successful. Detection means should ensure that the maintenance error is evident under all maintenance conditions, easy and quick to detect, and detected before flight.

Example – JSF Landing Gear Sensors
The Joint Strike Fighter team has broken new ground by the use of landing gear sensors purely on the basis of improving maintenance performance.

Landing gear present many maintenance problems – one particular problem is the measurement the amount of hydraulic fluid by observation. This maintenance task has lead to damaged landing gear due to overfilling.

The JSF programme, on the recommendation of its prognostics team, has agreed to embed sensors in the landing gear in order to report the exact level of hydraulic fluid, and in doing so has avoided maintenance error and saved cost.

Adapted from A Prognosis Sensor Victory on the Joint Strike Fighter (JSF), DSI International, November 2004

4. Conclusion

There is a growing awareness of the vital role that design has to play in influencing maintenance performance and, more specifically, the avoidance or mitigation of maintenance error and its negative effects on safe and effective maintenance activity.

The maintainer interacts with aircraft systems and components through maintenance tasks that are generated by design characteristics. Design will determine the characteristics of the maintenance task and influence the possibility of occurrence of error – it will also determine the possibility for error avoidance and tolerance. The purpose of this paper has been to put forward general design principles that can be practically adopted and implemented by designers to develop practicable solutions that address reasonably foreseeable maintenance errors.

The design principles have been developed from extensive investigation of maintenance error, its causes and consequences to specifically encourage the designer to consider the impact of physical design on the behaviour of the maintainer. The approach is not intended to prescribe design practice, to teach designers how to design, or to advocate further constraints to the design process but rather to add a vitally important dimension to existing knowledge and skills that will enhance maintenance performance and aviation safety.

References

Airbus (2005) FAST Technical Magazine A320 Special, May.

Courteney H. (2001) Human Centred Design for Maintenance, UK Civil Aviation Authority.

DSI International (2004) A Prognosis Sensor Victory on the Joint Strike Fighter (JSF), November.

Hessburg J. (2001) Air Carrier MRO Handbook, McGraw Hill.

Sabbagh K. (1996) 21st Century Jet – The Making of the Boeing 777, Pan Books.

Worm CM. (1997) The Real World – A Maintainer's View, Proceedings IEEE Reliability and Maintainability Symposium, IEEE.

Durability Driven Logistics Demand Analysis

J. Knezevic
Centre for MIRCE, University of Exeter, U.K.

Abstract

Accurate selection of the quantity of logistic support resources has a strong influence on mission success, system availability and the cost of ownership. At the same time the accurate prediction of these resources depends on the accurate prediction of the durability measures of the items involved. This paper presents the method for the advanced and accurate calculation of the durability measures of complex space systems which are the basis for the determination of the demands for logistics resources needed during the operational life or mission of space systems. The applicability of the method presented is demonstrated through several illustrative examples.

1. Introduction

Practice shows that, in a majority of cases, the shortage of logistic support resources causes a much higher delay in performing a maintenance task than the delays caused by any other reason [2]. Consequently, the users select, control and manage resources, the quantity of which has a strong influence on system availability and the cost of ownership. An over-estimated quantity of results in a higher support cost with a great deal of capital tied up, whereas an under-estimated quantity results in a reduction of availability/profit. Therefore, the accurate prediction of the quantity and content of logistic support resources required is imperative for cost effective support of the operation and maintenance process. At the same time the accurate prediction of these resources depends on the accurate prediction of the durability measures of the items involved.

One of the most frequently used durability measure, in engineering practice, is the hazard function, z(t), defined as:

$$z(t) = P(TTF \geq t + \triangle t \,|\, TTF > t) = \frac{f(t)}{D(t)} \quad (1)$$

where: f(t) is a probability density function of the random variable which represents time to failure, TTF, and D(t) is a corresponding durability function which quantitatively expresses the probability that the failure will not occur up to time t, P(TTF>t). Generally speaking, the hazard function could be an increasing, decreasing or constant function of time, which depends on the real process of the change in the physical condition of the item analysed. In the case that the time to failure is modelled by the exponential distribution, the above function becomes:

$$z(t) = \frac{f(t)}{D(t)} = \frac{\lambda e^{-\lambda t}}{e^{-\lambda t}} = \lambda \quad (2)$$

The above expression has a constant value, and it is known as a failure rate. It is necessary to stress that Eq. 2 is applicable only in the cases where the time to failure can be modelled by the exponential probability distribution, which is applicable to a time independent processes.

Analyses of models which deal with the determination of the quantity of the logistic support resources needed [1],[4],[7],[8], shows that all of them are based on the failure rate. However, this assumption is not always correct, because there are many items whose failures are influenced by the time dependent processes, like corrosion, thermal deformation, fatigue, bedding-in, and similar. In these cases the failure rate, which reflects a time independent process has to be replaced with a hazard function, which represents a time dependent process. Therefore, the application of models based on the constant failure rate to the determination of number of spares needed and other resources for items whose hazard function is decreasing or increasing during operational life, could generate results far from optimal [5].

Thus, the main aim of this paper is to demonstrate the approach to the durability modelling of the complex systems, which would provide correct results relative to the prediction of the demands for the logistic support resources.

2. Present Practice

In order to set up the scenario for this paper the very simple example related to the evaluation of the mean time to failure of the complex system, MTTFs, will be used.

Thus, let as look at a system, which consists of three items, say A, B, and C, connected in series from the point of view of durability. The task is to calculate the MTTFs of the system, if the $MTTF_A=MTTF_B=MTTF_C=1000$ hours.

This very simple problem could be easily solved by applying the following technique which is commonly used by many durability practitioners. Thus, the failure rate of each module is $\lambda_A=\lambda_B=\lambda_C=1/1000=0.001$, and as the items are connected in series the sum of their failure rates will give the failure rate of the system. Thus, the failure rate of the system is $\lambda_S=0.003$, which means that the mean time to failure of the system will be MTTFs=333.3 hours.

Many durability engineers would finish the analysis at this point and use the obtained value for the MTTFs of the system in all further calculations related to the provision of the logistic support resources.

Regarding this paper the above example is only the starting point. First of all, it is necessary to stress that the result obtained is valid only under the assumption of the constant failure rate. In cases where the items considered demonstrate increasing or decreasing failure rates during operational life this approach would provide an incorrect solution.

In order to illustrate the point made above, let us use the same example, but this time we shall fully defined the problem, which practically means that the process of the change in the condition of the items considered will be defined. Instead of assuming the constant failure rate we shall specify the probability distributions of the time to failures of the corresponding items, as shown in the table below:

Table 1. Durability data for the items considered.

Item	Distribution	Parameters of TTF		MTTF	z(t)
A	Exponential	λ=0.001	/	1000	Constant
B	Normal	μ=1000	σ=375	1000	Increasing
C	Weibull	η=790	β=0.7	1000	Decreasing

Now, we have fully specified the problem, but we do not have the fully defined algorithm for its solution, because the ``classical" durability theory and available national and international standards do not address this problem in spite of the fact that it exists in every day engineering practice.

Hence, this paper will present the algorithm for solving this and any other problem of forecasting and calculating the durability measures of complex engineering systems using the ``bottom up" approach.

3. Durability measures of a Single Engineering Item

In every day practice the occurrence of an uncertain event is described by the probability distribution of the chosen random variable through one of the well-known theoretical probability distributions. The most frequently used distributions for continuing random variables, in the area of durability, maintainability and supportability engineering, are: exponential, normal, lognormal and Weibull [5]. Each of them represents a family of distributions where every member of the family is defined by some parameters, like: scale, shape and minimum value. Hence, if those parameters are specified the characteristics of probability distribution of the random variable like: expected value, E(X); variance, V(X); cumulative distribution function, F(x); probability density function, f(x) and others, are fully known.

It is necessary to say that the expected value, E(X), defined by mathematicians means exactly the same as the mean time to failure used by the durability practitioners. Thus, X=TTF, and E(X)=E(TTF)=MTTF.

As the expected value is the subject of discussion generated by this paper, let us remember its general expression for the continuous random variable, say X:

$$E(X) = \int_0^\infty x \times f(t)dt \quad (3)$$

where f(x) is the probability density function of a random variable X. Applied to the time to failure, as a random variable, the above equation could be rewritten as [5]:

$$E(TTF) = MTTF = \int_0^\infty D(t)dt \quad (4)$$

From the point of view of mathematics, MTTF defined as above is fully known characteristic, but what does it mean to logistics engineers? Not a lot, because it only defines a single point of the probability distribution. In order to illustrate this statement, several examples are given and in Table 2, each of which exhibits identical mean time to failure of 1000 hours.

Table 2 Illustrative example, input and output data in hours

Distribution	**Scale**	**Shape**	**MTTF**	**TTF$_{10}$**	**TTF$_{50}$**	**TTF$_{90}$**	**Curve**
Exponential	1000	N/a	1000	105	693	2303	1
Normal	1000	150	1000	810	1000	1195	2
	1000	300	1000	620	1000	1385	3
	1000	450	1000	455	1000	1615	4
Weibull	1000	1	1000	105	695	2303	5
	1115	1.59	1000	270	885	1884	6
	1126	2.67	1000	484	981	1539	7
	1100	4.22	1000	645	1008	1340	8

where; TTF$_p$ represents the length of operation up to which 10, 50 and 90 percent of population will fail. The understanding of the behaviour of the random variable cannot be based on the information related to the expected value only. The last three columns in the above table clearly illustrate this statement.

The impact of the type of the distribution and values of scale and shape parameters on the durability measures is illustrated by Fig. 1. Clearly, the differences are significant. For example, the values of the durability function at 500 hours for all of them are scattered within a wide range of values (0.63 to 0.995). Certainly, there are an infinite number of durability functions mean value (MTTF) of which is equal to 1000 hours, and each of them will have different values of durability at different instances of operating time.

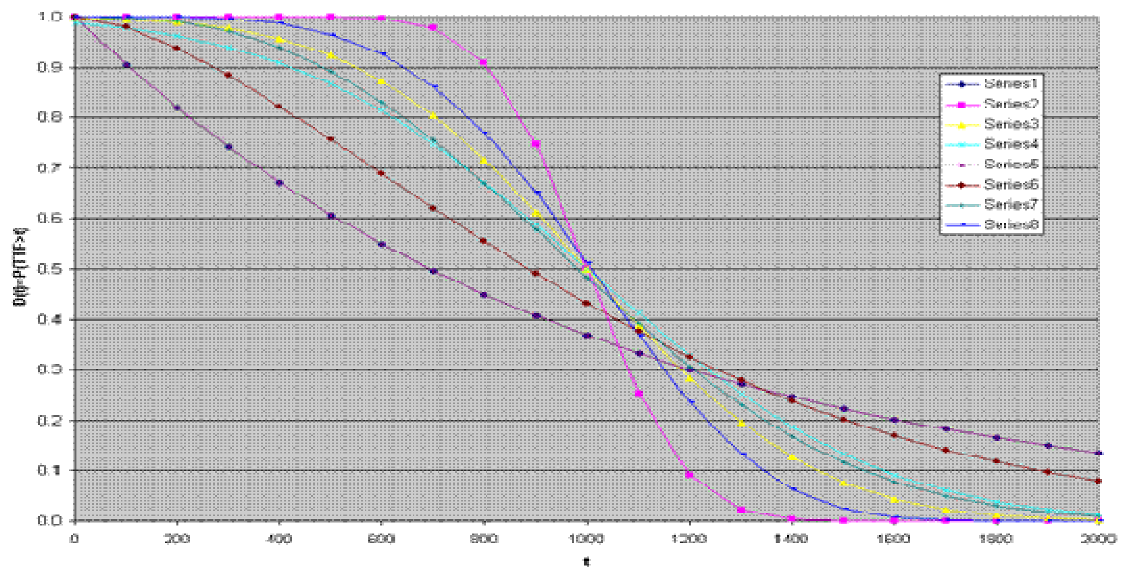


Figure 1. Durability functions for several items with MTTF=1000 hours

The main objective of the example used was to show that it is absolutely crucial to understand the process of change in the condition of the item in order to get a full picture about its durability measures.

4. Durability of Complex Engineering Systems

In the cases where the random variable analysed represents the complex event, its probability distribution depends on the probability of occurrence of consisting events. From the point of view of mathematics, the complex event is any event, which consists of two or more related events. The probability of occurrence of the complex event depends on the relationship between consisting events. For example, if the complex event is defined as the intersection of two or more events then the probability of its occurrence is equal to the product of probabilities of occurrence of consisting events. Making use of equation 2, the expression for the mean time to failure of the complex system, which is defined by the complex random variable, TTFs, will be:

$$E(TTFs) = MTTFs = \int_0^{\infty} Ds(t)dt \qquad (5)$$

where Ds(t) is the durability function of the complex system.

Clearly, the main problem facing the analyst is the determination of the durability function of the complex system, Ds(t).

In the case that the consisting items (items, units, components) are independent and connected in series, from the point of view of durability, the durability function of the system is defined as:

$$Ds(t_s) = \prod_{i=1}^{nci} Di(t_i) \qquad (6)$$

where: nci is the number of consisting items, Di(t), durability function of each consisting item representing the probability that the time to its failure is greater than t. Thus, the expression for the MTTFs of the complex system could be obtained by combining equations 5 and 6, thus:

$$MTTFs = E(TTFs) = \int_0^{\infty} \prod_{i=1}^{nci} D(t)dt \qquad (7)$$

The above expression can be used for the calculation of the mean time to failure of the system, MTTFs, which consists of any number of items, which are connected in series from the point of view of durability, and whose failure rate could exhibit any pattern of the failure rate, i.e. any mixture of increasing, constant and decreasing.

In the cases where the analytical integration of the above expression is complicated, the required value could be obtained by using the graphical method.

5. Illustrative Example

In order to illustrate the approach presented let as calculate the mean time to failure of the system whose consisting items are defined in Table 1.

Making use of equation 7, the mean time to failure of the system of 363 hours, was obtained by applying graphical method. This represents an increase of 10 % in comparison with the corresponding value of 333.3 hours obtained by the ``constant failure rate approach". The differences between these two approaches to the determination of the durability measures are even more significant when they are used as a basis for the prediction of the demands for the logistic support resources.

Based on the practical experience and the illustrative example used it is extremely difficult to justify the use of the constant failure rate approach to the calculation of the durability measures for the complex systems which consist of the mechanical, hydraulic, pneumatic, and similar items.

To illustrate further advantages of the method proposed, the situation where the increase of the reliability of the system is intended to be achieved by use of parallel configuration of two items of the same kind will be used, as shown in Figure 2.

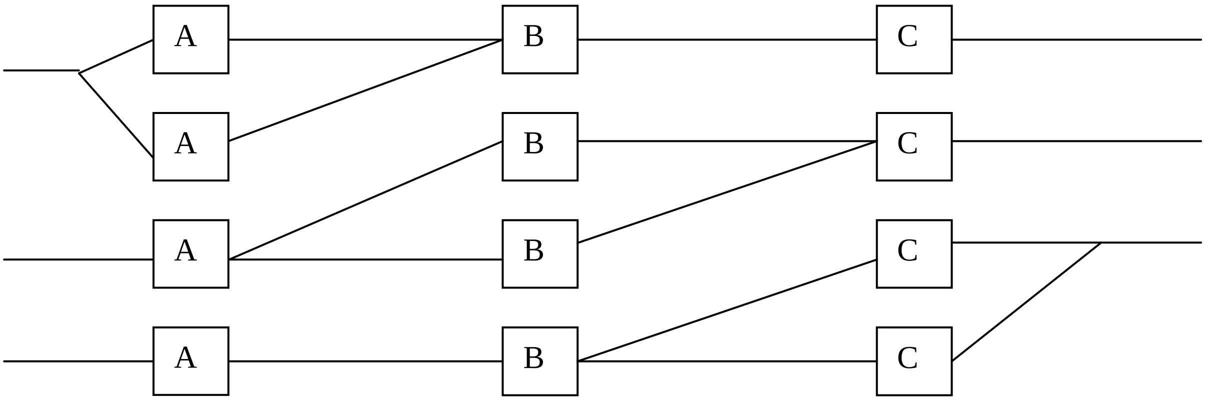


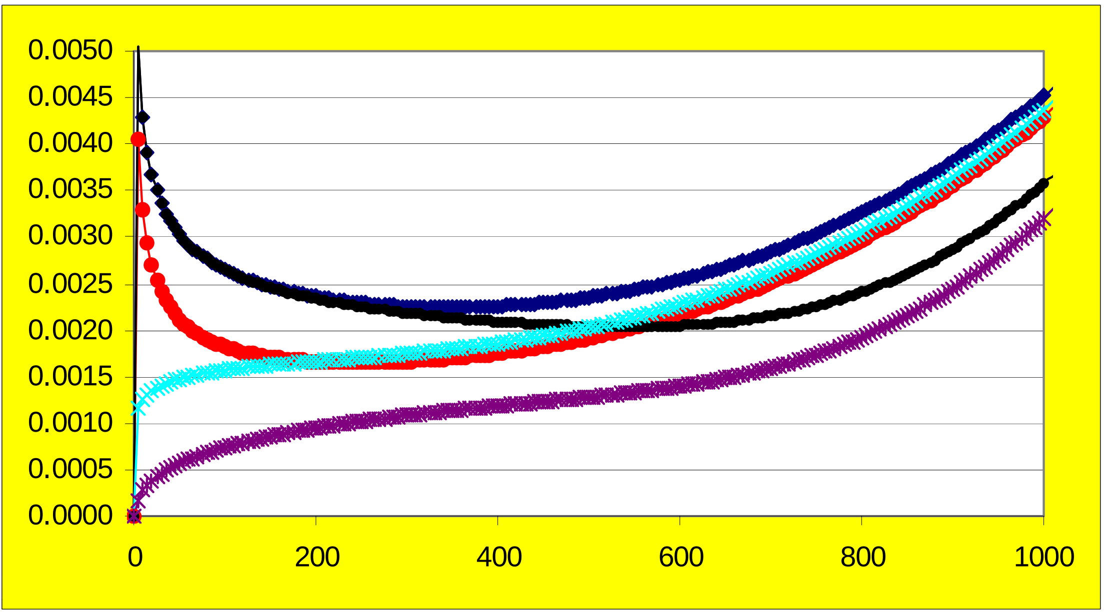
Figure 2. Possible configurations of the system

In the case of the constant failure rate approach it is irrelevant which item, A, B or C, should be connected in parallel, because the MTTFs will have identical. However, in all cases where the constant failure rate cannot be used as a model for the process of change in the condition of the consisting items, the above statement will be incorrect, as the Table 3 shows for the example used.

Table 3. Durability Analysis of Complex System

Configuration	A	B	C	MTTFs	TTF_{10}	TTF_{50}	TTF_{90}
1	1	1	1	333	35	231	767
2	1	1	1	363	25	246	849
3	2	1	1	435	35	346	978
4	1	2	1	375	25	256	949
5	1	1	2	472	75	407	989
6	2	2	2	678	165	648	1241

The usefulness of the durability analysis to the design regarding the selection of the optimal configuration is obvious, especially in cases where due to weight, cost and space restrictions using a parallel configuration is very limited. The graphical representation of the pattern of the hazard function for each analysed configuration is given in Figure 3.



F

6. Conclusion

The main objective of the paper was to initiate a discussion on the accuracy of the determination of the estimated values of the measures of durability and maintainability. The accurate way for calculating the expected value of the probability distribution of the random variable that represents the complex event has been demonstrated here. As a result of that, the accuracy of the mathematical models used by durability, maintainability, and supportability engineers will increase and in consequence the credibility of the profession should increase among other engineering disciplines.

Based on several simple examples and brief theoretical analysis it is possible to learn the following lessons, from this paper:

a) The calculation of the expected value of the complex random variable cannot be based on the information related to the expected values of consisting events only. The type and parameters of the probability distributions of the consisting events are of crucial importance for the accurate results, as demonstrated;

b) The accuracy of the calculation of the expected values for the measures like: Mean Time To Failure, (MTTF), Mean Time Between Failure, (MTBF), and similar, could have crucial effects to the final results of the durability analyses, especially in the cases of engineering systems which consist of several thousand components.

It is important to underline that the same conclusion is applicable to the calculation of the expected values of the random variables, which describe other types of configurations of the system (parallel, mixed, m out on n) as well as measures of maintainability and supportability [2].

7. References

1. Abaretier, E., ``Availability Optimisation Model", Proceedings of Society of Logistics Engineers 21st Annual Symposium, 1986.
[2] Blanchard, B.S., Logistics Engineering and Management, fourth edition, Prentice Hall, New Jersey, 1992.
[3] Equipment Designer's Cost Analysis System, University Edition, EDCAS-UE, Systems Exchange, Los Angeles, 1991.
[4] Knezevic, J., Durability, Maintainability, Supportability, An Probabilistic Approach, McGraw Hill, London, 1992.
[5] Knezevic, J., ``Durability Modelling of the Systems whose components have non-constant failure rate", Proceedings of the ESA Symposium, Netherlands, 1991.
[6] Knezevic, J., ``Logistics today: Mean Values, Logistics Tomorrow: Entire Distributions", Proc. 25th International Logistics Symposium, pp 163-167, Phoenix, Arizona, August 1990.
[7] Price, B.C., ``Achieving a System Operational Availability Requirement Optimally", Proceedings of Society of Logistics Engineers 20th Annual Symposium, 1985.
[8] Waak, O., Spares Calculation, Logistic Engineering Training Course Book, Systecon AB, Sweden, 1987.

Determination of Operations Down Time for Group Replacement Maintenance Policy

Dr J. Knezevic,

MIRCE Akademy, Woodbury Park, Exeter, EX2 7YX, U.K.

Prediction of the duration of the down time caused by maintenance, especially in the cases where system considered consists of several repairable items, presents a challenge for maintenance managers, because of possible revenue losses during these intervals of time. The paper responds to this challenge through the new methodology for the fast and accurate prediction of maintainability measures related to the group replacement maintenance policy. It is applicable to group maintenance tasks whose comprising of individual replacement tasks are performed: simultaneously, sequentially, and combined. The method presented could be successfully used at the planning stage of operations process when the information available is based on previous experience only, as well as, at the stage when process is performed. The applicability and usefulness of methodology proposed is demonstrated through an illustrative numerical example.

1. Introduction

There are a large number of man-made products, the functionability of which has to be maintained during the operations process by the user. The process during which the ability of a product to perform a function is maintained, is known as the maintenance process, and it is defined as a set of tasks performed by the user in order to maintain the functionability of the product during its operational life. Clearly, resources like: spares, material, trained personnel, tools, equipment, maintenance manuals, facilities, software, and similar are needed to facilitate this process, Blanchard (1992). At the same time interruptions of the operations processes caused by maintenance could reduce the expected revenue or initiate unwanted down times, Jardine (1973).

One of the possibilities to minimise down time of operations processes and reduce the cost of revenue lost is the application of the group replacement maintenance policy, Knezevic (1985). Thus, when any one item from the group fails, the replacement of all the items from that group takes place. The reason for this is the fact that as the number of items in the group increases, the maintenance cost will increase because all the items will not be used to the full. The number of group replacements could decrease because there will be fewer interruptions to the operations initiated by failures which reduces the revenue losses.

The most useful information for the operations managers is related to the length of down time caused by performing each maintenance task. Assuming the ideal logistic support, Blanchard (1992), the length of down time could be quantified through maintainability measures related to maintenance tasks. These measures are expressed through the probability distribution of the random variable known as time to replacement, TTR. Most frequently used maintainability measures are, Knezevic (1992):

* Maintainability function, M(t)
* Mean Time To Replacement, MTTR
* Percentual Replacement Time, TTRp

Definitions and brief descriptions for each of them are given in the Appendix.
In daily practice, the numerical values for maintainability measures, if they exist, are related to the replacement of one item only. Thus, in the cases where the application of the group replacement maintenance policy is beneficial the corresponding maintainability measures have to be determined by the maintenance managers. This is a very difficult prediction task due to complex interaction between the sequence of activities within each task and the arrangements for the sharing of maintenance resources. Thus, the main objective of this paper is to present a methodology for the prediction of maintainability characteristics for the group replacement of several heterogeneous items, based on the corresponding measures related to individual replacements of each of them.

2. Analysis of Group Replacement Strategies

According to the methodology proposed in this paper each group replacement is considered as a set of maintenance tasks related to the replacement of items from the group. Based on the timing and the sequence in which replacements of individual items are performed, the following strategies are available:

1) Simultaneous
2) Sequential
3) Combined.

Definitions and brief descriptions of each of the above mentioned group replacement strategies are given below.

2.1 Simultaneous Group Replacement Strategy

Simultaneous replacement strategy represents an approach where the mutually independent tasks related to the individual replacement of several heterogeneous items are performed concurrently. This, practically, means that replacement tasks of individual items from the group are starting at the same instance of time and are performed simultaneously but independently of each other. The group replacement task is completed when all consisting replacements have been successfully completed.

A typical example of a group replacement task is the pit stop of a racing car, where tyre replacement, fuel refilling and windscreen cleaning are performed simultaneously. Clearly this situation requires more maintenance resources and complex logistics, but it minimises the consequences caused by the down time. Hence, the replacements are performed simultaneously and the whole task is finished when all of the consisting tasks are successfully completed by the corresponding specialist members of the team, or teams involved.

2.2 Sequential group replacement strategy

Sequential replacement strategy represents an approach where mutually independent tasks related to the replacements of several heterogeneous items are performed in the predetermined order. This clearly states that the replacement of each subsequent item starts after the successful replacement of the previous one. Thus, none of the subsequent tasks can be performed before the completion of the previous ones. The group replacement is completed when the last item has been replaced.

The example of the racing car could be used again, but in this case tasks are performed in the following order: tyre replacement followed by refuelling and finished with windscreen cleaning. Clearly, in this situation, the interruption of the operations process would be considerably longer but the demand for maintenance resources would be much less and logistics simpler.

2.3 Combined replacement strategy

Combined replacement strategy consists of the combination of the sequential and simultaneous. Thus, the relationship between comprising replacement tasks has to be predetermined according to the permissible down time and availability of the maintenance resources.

Today, in the majority of cases, maintenance managers are selecting this strategy because systems become more complex and associated replacement tasks require more maintenance resources and complex logistic support.
A typical example of the combined replacement task is the overhaul of an engine or gearbox, where some of the tasks have to be performed in a specific sequence whereas others could be performed simultaneously in order to reduce total time in repair.

3. Determination of Maintainability measures for group replacement strategies

The main objective of this part of the paper is to derive the expressions for the prediction of the maintainability measures for a sequential, simultaneous and combined group replacement strategy based on the corresponding measures related to individual replacement of comprising items. The predicted figures serve as an indicator for decisions that have to be made by operations managers in the selection of the most suitable replacement strategy.

Regardless of the type of replacement task the following symbols will be used here:
TTRI_i, random variable which stands for the Time To Replace, Individually, the i^{th} item;
$M_i(t)$, maintainability function for the individual replacement of i^{th} item.

The methodology proposed in this part provides a tool for the prediction of the maintainability measures related to all three group replacement strategies based on the corresponding characteristics of the individual replacement tasks. Thus, as the maintainability measures for the replacement of each item are fully defined by the probability distribution of the random variable TTRI, and corresponding measures for the group replacement strategies are defined by the probability distribution of the random variable TTRG, which defines the whole task.

3.1 Maintainability Function of Simultaneous replacement strategy

Maintainability function for the simultaneous replacement strategy of the items from the group can be derived from the maintainability functions related to the replacement of the consisting items. Thus, the maintainability function related to the simultaneous replacement strategy, \cal M(t), represents the probability that the replacement of all items from the group will be successfully completed by the stated instant of time, t. Making use of equation A1, the maintainability function for the simultaneous group replacement strategy, according to the methodology proposed, can be represented as:

$$M(t) = P(TTRG \le t) = P(TTRI_1 \le t \bigcap TTRI_2 \le t \bigcap TTRI_3 \le t \bigcap .. \bigcap TTRI_{nci1} \le t)$$

where: nci is the number of consisting items. The above expression mathematically describes the replacement task whose comprising tasks are performed simultaneously, as an intersection of events at a stated instant of time whose cumulative probabilities are defined as, P(TTRI≤t). It clearly states that the group replacement under consideration will be completed if, and only if, the replacement of all comprising items have been successfully completed before or at the specified instant of time t.

In the case that random variables TTRI_i, i=1,nci represents independent events the above expression becomes:

$$M(t) = P(TTRG \le t) = P(TTRI_1 \le t) \times P(TTRI_2 \le t) \times P(TTRI_3 \le t) \times ... \times P(TTRI_{nci} \le t)$$

The expression on the right hand side is a maintainability function related to the replacement of i^th item. Consequently, the maintainability task which comprises the replacements of any number of consisting items can be calculated according to the following equation:

$$M(t) = \prod_{i=1}^{nca} P(TTCI_i \le t) = \prod_{i=1}^{nca} M_i(t)$$

It is necessary to underline that the above expression could be very complex. The reason for this is the fact that the maintainability functions of the comprising tasks, Mi(t) where i=1,nci, can be defined through any of the well-known theoretical probability distributions, product of which cannot be expressed by any of them. Consequently, their numerical values have to be calculated by numerical methods. This calculation is considerably easier today with extensive use of modern computers.

3.2 Maintainability Function of Sequential replacement strategy

The maintainability function for the sequential replacement strategy of items from the group, according to the proposed methodology, can be represented as:

$$M(t) = P(TTRG \le t) = P(TTRI_1 + TTRI_2 + TTRI_3 + ... + TTRI_{nci} \le \mathrm{t})$$

The above expression mathematically describes the sequential replacement of consisting items through a sum of independent random variables, $TTRI_i$ where i=1,nci. It clearly states that the task under consideration will be completed when, and only when, the successful completion of comprising replacement tasks is performed in a specified order. Making use of the principles of the renewal theory, Cox (1962) the above expression could be rewritten as:

$$M(t) = M^{nci}(t)$$

where $M^{nci}(t)$ represents nt^h convolution of comprising maintainability functions. The convolution of maintainability function for it^h replacement activity, $M^i(t)$ could be determined according to the following expression, Cox (1962):

$$M^{i}(t) = \int_{0}^{t} M^{i-1}(t - t_i) dM_i(t_i) \qquad \text{where: i=1,nci and } M^1(t)=M1(t).$$

It is necessary to underline that the above expression could be very complex and difficult for use. The reason for this is the fact that the maintainability functions related to the replacement of comprising items can be defined through any of the theoretical probability distributions and in the majority of cases their convolution cannot be expressed with any of the well known distribution functions.

3.3 Maintainability Function of Combined replacement strategy

As the definition for combined replacement strategy suggests it is the combination of some replacement tasks being performed simultaneously and some being performed in a predetermined sequence. Thus, the maintainability function for the combined replacement strategy depends on the configuration selected.

4. Illustrative Example

In order to illustrate the applicability and practicality of the methodology proposed, a hypothetical example will be used. Managing the operations of a racing car is a very exciting business, from a maintenance point of view, because the consequences caused by down times initiated by the failures could be fatal for the final success of the whole process. In this particular case the preventive replacement of a set of 4 tyres, cleaning the windsreen, and fuel refilling during a pit stop will be analysed. According to data available, Manson (1991) the maintenance tasks analysed and resources needed for their completion are as follows:

Table 1. Maintainability data for tasks analysed

Maintenance Task	Distribution	Parameters	Resources
Tyre replacement	Weibull	eta = 45, beta =2.7	MR30
Windscreen cleaning	Normal	mu= 8, \sigma = 2	MR45
Fuel refilling	Lognormal	\mu= 3.67\sigma= 0.19	MR2

where: MR30, MR45 and MR2 are sets of resources needed for the completion of the corresponding maintenance tasks, Manson (1991).

Making use of Equation 5 the maintainability function for the simultaneous group replacement strategy has been derived. The corresponding function for the sequential group replacement strategy has also been calculated , and numerical values for the mean time to group replacement, MTTRG, and the perceptual replacement times, $TTRG_p$, based on Equation A3, for both replacement strategies are given in the Table 2.

Table 2 Maintainability data for group replacement strategies

Strategy	MTTRG	$TTRG_{10}$	$TTRG_{50}$	$TTRG_{90}$
Simultaneous	58.3	45.5	57.8	73.18
Sequential	l 209.1	167.3	207.5	252.6

where: $TTRG_{10}$, $TTRG_{50}$ and $TTRG_{90}$ are the lengths of down times, caused by the group replacement, up to which 10, 50 and 90 percent of maintenance tasks will be successfully completed.

There are several possible combined replacement strategies. For instance, simultaneous replacement of the front tyres, sequentially followed by simulateneous replacement of the rear tyres, sequentially followed by simultaneous fuel refilling and windscreen cleaning is one of the possibilities. Clearly, the maintainability measures for all combinations possible will be between corresponding values of simultaneous and sequential strategy.

The procedure for the determination of maintainability measures for any configuration of the combined group replacement strategies are identical to the above.

It is necessary to notice that the demand for the maintenance resources is varying considerably, between different group replacement strategies.

5. Conclusion

The main objective of this paper was to demonstrate the methodology for the prediction of the operations down time for the group replacement maintenance policy. The method proposed is based on the maintainability measures related to the individual replacement of comprising items from the group.

The method proposed is applicable to replacement tasks whose consisting items are replaced: simultaneously, sequentially, and combined. Thus, it is a generic model for the prediction of maintainability measures, which in turn represents vital information needed by maintenance managers for the selection of the most appropriate maintenance policy and strategy for the successful support of the operation process.
It is necessary to stress that the method presented could be successfully used at the planning stage of operations process when the information available is based on previous experience only.

The numerical example used clearly illustrates the ability of the proposed methodology to quantify the consequences of the decisions made related to the possible group replacement strategies on the length of the down time and the magnitude of the revenue lost during these unoperable periods.

References

[1] Blanchard, B.S., Logistics Engineering and Management, fourth edition, Prentice Hall, New Jersey, 1992.

[2] Cox, D.R., Renew Theory, Methuen \& Co Ltd., London, U.K., 1962

[3] Jardine, A.K.S., Maintenance, Replacement and Reliability, Pitman, U.K., 1973.

[4] Knezevic, J., Reliability, Maintainability, Supportability, An Probabilistic Approach, McGraw Hill, London, U.K., 1992.

[5] Knezevic, J., Methodology “EXETER" For Selecting An Optimal Part-Replacement Policy, Maintenance Management International, Vol. 5 No. 3, Elsevier, 1985.

[6] Manson, P.D., Maintainability Considerations in the Motor Vehicle Life Cycle, Final Year Project, School of Engineering, Exeter University, 1991.

INCREASING PROFITABILITY AND RELIABILITY THROUGH FAILURE MANAGEMENT

Jezdimir KNEZEVIC, MIRCE Akademy, Exeter, UK

***Abstract*:**

Commonly, maintenance is perceived as "fixing broken things". As such, it is associated with failure consequences and unplanned expenses, both of which negatively impact business plans or customer satisfaction. However, as failures are an inevitability of the life of any technological system, it would be worthwhile to start looking at maintenance as opportunity for dealing with them and making t positive impact on business plans or customer satisfaction, by generating profitability and reliability. Thus, the main objective of this paper is to present the Mirce-mechanics approach to maintenance that is focused on the way that failures, once scientifically understood, could be managed in the way that reduces the number of in-service interruptions and operational costs, which in turn will generate profit for private companies or increases the reliability for public services like health, transportation, tourism up to the national defence.

INTRODUCTION

The main business of business is to stay in business. To stay in business the expected "business function" must be provided through time at minimum investment in resources. Hence, the generated profit is equal to the revenue generated by the monetary value of the "business function", R, minus the cost of the resources used to run the business, C, during a given interval of time T, $P(T)=R(T)-C(T)$. Hence, the main concerns of the owners and users of industrial systems are related to how much of the "business function" will be delivered during the life time of a system and how much maintenance and support efforts are expected from them to keep the system going[14]. For example, the business function of a passenger aircraft is to transport a passenger and cargo trough air over a life time of 25-30 years. To stay in business an airline is required to maintain it in airworthy condition. Hence, for each of the business processes these two main factors are obtained at the end of each financial year or at the end of the industrial system. [1]

This, type of performance, of industrial/business systems is known as functionability[15] performance. Regrettably, producers/constructors of industrial systems do not provide answers to this type of performance on the delivery day. Instead, years later the statistics for various functionability measures become available. The reason for this is the fact that in-service behaviour of industrial systems is governed by the complex processes that are governed by the laws of science, human rules and environmental impacts, which are characterised by indeterminism, irreversibility, inseparability, and dependence on time, location and humans.

---

[14] Boeing 747, registration number N747PA, which belonged to Pan Am transportation system, have delivered the work of 80,000 flying hours and received 806,000 maintenance man-hours, during the 22 years of in-service life

[15] Functionability, n, defined as the ability of being functional through life, in the book Reliability, Maintainability and Supportability – A probabilistic Approach, by J. Knezevic, pp. 291, McGraw Hill, London 1993. ISBN 0-07-707691-5

Consequently, the main objective of this paper is to present the Mirce-mechanics approach to functionability, as scientific foundation of keeping system in business through failure management. It is focused on the way that failures, once scientifically understood, could be managed in the way to maximise the time in operation and minimise the time in maintenance, which in turn will generate profit for private businesses or increase public satisfaction for common services like health, transportation, education, tourism all way up to the national defence.

The paper is aimed at business decision makers, who should be educated what a rational to maintenance could do for them, rather then to show them how it should be done. Members of the organisations with the wider horizons are needed to fully appreciate the opportunities presented to them by Mirce-mechanics to increase business competitiveness or public satisfaction.

2. FUNCTIONABILITY QUESTIONS

One of the major concerns of design engineers and project managers are predictions of operation, maintenance and support resources required for maintaining systems in "business as usual" state through their lives. These include diagnostic equipment, skilled and trained maintenance personnel, maintenance facilities, spare parts, inspection tools, technical data, storage facilities, means of transportations and so forth. Often the cost of these resources considerably exceeds the purchase cost of system itself. Equally, the lack of maintenance resources causes further delays in keeping systems in the "out of business" state. Hence, some balance between investment in the resources and the time delays incurred by their deficiency is required. To make that trade off, engineers and managers, need to find the answer to the following functionability related questions:

- How many Failures are going to occur?
- What types of Failures are going to occur?
- What frequencies of Failures are going to be?
- How Failures will be detected?
- How long systems are going to be "out of business"?
- What resources are needed to return it to the "business"?

Unlike the functionality questions to which existing laws of science readily provide the answers, the above raised functionability questions stayed unanswered. Existing equations of motion are not able to even the address the above questions, not because they are incorrect, but because they are not created to address these phenomena.

In summary, without ability to provide accurate answers to functionability questions design engineering and project manager are not in the position make the trade off between the cost of resources required to maintain systems in "business as usual" state and the consequential losses while the system is "out of business" state, also know as the "failed state".

3. DEFINITION OF MAINTENANCE

Commonly, maintenance is perceived as "fixing broken things". As such, it is associated with failures and unplanned expenses, both of which negatively impact business plans or customer satisfaction. However, as failures are an inevitability of the life of any industrial system, it would be worthwhile to start looking at maintenance as opportunity for dealing with them and making t positive impact on business plans or customer satisfaction, by generating profit through rational maintenance. Most will agree that failure is a frequent surprise, as it always occurs at inopportune times. Thus, it makes sense asking "is it possible to manage failures" of systems and components in order to keep "business in business"?

Consequently, to answer this question, it is necessary to address the question "What is Maintenance?" Sound rather strange to ask this question at the Maintenance Conference, as everybody knows the answer. Although there are many definitions of maintenance, somehow all of them focus on "finding failure and fixing failed stuff." Consider the commonly accepted definition which states that"Maintenance is the action necessary to sustain or restore the integrity and performance of the industrial system. It includes inspection, overhaul, repair, preservation and replacement of parts. Well, finding failure and fixing stuff is not maintenance is well needed and respected skill, but it is rather a consequence of maintenance. In author's view, maintenance could be considered as the "the management of failure." As industrial systems are exposed to continuous process of decay, the primary consideration of all maintenance decisions is neither the failure of a given item nor the frequency of its occurrence, but rather the consequences of that failure upon the "business" state of an industrial system. Hence, managing the business requires management of failures and who else can do that than maintenance.

4. TYPES OF FAILURES

In order to better manage failure, it helps to understand that there are two consequences of failure: those affecting safety and those affecting the economics of business (revenue, profit, reputation, etc.). Thus:

- *Safety related* failures are those that jeopardises the safety of the industrial system or places in peril environment or humans must be prevented. Safety significant industrial systems, like aircraft, submarine, train, nuclear reactor and similar can not be of such design that any single failure of the device will have catastrophic results. This is safety engineering dogma. Today's industrial systems of this type are subject to very few critical failure modes. This safety-related reliability is attributed to the design requirements of the relevant governmental regulations as well as the specifications of operating organizations and manufacturers. Current design practice ensures that vital functions are protected, which means, that, if there is failure, a given function will remain available from other sources to insure a safe completion of operation.

- *Economic* related failures are those where the loss or deterioration of a particular function neither endangers the industrial system nor its environment, but it affects the "business" state of a system. Examples include systems, components, or features in a design that are not specifically required to demonstrate conformity to the basis of safety certifications. However, a failure of a single components or module can cause the loss of functionability of the industrial system and causes a loss of business until repair or replacement is accomplished.

Based on the above, it possible to conclude that one of the fundamental "business" questions is how to manage failures that take a "business out of business" at the most cost effective manner?

5. MANAGEMNT OF FAILURES

The most effective way of managing failures is to address them at the early stages of design. Generally speaking there are two main design solutions for minimising the amount of time during which the system is in "not in business" state. Thus:

- The components and systems to be designed to an exceptional degree of reliability by selecting "exotic materials", high kevel of tolerances, extensive testing and similar solutions. This could be an inordinately costly strategy. Cost-effective design trades must be made between the loss of functionability arising from a system being in "not in business" state situations and the cost of exceptionally reliable components.
- Minimising the time that a system spends in "not in business" state. The design approach embraces the incorporation of features that are extra to those required for safety certifications. These include:
    - redundancy,
    - fault tolerance
    - fail safe,
    - fail passive features
    - group replacement.

  It is necessary to stress that all of these efforts are beyond those required to certify the safe design of industrial system. Of course, this is not without its price, however. It increases the number of failure possibilities, adds more items that can fail, and results in equipment that is more complex and integrated — making fault isolation more difficult. It adds to the cost of the industrial system, so it must be done carefully to keep costs under control.

Regarding this fundamental design options, Jack Hessburg[16], the Chief Mechanic of the Boeing New Airplanes (1990-1999), has said "*I as a designer I have to fill my customer in as well, I have to decide where I'm going to put economic redundancy into my design, because it costs money. If you have the full answer to that, would you please see me after this meeting! There's a Nobel Prize in it. We have really not developed the discipline where we know how to normalise that, yet*."

6. THE MIRCE-MECHANICS

Following the philosophy of the French Emperor, Napoleon Bonaparte who said that "*a soldier without ambitions to become a general is a bad soldier*", the author of the paper started thinking about the process that will facilitate that achievement of his ambitions. However, it became evidently clear that the problem to the solution is generically imbedded in the educational structure which is based on the division of knowledge into separate subjects, like physics, chemistry, mathematics, electronics, biology, engineering, meteorology, physiology and similar disciplines. However, it is the complex interactions between all of them that govern the in-service behaviour of any industrial system, which generates the desired functionality performance on one hand and occurrence of functionability phenomena that cause them to "not in business" state, resulting from the observable physical processes like fatigue, corrosion, maintenance induced failure, foreign object damage, design error, quality problem, transport damage, shortage of spare parts and so forth.

---

[16] Jack Hessburg 27th January 1998, M.I.R.C.E. Industrial Lecture, Exeter University, UK.

The author could not have seen how to proceed with his research topic within departmentalised academic institutions and training processes. Hence, he left the School of Engineering at Exeter University in UK and start an independent research, education and training organisation, named the MIRCE Akademy at Woodbury Park, Exeter, UK, in 1999, with only one clear statement of intent “Never to departmentalise any research activities.” Staff, Fellows, Members and students of the Akademy have endeavoured to subject in-service behaviour of industrial systems to the laws of science and mathematics to:

- Determine the trajectory of the motion of industrial system through functionability states, which is defined by the sequence of occurrences of positive and negative functionability events, resulting from the atomic, environmental and human actions. Understand mechanisms that lead to the occurrence of functionability events starting from atomic structure that drives the behaviour of matter, up to the solar system that drives the energy conversions (a physical scale ranging from 10^{-10} to 10^{10} metre).
- Define a mathematical scheme for predicting expected in-service functionability measures of a given industrial system together with the expected work done on the system under a given maintenance policies and planned support strategy.

While in classical mechanics a force is said to do work if, when acting on a body, there is a displacement of the point of application in the direction of the force, in Mirce-mechanics a given system is said to do work, if there is a provision of measurable functions in the direction of time, which is exactly what is expected from a business. In summary, the body of knowledge comprising of axioms, mathematical equations and methods that enable engineering, predicting and managing the functionability performance of industrial systems, based on the scientific understanding of the mechanisms that drive an industrial system through states “business as usual” and “out of business” through the life, constitutes Mirce-mechanics.

7. THE CONCEPT OF MOTION IN MIRCE-MECHANICS

Motion is one of the most complex concepts of science. The images it creates in our minds are diverse as the “jiggling” of atoms and molecules to the movement of planets, and beyond. Since the earliest years of science the only idea of motion imagined was that of mechanical motion, so there is a tendency to view all other kinds of motion in terms of the concept of trajectory. As the science progressed, this naturally became impossible, for instance when the attempt was made to conceive the electrical motion. It could be possible, of course, to think in the case of a high-voltage transmission line that wire is the “trajectory” of the electric signals. However, such a mental picture would have no practical purpose, as the electromagnetic waves could not have been viewed as a liquid flowing through the wires.

Consequently, the question by which the motion of industrial systems through functionability/business states through time must contain only those quantities that can be measured physically. Research performed shown that a life of any industrial system could be viewed as a sequence of occurrences of positive and negative functionability events that “move” systems through functionability/business states.
Functionability state variables uniquely determine the functionability states of a system.

The motion of Industrial Systems through functionability states stays is result of imposing physical processes or human decisions, jointly called imposing actions. To understand the mechanisms that generate those actions analysis of tens of thousands of components, modules and assemblies of systems in defence, aerospace, nuclear, transportation, motorsport, communication and other industries, had been studied at the MIRCE Akademy. As it has a profound impact on all aspects of the in-service life on any industrial system, several research studies have been performed by the Master and Doctoral students of the MIRCE Akademy [2,3,4]. All physical phenomena that cause the motion of a system from the positive to negative functionability states are known as negative functionability events. Actions that generate negative functionability events belong to the following categories:

- **Inherent actions,** generated by mechanical, electrical, thermal, radiation, chemical and other types of energy, that have been introduced into system prior to the operation process through activates associated with manufacturing, transportation, maintenance, storage and similar processes.
- **Potential actions,** generated by mechanical, electrical, thermal, radiation, chemical and other types of energy, that exceed the strength of components and systems subjected, resulting from phenomena like foreign object damage (birds, hail, rain, snow), lightening, abuse by operator (pilots, driver and user errors), single event upset [3] and similar.
- **Continuous actions,** generated by mechanical, electrical, thermal, radiation, chemical and other type of energy, that continuously act on a system through in-service life of systems and generate processes like, corrosion, fatigue, creep, wear and similar, which are result of natural decay of matter.

All physical actions that cause the motion of a component or a module from the negative to positive functionability states are known as positive functionability events. Mechanisms that generate positive events belong to the following categories [6]:

- Servicing: replenishment of consumable fluids, cleaning, washing and similar.
- Lubrication: installing or replenishing lubricant.
- Inspection: Examination of an item against a defined physical standard.
    - General visual inspection: performed to detect obvious unsatisfactory conditions. It may require the removal of panels and access doors, work stands, ladders, and may be required to gain access.
    - Detailed visual inspection: consists of intensive visual search for evidence of any irregularity. Inspection aids, like mirrors, special lighting, hand lens, boroscopes, etc. are usually required. Surface cleaning may be required, as well as elaborate access procedure.
    - Special visual inspection: an intensive examination of specific area using special inspection equipment such as radiography, thermography, dye penetrant, eddies current, high power magnification or other NDT. Elaborate access and detailed disassembly may be required.
    - Check: a qualitative or quantitative assessment of function.
- Examination: a quantitative assessment of one/more functions on an item to determine whether it performs within acceptable limits.
- Operational: a qualitative assessment to determine whether an item is fulfilling its intended function. It does not require quantitative tolerances.
- Restoration: perform to return an item to a specific standard. This may involve cleaning, repair, replacement or overhaul.
- Discard: removal of from service.

All of the above listed mechanisms of the motion of systems through positive and negative functionability states are observable physical processes or recognisable human actions. [5]

8. MIRCE FUNCTIONABILITY EQUATION

Results of experiments and observations performed over several decades by the author unquestionably lead to conclusion that the deterministic regularity found in the predictions based on continuous motion through time, such as speed, acceleration and similar, studied by classical mechanics, cannot be found in respect to the motion of functionability through time. Thus, trajectories, generated by the motion of individual copies of a given system type, under similar in-service conditions, demonstrate variability, to the degree that no two trajectories are identical. Therefore, the proven formulas of Newtonian mechanics that govern the motion of macroscopic bodies through time cannot be used for predicting the motion of functionability through time, as far as the functionability trajectory is concerned Thus, Mirce-mechanics Formulas, developed at the MIRCE Akademy, by D Knezevic, are mathematical expressions of the physically observed processes of the motion of industrial systems through functionability states and they define and predict physically measurable properties of system functionability performance in the probabilistic terms.

The laws of probability are just as rigorous as other mathematical laws. However, they do have certain unusual features and clearly delineated domain of application. For example, it can be readily verify that in the case of a large number of systems failure phenomena will occur in a specific number of the cases, and the law is more accurate the more systems are observed. However, this accurate knowledge will be of no help in predicting the occurrence of functionability events in each individual case.
The unusual features of the laws of probability have a natural explanation. In fact, most probabilistic events are results of quite complex physical processes, which in many cases cannot be studied or understood in all of its intricacy. Such inability takes its toll, as it is only possible to predict with certainty the average result of numerous identical tests.. Probabilistic predictions of the functionability trajectory are based on the framework of the sequence of occurrences of functionability events, positive and negative, which are occurring with a probabilistic regularity.

Having determined the probability distribution and its governing parameters of the times to subsequent functionability events, it is possible to develop a mathematical scheme that will provide opportunity to predict the future sequence of functionability events for any given industrial system. This is the essence of the Mirce-mechanics, which is the only theory available to design engineers and project managers to quantitatively predict the consequences of all of their decisions on in-service behaviour of their future systems and their “business” performances.

The trajectory of the motion of an industrial/business system through functionability states is uniquely defined by the sequence of occurrences of functionability events, from the birth of the system to its decommissioning. Thus, the fundamental equation of Mirce-mechanics, the Mirce Functionability Equation [7] and it defines the probability of an industrial system being in positive functionability state or “business as usual” state, at a given instant of time t, thus::

$$y(t) = P(PFS\,@\,t) = 1 - \varphi(t) + \mu(t)$$

where: $\varphi(t)=\sum_{i=1}^{\infty}P(TNE^i\le t)$ is the expected number of negative functionability events that will take place from the birth of a system and a given instant of time t and

$\mu(t)=\sum_{i=1}^{\infty}P(TPE^i\le t)$ is the expected number of positive functionability events that will take place from the birth of a system and a given instant of time t.

Finally, the work done by an industrial system during the stated interval of time T, W_{by}(T), can be calculated by making a use of the following expression:

$$W_{by}(T)=\int_0^T y(t)dt \qquad \text{[Hr]}$$

Hence, the numerical value of the above expression presents the amount of time during which a given industrial system will be in the state of"business as usual" during the stated calendar time T

For the most generic case, where the business can be only in the state of "business as usual" and the "not in business", the work done to the system is determined by the following expression:

$$W_{to}(T)=T-W_{by}(T) \qquad \text{[Hr]}$$

9. MIRCE PROFITABILITY EQUATION

The creation of Mirce Functionability Equation enabled calculation of the work done by the system, during a stated period of time T. That enabled the development of the Mirce Profitability Equation that links the revenue and cost sides of business at one place as a function of the engineering configurations of a system, adopted business methods associated with the relevant project management decisions and characteristics.

Thus the expected revenue of a given industrial system, during the stated interval of time, *R(T),* expressed in the monetary units, MU, is equal to the product of the Hourly Income generated by the provision of business function, HI and the amount of the work done by the system, thus:

$$R(T)=HI\times W_{by}(T) \qquad [MU]$$

In general term, the cost of doing business during the state period of time, is equal to the sum of the cost of operation, *CO(T),* which is equal to the sum of the fix cost of operation, $CO_{fix}(T)$ and variable cost of operation that is equal to the product of the Hourly Cost of Operation, HC_{op} and the work done by the system, hence

$$CO(T)=CO_{fix}(T)+HC_{op}\times W_{by}(T) \qquad [MU]$$

Equivalent cost for maintaining a system in the "business as usual" state, during the stated period of time, *CM(T)*, which is equal to the sum of the fix cost of maintenance, $CM_{fix}(T)$ and variable cost of maintenance that is equal to the product of the Hourly Cost of Maintenance, HC_{mt} and the work done to the system, hence:

$$CM(T) = CM_{fix}(T) + HC_{mt} \times W_{to}(T) \qquad [MU]$$

Finally, the profit expected to be generated by a given industrial system, during the stated period of time, could be calculated by making use of the Mirce Profitability Equation, thus:

$$P(T) = R(T) - C(T) = \left\{ HI \times W_{by}(T) \right\} - \left[CO(T) + CM(T) \right] \qquad [MU]$$

In summary the above equation is the only one, known to the author, which unifies all aspects of in-service performance of an industrial/business system. It enables the accurate predictions of the expected profit to be made for each operational scenario, maintenance policy and support strategy. The above equation "unites" the whole organisation into an analytical scheme, rather than to be a collection of a large number of self standing models that address a few components of the time, or a few performance parameters of the system.

System effectiveness is an emerging property of a in-service life of a system generated by the complex and time dependent interactions of the following properties:

- Functionality principles of a system (mechanical, electronic, thermal, electrical, nuclear, etc.)
- Structure/construction of a system (dependencies and redundancies)
- Operational concepts and scenarios (continuous, seasonal, one off)
- Maintenance rules (schedule inspections, replacement, testing and so forth)
- Support Strategies (training, spares, facilities, tools, equipment, etc.)
- Environmental conditions (climate and weather)

10. THE IMPACT OF MAINTENNACE ON PROFITABILITY AND RELIABILITY OF INDUSTRIAL SYSTEMS

Although science has to be truthful, rather then useful, the body of knowledge of Mirce-mechanics is essential for scientists, mathematicians, engineers, managers, technicians and analysts in industry, government and academia to predict the work done by the system and to the system , for a given configurations, in-service rules and conditions, in order to manage failures in the way that the functionability performance is delivered through the life of system, at least investment in resources and environmental impact. For that to happened, the science proven method is needed, very much different from the classical scientific knowledge, because functionability performance is defined in the following way:

- Every scheduled flight will leave on time with a probability of at least 0.97 or in other words, it is acceptable to have no more than three delays, on average, out of 100 flights;
- The direct maintenance cost during the first 10 years will not exceed 25 % of the purchase cost with a probability of 0.95;

- The probability that the production line will be fully operational during the specified in-service time will be not less than 0.91;
- In system consisting of several systems, at least 90% of them will be operational at all times with a probability not less than 0.925;
- The mission reliability will be greater than 0.98 for missions up to 500 hours;
- Each 10-hour flight will be successfully completed with probability of 0.995, during the first 20 years of operation

Consequently, the only way to address functionability performance targets formulated in the way above is to use concept and principles of Mirce-mechanics to evaluate engineering and management options, at the time when fundamental and irreversible decision are made regarding the management of failures of future industrial systems.

11. CONCLUSION

The main objective of this presentation is to present the Mirce-mechanics approach to failure management process regarding the increase in profitability and reliability of industrial systems, as a new approach to maintenance. It is focused on the way that failures, once scientifically understood, could be managed in the way to maximise the time in operation and minimise the time in maintenance, which in turn will generate profit for private businesses or increase public satisfaction for common services like health, transportation, education, tourism all way up to the national defence.

Unlike the classical mechanics, where the continuous uniform motion is natural state of the macro world that is fully defined and predictable by Newton’s equations, in Mirce-mechanics continuous change in the functionability states is a natural state of industrial systems during their in-service life, which is fully defined and predictable by Mirce Functionability Equation. Finally, Mirce Profitability Equation is presented as the scientific foundation of the System Engineering and Management predictions and analysis that brings together the revenue and cost elements of businesses that are dependent on the behaviour of industrial systems.

12. REFERENCES

[1] J. Knezevic, *Functionability in Motion*, Proceedings 10th International Conference on Dependability and Quality, DQM Institute, 2010, Belgrade, Serbia.

[2] J. Knezevic, *Scientific Scale of Reliability*, Proceedings of International Conference on Reliability, Safety and Hazard, Bhabha Atomic Research Centre, 2010, Mumbai, India.

[3] I, Zaczyk, J. Knezevic, *Cosmic Phenomena in Mirce-mechanics Approach to Reliability and Safety,* International Journal of Life Cycle Reliability and safety, Vol 2, Issue No 2, 2013, ISSn-2250 0820, Society for Reliability and Safety, India.

[4] J. Knezevic, *Atoms and Molecules in Mirce-mechanics Approach to Reliability,* SRESA Journal of Life Cycle Reliability and Safety Engineering, Vol 1, Issue 1, pp 15-25, Mumbai, India, 2012. ISSN-22500820

[5] C, Hirtz, *Impact of Environment and Human factors on Duration of Maintenance Task,* Doctoral Diploma Dissertation, MIRCE Akademy, Exeter, UK, May, 2012.

[6] Ben-Daya, Duffuaa, Raouf, Knezevic and Ait-Kadi, D. (2009), *Handbook of Maintenance Management and Engineering*, Springer, Dordrecht, Heidelberg, London and New York, NY.

[7] J, Knezevic, Mirce Functionability Equation, Journal of Engineering Research and Applications, ISSN: 2248-9622, Vol. 4, Issue 8, August 2014, pp 93-100.

Wear Check Oil Diagnostics: Way to Improve Machine Health by Condition Monitoring[17]

Dr. Mária Sutyinszki, MOL-LUB Ltd , H-2931 Almásfüzitő, Fő út 21, Hungary
Tonća Ćaleta Prolić, MIng Chem. INA Maziva d.o.o, Radnička cesta 175, Zagreb, Croatia

Abstract:

A well-run condition monitoring program can achieve significant benefits in operational reliability of machinery. According to a study by Dr. Rabinowicz of MIT, 70% of component replacements are due to wear and corrosion that are strongly related to lubrication and condition monitoring practices. The paper shows the WearCheck oil and wears particle analysis system as the tools to manage a condition monitoring program for lubricated systems. It can save money by maximizing oil change interval potentials and by detecting the ingress of contaminants from the operating environment as well as the abnormal changes in oil and component wear due time. Early warning by recognizing such changes leads to saving the oil and avoiding excessive wear. Primary goals of oil analysis are to support predictive and proactive maintenance.

1. Introduction

The essence of the WearCheck and CoolCheck concept is decoding, interpreting and acquisition of diagnostic information in a drop of oil or coolant to support maintenance with the help of targeted testing. The metrics of a lubricant's physical and chemical properties, the intensity of changes in them, the types and quantity of contaminants entering the lubricant and the nature and proportion of wear particles together represent important information from which we can infer the correct or irregular operation of machines as well as correct or incorrect choice of lubricant and its continued usability. The analysis of the lubricants diagnosed condition of measuring equipment and in the early stages indicates a potential problem in the operation and maintenance

MOL's WearCheck laboratory has been a member of WearCheck International since 1997. This professional association unites laboratories operating on four continents around the world. Regular exchange of experience and knowledge-sharing among members ensures the continuous concept development and that laboratories and diagnostic methods are always up to date [1].

2. Process of Oil Testing Procedure in Wearcheck Laboratory

2.1 Lubricants and test methods

There are different requirements identified for oil samples from different machines. While for example a motor oil should have excellent cleaning power and able to keep large volume

---

[17] Paper was presented at the 22 International Conference "Maintenance 2016", in Sibenik, 16-18 May 2016, Croatia, organised by the Croatian Maintenance Society, www.hdo.hr

of solid particles (soot) in flotation, on the other hand a turbine oil should be easily separated from water, and have long lifetime, etc. As a consequence, we should perform different test series for different types of oils.

The following table presents the summary of routine and potential supplementary tests applicable for various product groups without the need for completeness.

	Motor-oils	Gear oils	Gas motor oils	Hydraulic oils	Turbine oils	Industrial transmission oils	Compressor oils	Heat transfer oils	Slideway oils	Transformer oils
Viscosity	X	X	X	X	X	X	X	X	X	X
Base number (BN)	X									
Acid number (AN)		X	X	X	X	X	X	X	X	
Additive elements, ICP	X	X	X	X	X	X	X	X	X	
Wear metals	X	X	X	X	X	X	X		X	
Contaminants	X	X	X	X	X	X	X	X	X	X
Ferrography	X	X	X	X		X	X		X	
Wear index	X	X	X	X		X	X		X	
Cleanliness – ISO 4406		X		X	X	X	X		X	X
Water, ppm, %	X	X	X	X	X	X	X	X	X	X
Motor fuel content	X									
Dispersancy	X									
Soot content	X									
Additive content, FT-IR							X	X		X
Degradation products	X		X		X			X		
Emulsion indicators				X	X	X	X		X	
Flash point (COC)	X		X				X	X		

Table 1: Lubricants and test methods [1].

2.2 Preparing sample and procedure

Machine operator is usually responsible for taking samples, and MOL WearCheck laboratory provides special equipment for this action. It must be ensured that the sample represent the entire oil lubricant, and also that no tramp pollutants can get into the samples during the sampling process. Sampling vessels have extraordinary purity, and the operating principle of the manual sampling pump can ensure that oil samples cannot be mixed up during the consecutive sampling processes.

After the samples are delivered, their analysis begins with performing a so-called routine test series (water content, kinematic viscosity, index viscosity, base number, flash point). Diagnostic engineers study the results of these routine tests. There are cases when results of these routine tests do not enable forming a clear-cut expert opinion. In this case further and usually more complex tests should be performed, following the required consultations.

Results of these tests can support diagnostic engineers in developing an expert opinion which is beyond doubt.

2.3 Example of testing

According to a study by Dr. Rabinowicz of MIT (Massachusetts Institute of Technology), 70% of component replacements are due to wear and corrosion which are strongly related to lubrication and condition monitoring practices [2]. That is why, it is very important to determine wear metal content and origin. In general Wearcheck laboratory uses tyhe following three methods for measuring wear metal content,

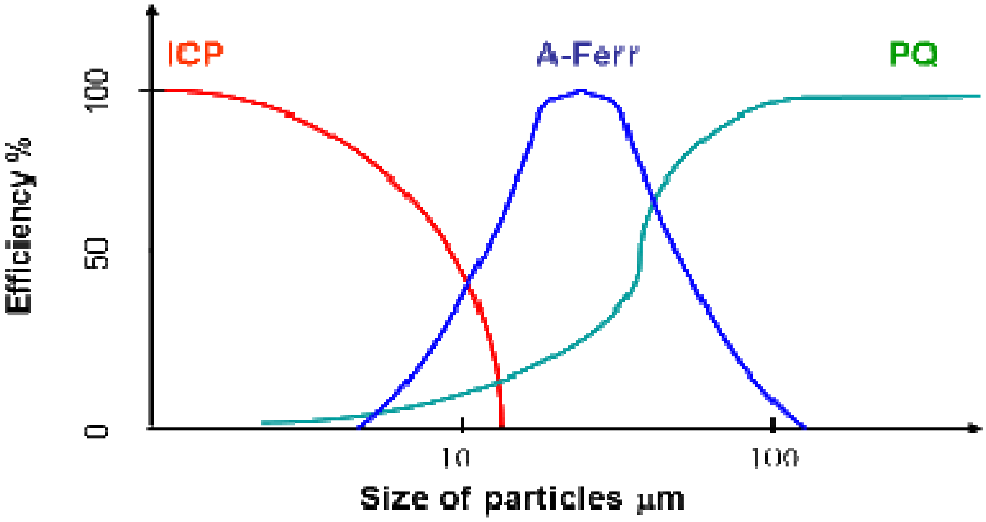


Figure 1: Methods for measuring wear metals [3]

where: ICP: measures additives, wear metals, contaminants: 2-8 µm size (quantity and quality analysis), PQ: detects and measures the mass of ferrous wear debris. Analytical ferrorgraphy (A-Ferr): reveals both the wear mode(s) present as well as alloy compositions of the wear particles present (Figure 1). Gives clear picture of the component(s) which are wearing in the system. (Figure 3).

Figure 2: Ferrogramm maker and Ferroscope [3]

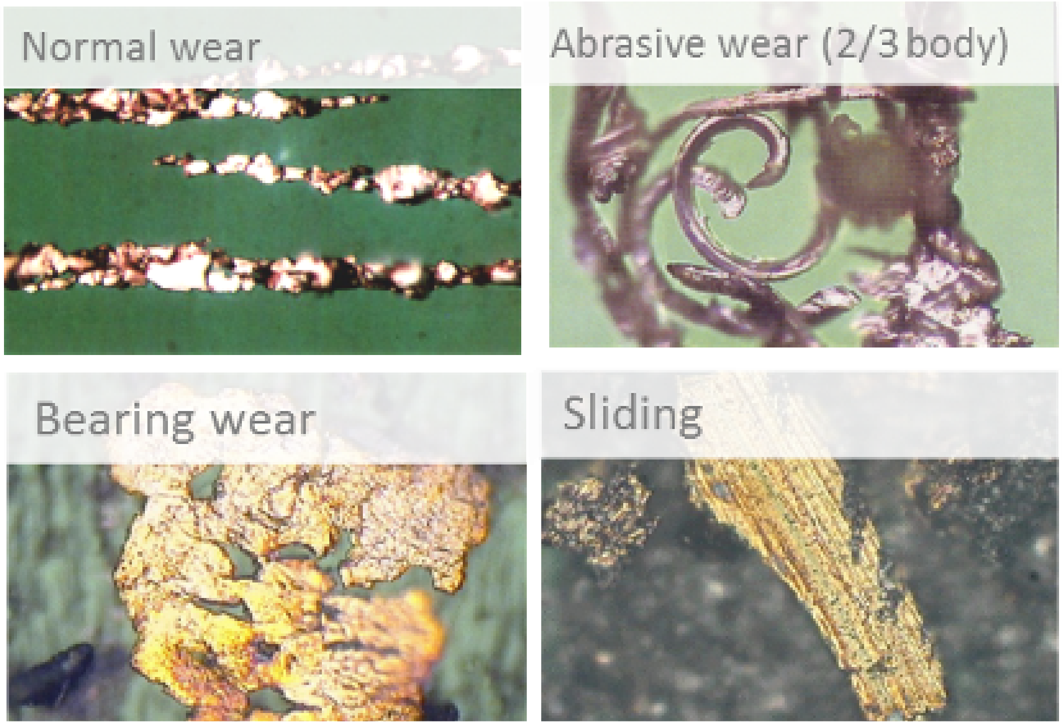


Figure 3: Different type of wear particles [3]

2.3.1 Wear and type of lubrication

Wear is the gradual loss of material from the surface of a solid body due to dynamic contact with another solid body, fluid, and/or particles. [4]
There are four fundamental mechanisms of wear: [5,6]

- abrasion
- adhesion
- surface fatigue
- tribocorrosion

Abrasion is wear resulting in the removal of material, caused by hard particles or hard protrusions. Adhesion wear is characterized by a transfer of material from one sliding surface onto another in relative movement, due to the process of solid-phase welding. We distinguish three phases: the creation of adhesion pair in the area of contact of protrusions; severance of the adhesion pair; detachment of wear particle, or the particle remains permanently "glued", or welded onto another sliding surface (Fig. 4). Surface fatigue is a type of wear in which the separation of particles arises due to the cyclical changes of stress.

Tribocorrosion, or tribochemical wear, is a mechanism of wear in which the chemical or electrical-chemical reactions between the material and the environment are predominant.

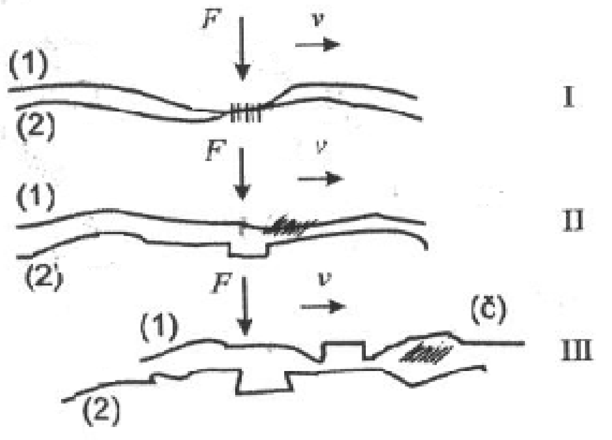


Figure 4: Unit event of adhesion [5,6]

To avoid wear in the different system we need lubricants with good rheological properties.

Rheological properties of the lubricant means the viscosity at high and low temperatures, which during the application must keep within the prescribed requirements. It is necessary to maintain elastohydrodynamic lubricating film in the entire range of operating temperatures.

There are three types of lubrication: borderline, mixed lubrication and complete layer of lubricant (Figure 5).

In boundary lubrication lubricants required thickness to prevent contact of solid bodies, with mixed lubrication film of lubricant is partially destroyed, but there is partial contact solid surfaces. In hydrodinamic lubrication, lubricated surfaces are totally separated by the continuous lubricant film. This kind of lubrication can be hydrodynamic and elastohydrodynamic lubrication.

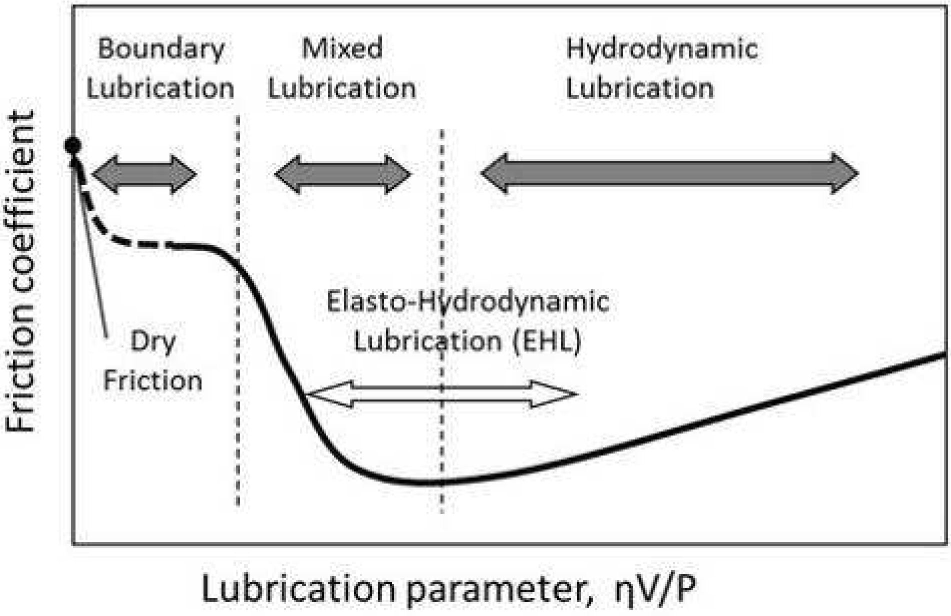


Figure 5: STRIBECK CURVE - Conditions and types of lubrication [2].

2.4 Test report

After the laboratory work and preparation of diagnosis machine operators receive a report. It contains sample identification number given by the laboratory, information about lubricant or coolant and the equipment according to the analysis order (sampling) form. It contains test results and expert's opinion on the lubricant and equipment, as well as the proposals for the required interventions or actions.

3. Case Study

3.1 Trucking case study-Engine oil

The modern type of tractors need to lubricate separate engine and for the hydraulic, transmission parts and wet brakes need another lubricant. In this case study we used HDDO engine oil viscosity grade SAE 15W-40 in JOHN DEERE Tractor (Figure 6).

This is an engine oil consisting of mineral oils produced using modern oil refining processes and containing a high performance balanced additive system that improves flow characteristics.

On this field testing according WearCheck analysis drain interval was extended about 50%.

Figure 6: JOHN DEER tractor

3.2 Industrial case study-Hydraulic fluid

The main causes of Pump failure are dirt and product of the corrosion.
Hydraulic oils used in hydrostatic power transmission systems operates under normal thermal and mechanical load. They provide good oxidation stability and wear protection, reduce deposit formation and protect hydraulic systems against rust and corrosion.
In Wearcheck laboratory additionally we tested Cleanliness against ISO 4406 method (Figure 7).

Figure 7: Equipment for testing hydraulic oil cleanliness

The hydraulic pump and filters during the normal condition of use contain wear and contamination debris. Filter analysis involves the removal of a small amount of the filter medium. This is agitated with special solvents to remove the debris. The solvent is then filtered through a membrane and examined under a microscope. Basic metal types such as iron, copper, white metal and aluminium are identified and quantified according particle size.

Figure 8: Mechanical filtration [7]

During Optical particle analysis measurement the fluid is filtered with 0,8 µ pore size filter, and the residue is checked under microscope (Figure 8).

.4. Summary

The main benefits WearCheck oil diagnostics are:

- Shows the condition of the equipment
- Spot potential problems at an early stage, support preventive maintenance
- Provides optimum equipment life
- Maximizes oil and coolant performance capabilities
- Allows to safely extend oil and coolant drain interval
- Allows to optimize maintenance intervals
- Allows to plan and schedule maintenance in advance
- Lowers repair and labor costs
- Reduces downtime and lost operation

The main disadvantages WearCheck oil diagnostics are:

Inadequate sampling procedure may cause false, not relevant results and diagnosis. Without accurate knowledge of equipment operating standards the evaluation of test results may be incorrect.

5. References:

1. MOL-LUB Ltd.: WearCheck and CoolCheck diagnostics (brochure), Budapest, 2006
2. Rabinowicz, E.: Friction and Wear of Materials, New York,1965
3. PREDICT: Advanced Analytical Ferrograpy Issue 1.1, Cleveland, OH
4. Glosary of terms and definitions in the field of friction, wear, lubrication and tribology, OECD Publications, Paris, 1969
5. Ivušić,V., Grilec, K.: *Tribologija*, autorizirana predavanja, Zagreb, 2011
6. Ivušić, V.: Tribologija, Hrvatsko društvo za materijale i tribologiju, Zagreb, 2002.
7. MOL-LUB Ltd.: Mechanical contamination MOL-LUB M-65 (method), 2007

The shape of things to come: New Way for Predicting In-service Reliability of New Equipment.

Alex Mulholland BSc CEng MIET HFMA
Finmeccanica, Airborne & Space Systems Division

ABSTRACT:

For many years military programmes have used constant failure rate to model reliability of the new electronic equipment designs. They re-enforced this constant model by measuring achieved performance by dividing the number of failures by the unit of operation (hour/landing etc.). In parallel, Companies and Customers acknowledged that "predicted" reliability was unlikely to be achieved from day one in service. So, we included a "fudge factor" or perhaps even a reliability growth profile. These profiles, often based on historical performance or "best engineering judgement", are applied to the failure rate prediction to provide a "more realistic indication" of the real in-service reliability. This paper describes the surprising differences I found in the financial or operational risks we accept by trying to "fudge" a constant failure rate model to address the reality of how the different identifiable and definable failure mechanisms will contribute to the "real" failure profile of new equipment

1. Introduction

For many years military programmes have used constant failure rate to model reliability of the new electronic equipment designs. They re-enforced this constant model by measuring achieved performance by dividing the number of failures by the unit of operation (hour/landing etc.). In parallel, Companies and Customers acknowledged that "predicted" reliability was unlikely to be achieved from day one in service. So, we included a "fudge factor" or perhaps even a reliability growth profile. These profiles, often based on historical performance or "best engineering judgement", are applied to the failure rate prediction to provide a "more realistic indication" of the real in-service reliability. This paper describes the surprising differences I found in the financial or operational risks we accept by trying to "fudge" a constant failure rate model to address the reality of how the different identifiable and definable failure mechanisms will contribute to the "real" failure profile of new equipment

For most of my life working life I have been involved in modelling support solutions. These have range from simple repairs or spares models to full support services including spares, repairs, storage and transportation volumes, test equipment loading, manpower requirements and so on covering many years of in-service operation. All these models, however complex we wanted to make them, were based on the premise that because we were modelling complex electronic equipment, with many different patterns of failure and repair, then the exponential distribution is an appropriate model to use. In fact, in many of our contracts the use of the Military Handbook 217F Reliability Prediction of Electronic Equipment (Department of Defense, 1991), more commonly referred to as MIL-HDBK-217F, was a mandated requirement. This was convenient for us on many levels. The use of the exponential distribution to model the time to failure of parts meant we could convert them to failure rates and conveniently add them, making the analysis task easier and simplifying the modelling tools needed to develop the support solutions. We could also attend 3 day reliability engineering course to learn the basic mathematics and principles of reliability engineering, to drive software based on this model.

As a way of almost reinforcing the validity of the constant failure rate model was the way we collected and verified our equipment's reliability from in-service data. We were given the total number of hours operated by the equipment over a given period and divided them by the total number of failures in the period to get a Mean Time Between Failures (MTBF) or failure rate, λ=1/MTBF.

Not unsurprisingly we discovered that the predictions we made using the MIL-HDBK-217F were not the same as the reliability we were observing in operation. Rather than question the validity of our modelling assumptions we applied our Engineering Judgement and added in a Reliability Growth Factor. We could assess this factor based on historical data and then simply apply it to the new equipment as it entered into service. We justified this to our engineering colleagues and programme managers that we were taking account the effects of the Reliability Bath Tub (See Figure 1).

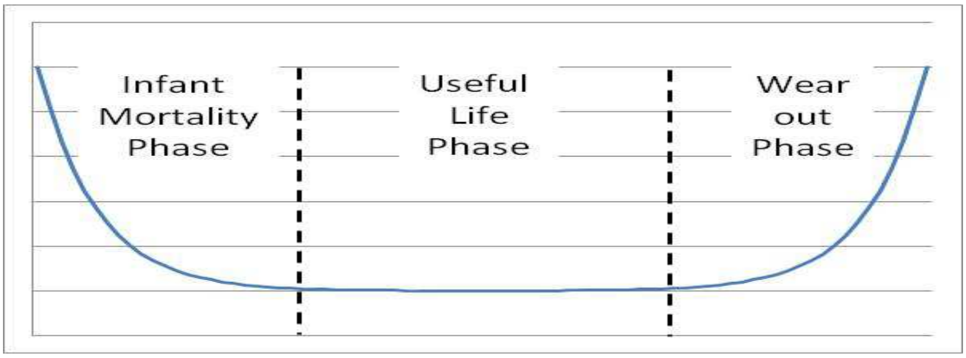


Figure 1.Idealised Reliability Bath Tub Curve.

So our basic prediction was given a reliability profile based on similar equipment and historical data. We applied a factor of 4 or 5 or maybe 10 to year 1, a lower number to year 2 and so on. If the support contract was over a long period or the equipment we were supporting was getting older, we could also apply a reliability degradation factor to address the expected increase in failures. Problem solved, so what is the issue? Well we didn't really know what it is that is driving the need for the reliability factor (growth or degradation); we just use what worked before and a bit of our engineering judgement from our years of experience to convince our engineering brethren we knew what was going to happen. But as W. Weibull argued in 1951 "it is believed that ….the only practical way of progressing is to choose a simple function, test it empirically, and stick to it as long as none better has been found" (Barlow & Proshan, 1996). So even though our estimates were not that accurate, with the variability of operational profiles, the vagaries of reliability root cause analysis and a bit of risk management we always managed to explain away any differences from prediction to measured reliability. And we stuck with it!

My problems began when we began developing systems that had graceful degradation as a designed in characteristic rather than hard failure. This meant at best we had to consider two parts to our system. One I could model in the usual way with all my tried and tested tools, the other I had to model separately because it did not have a constant failure rate. It was designed to not have a constant failure rate to take advantage of it ability to cope with multiple failures and different parts of the equipment (known in military terms as a Line replaceable Unit) could tolerate different levels of failure. So we needed to model this separately. This meant developing models that would let us model both constant and non-constant failure rate together. As we could not describe the resultant composite reliability distributions mathematically, and approximating the distribution to an exponential would mean losing some benefit of the graceful degradation, we began to look at Monte Carlo simulations to get our spares and repair quantities. What we discovered was that the impact of having different reliability profiles combined with changes in operational hours and contract duration could make a significant difference to your repairs quantities and hence warranty or support costs.

We then began to question was it valid to assume that our reliability factors are applied at fixed periods (say each year of operation) when we know one of our reliability profiles is driven by operational hours. I did not have the expertise in modelling reliability other than using the exponential distribution, so I spent some time working with Dr Jezdimir Knezevic of the MIRCE Akademy to develop our ideas, modelling techniques and the need to understanding the contribution failure mechanism have on the reliability profile of a system.. As a company we also worked with Professor John Quigley from the University of Strathclyde to help us learn how to more effectively elicit reliability risks from our design teams, through the tailored application of their REMM (Reliability Enhancement Methods and Models) process (Walls, Quigley & Marshall, 2006).

This left us with a missing piece to our newly evolving jigsaw, how do you take a qualitative reliability risk and turn it into a quantifiable reliability distribution? To help us, we decided to have a look back at our in-service reliability and Failure Reporting and Corrective Action (FRACA) data, to investigate: what if we used the failure mechanisms we had observed in the past that contributed to the infant mortality, useful life and the wear out failures to determine the type of reliability distribution that described them best. We looked at a range of operational field data and root cause analysis to establish, as best we could, when in the operational life of a system they contributed to the failures of the system. We looked particularly for pattern failures that occurred soon after first delivery, appeared to happen throughout the life of the system, soon after repair and beyond the middle of the systems design life.

I then looked at a number of ways we could link the underlying failure mechanism of a reliability risk with an appropriate distribution and estimate of when it was likely to occur and final came up with a set of “guidelines” that would map failure mechanisms to an appropriate Weibull distribution in terms of is expected shape value and expected time of occurrence. But not all of these risks were certainties, so a view on the probability of the risk being present was also included in the analysis process.
This now gave us a chance to model the combination of equipment design reliability with the other inherited, induced and propagated reliability risks we had seen historically. When we modelled existing systems we could see a better correlation between our simulated repair quantities and the actuals, but the real shock came when we began to play with key contract parameters: what if the customer needed to fly more than modelled; what if the customer requested a longer or shorter warranty period or support period. When we modelled these scenarios and compared them to our old modelled techniques, the results were eye opening. The change in costs and risk as the two parameters varied was not highlighted using our old

modelling techniques. The impact on cost of reliability risk in short term warranty contracts was now evident, because there was not enough time for the reliability average out and stabilise . Also the impact of increased operating hours bringing in wear out effects, but reducing infant mortality risk duration was shown through our new models. For the first time in my 26 years of modelling reliability I could see the shape of things to come and it was predictable.

2. How we used to Model In-service Repairs

When I started modelling reliability to establish the quantity of spares required for components in our recommended spares lists. As with other military companies in 80's and 90's, we were using a combination of MIL-HDBK-217F reliability predictions and OPUS to get a recommended spares quantity. This was great, we used it, our competitors and customer used it, so our answers were al consistently based on the same core assumptions. But with every model came the need for "a bit of engineering judgement". Wiser and more experienced reliability engineers would say: "you can't believe the raw prediction; you have to factor them for real life". And so an engineering judgement would be applied to the component failure rates in order to get "more realistic" spares quantities.

As I progressed onto modelling circuit cards and assemblies, the same principles would apply. Carry out the MIL-HDBK-217F prediction and then apply an engineering judgement figure to convert it from the "modelling world" to the "real world" because MIL-HDBK-217F does not account for all the other non-equipment related things that can cause failures.

I had my reliability predictions based on equation 1 so we add our failure rates and calculate repair quantities. We had our Poisson based model for the number spares and we had a fudge factor to take account of everything else we did not know.

$$f(t) = \lambda e^{-\lambda t} \qquad (1)$$

So when the Customer asked us to model a support solution it was easy, we took the delivery schedule and the operating profile and did the maths. So let's take a look at a typical example. Logistic Parameters:, System Predicted MTBF = 3585 operating hours Equipment enter Service as per Figure 2

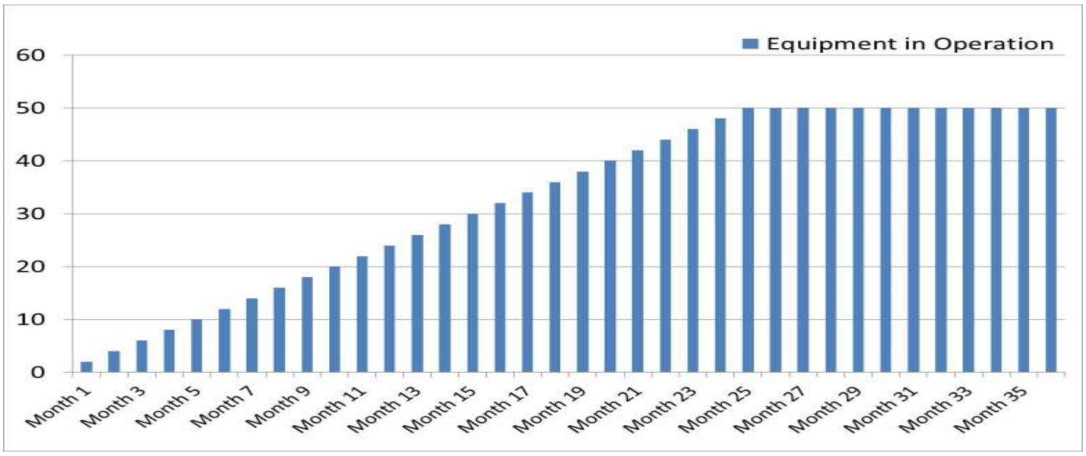


Figure 2.Equipment entering into operational service.

Equipment operate for 400 operating hours per year each

Equipment Warranty period = 12 months

From this we can calculate the warranty profile (Figure 3) and the cumulative warranty operating hours (Figure 4)

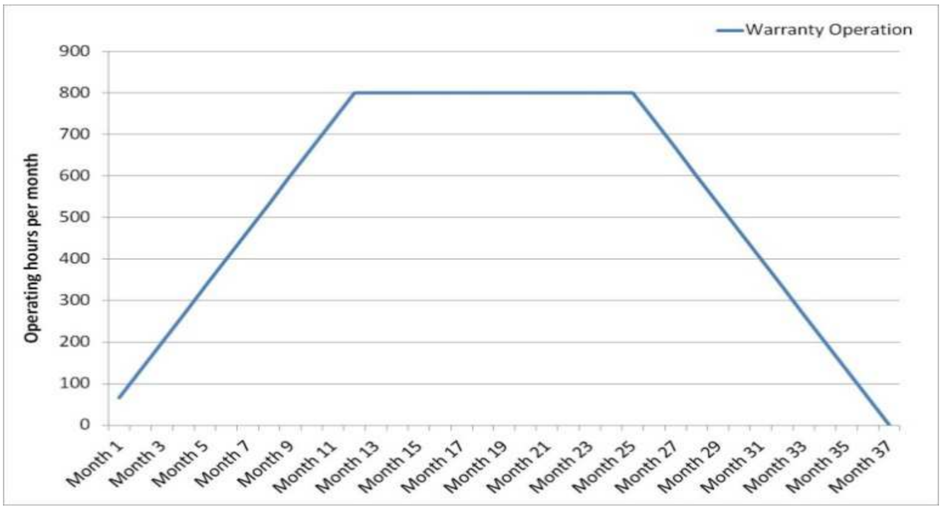


Figure 3. Total Equipment operating hours per month.

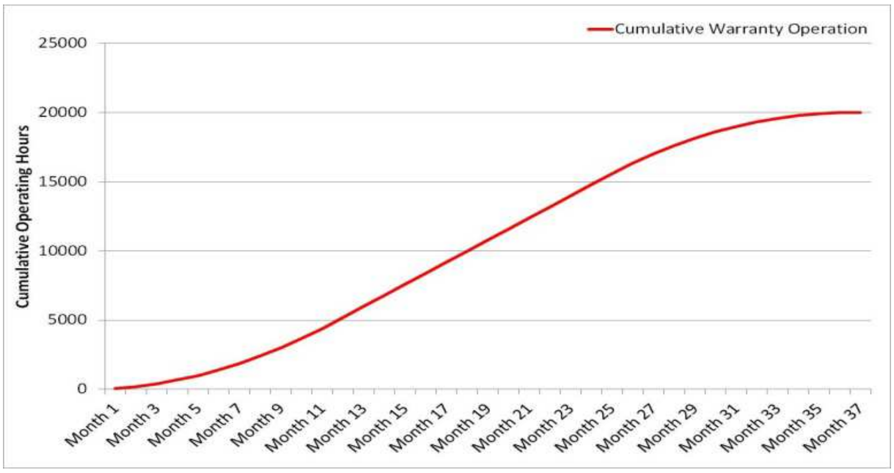


Figure 4.Cumulative Equipment warranty-operating hours.

Doing the simple maths

$$\text{Repair} = \frac{\text{Operating Hours}}{\text{MTBF}} = \frac{20000}{3585} = 5.57$$

$$\approx 5 \text{ to } 6 \text{ expected warranty repairs}$$

We can also plot this as a repairs profile (Figure 5) that can be used for test loading or transportation volumes etc.

At this point I would usually convert the number of repairs to the cost, because cost always gets more attention in the business than just numbers. But as costs can get a bit sensitive outside the business I will stick to repair numbers. I will let you do your own estimate as to what the cost may be to business.

But this does not take into account our fudge factor or to give it its more grand title reliability growth factor. So we need to add a bit more into the model

Figure 5.Repair profile.

3. Adding in Reliability Growth to the Model

This is where even if we believe the underlying MIL-HDBK-217F reliability model, we have to use a bit of best engineering judgement. What factor will we apply to each month or year of operation to reflect the fact we know our equipment enter service with lower than predicted reliability but through our Failure Recording, Analysis and Corrective Actions System and other good things we will grow the reliability to closer to the required prediction. So based on the past we agree the profile in Table 1:

Reliability Growth Profile	Failure Rate x Factor
Year 1	10
Year 2	5
Year 3	2.5
Year 4	1.25
Year 5	1.1
Year 6	1.1
Year 7	1.1
Year 8	1.1
Year 9	1.1
Year 10	1.1

Table 1 Failure Rate Multiplication Factors

We assume the profile is flat out to year 10 as the design life for the equipment on this platform is 25 years, so we should not expect any wear out issues. When we run the model this time we get very different results (See Figure 6)

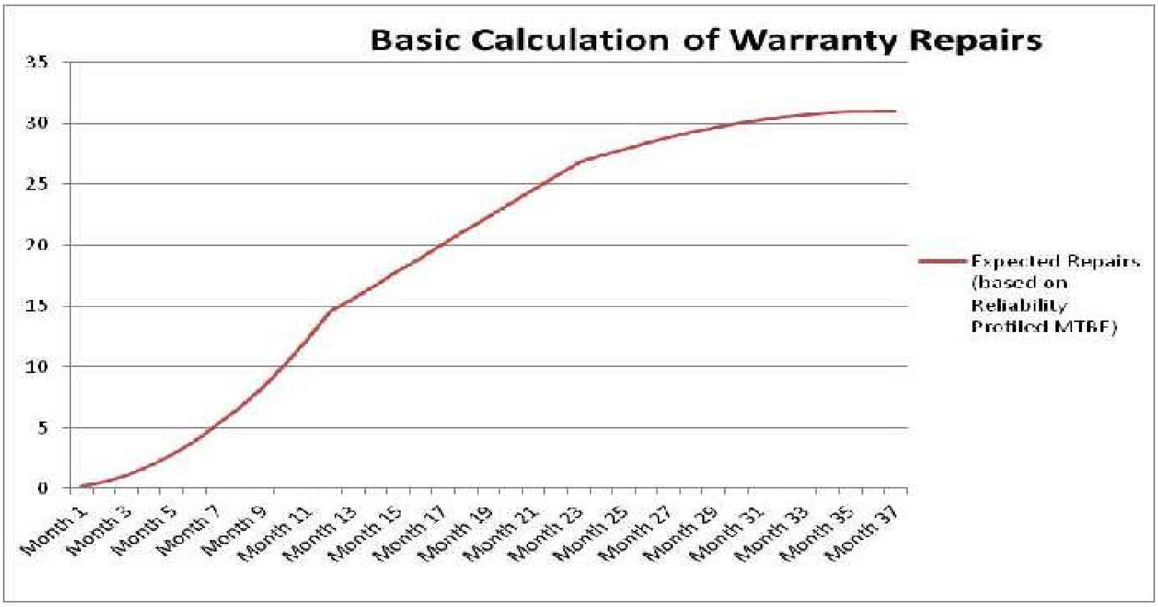


Figure 6.Repair profile with reliability growth.

These profiled models were used to provide the warranty repairs spend profile to build into our business plan

The concerns I was always left with were: What was the uncertainty (risk) in the calculations and why did I need to extrapolate some view of reliability growth?

This is where the idea of linking the reliability risks we could elicit from our design and manufacturing engineers with estimating an appropriate reliability distribution and risk of occurrence became the focus of my attention. Let’s compare the results.

4. Modelling Reliability Risks and using Monte Carlo Simulation

The first improvement modelling with reliability risks gave us was that we could model different failure mechanisms independently. This meant we could simulate our non-constant failure rate elements of the equipment independently of the assumed constant failure rate elements. It also let us add in those induced or inherited failure mechanisms that may be present, but not necessarily an intrinsic function of the design.

As we did with the simple model, let us look first at the intrinsic or underlying reliability of the equipment (as we predicted it using MIL-HDBK-217F). The two elements of the design are shown in Table 2 below:

Failure Mode/ Mechanism	Profile of Failure Life (α)	Expected time to Failure (1/λ)	Chance of happening
Constant Failure Mechanisms	1	4642	100%
Non-Constant Failure Mechanisms	6.43	7572	100%
Effective Mean Time to Failure		3585	

Table 2 Weibull parameters and probability of presence

The Effective mean time to failure had to be calculated by calculating the area under the probability density function, by combining the individual Weibull distributions, see equation 2, to create a composite probability distribution and estimate the area under the curve to give an indication of the effective mean time to failure.

$$f(t) = \lambda \alpha t^{\alpha-1} e^{-\lambda \alpha t} \qquad (2)$$

What is noticeable is the fact that it has a different profile characteristic then the exponential with the same expected time to failure (1/λ) as shown in Figure 7.

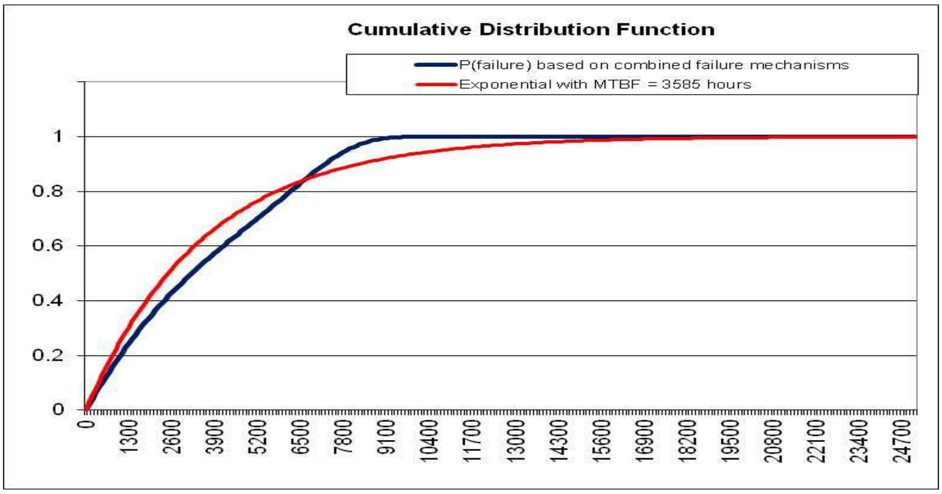


Figure 7.Cumulative Distribution Functions for original exponential model and composite distribution model.

When we run the simulation and compare it with our previous model we begin to see the differences in these profiles taking effect (see Figure 8).

Figure 8. Simulated repair profile compared to previous exponential model profile.

With the simulation we can see the reduction in expected repairs due to the slightly slower ramp up rate in the Cumulative Distribution Function (CDF). We can also look at adding confidence intervals from the simulation values showing us the potential estimating risk associated with the composite model.

So we can see the simple model and simulation are giving similar results and taking into account sample error the simple model would fall within the 95% confidence limits.

The next step was to ask the design and manufacturing team to identify those areas of concern they had with the design and manufacturing processes in order to establish a set of reliability risks for this specific equipment. The risks shown in Table 3 were identified.

We then asked them to estimate how many hours into life would they expect the failure to occur, would it be an early life type fault (Profile of life < 1) an random type failure (Profile of Life = 1) or a wear out type failure (Profile Life > 3). Finally we asked over what percentage of the manufactured population the risk would be likely to apply to. The results are shown in Table 4.

Failure Mode/Mechanism
CTE Mismatch causing fatigue failure
Surface Mount Connector is Un-proven causing fatigue life
Surface Mount Connector manufacturing robustness
RF connector matting issues (due to tolerancing)
Difficulties in accurately positioning components on small lands
Repair Induced Failures

Table 3 Reliability Risks

Failure Mode/ Mechanism	Profile of Failure Life	Expected time to Failure	Chance of happening
CTE Mismatch causing fatigue failure	10	3500	90%
Surface Mount Connector is Un-proven causing fatigue life	5	5000	3%
Surface Mount Connector manufacturing robustness	0.5	100	10%
RF connector matting issues (due to tolerancing)	0.5	50	20%
Difficulties in accurately positioning components on small lands	0.25	50	15%
Repair Induced Failures	1	15	10%

Table 4 Characterisation and Quantification of Reliability Risks

These reliability risks were added to the two predicted failure mechanism profiles (from Table 2) with some provisos on their probability of occurrence. These were attributable to the last two risks. The component placement problem was as a result of the mechanical assembly process, so could only happen once after initial manufacture, after that re-work would be manual and so the risk would not be continuous. Also the repair induced faults could only occur after the first repair action (resulting from any failure had occurred). So these requirements were also built into the simulation model.

We can see the impact of these reliability risks on the CDF (see Figure 9)

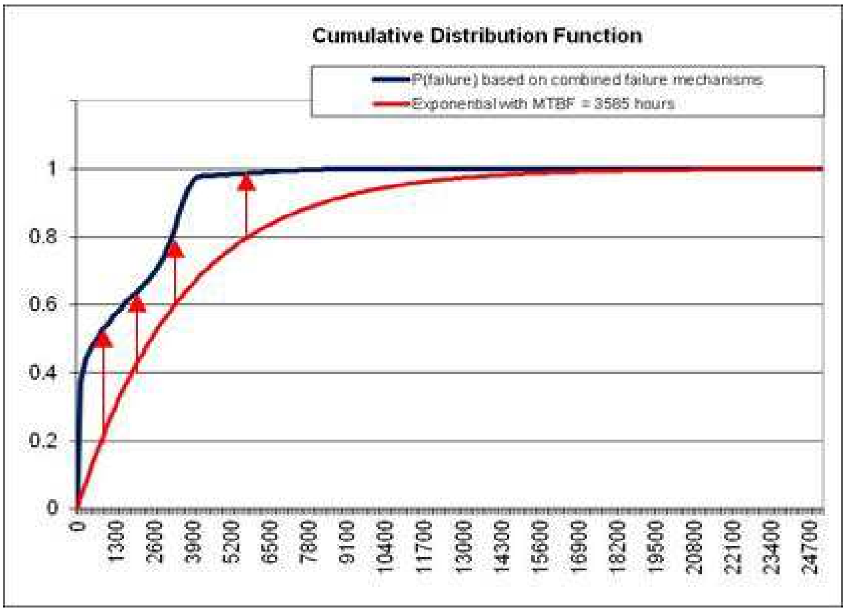


Figure 9. Cumulative Distribution Functions for original exponential model and reliability risk composite model.

From Figure 9 we can see why we needed to apply reliability growth factors to our old models: we were dealing with a number of complex failure mechanisms influencing the early part of the life of a product and not all are intrinsic to the design. Also there is an increase in repairs significantly earlier than the mid-life point that we had not considered before.

We can now look at the expected impact on warrant repairs and how these compared with our previous estimations using reliability growth (See Figure 10).

Figure 10. Simulated repair profile compared to previous exponential model profile modified by reliability growth.

We can see that the simulation and reliability growth modified exponential model give us similar profiles, and the original model remains within the 95% confidence limits over the warranty period, but we would be predicting a higher rate of spend in general after the first 9 months and so we may be being slightly risk averse and driving in unnecessary costs to our proposals.

The next question was what happens as the duration of the support/warranty period changes and what if a customer needs a different operating hours? Let's compare the results.

Compare and Contrast Approaches

We then began to explore what happens when we change the duration of the support contracts and the operating hours per year needed to be supported by the Customer. The changes to the Logistics parameters we will explore in this paper are:
Support Contracts of 1 Year, 2 years; 5 years and 10 years and Operating hours of: 200 hours per equipment year; 400 hours per equipment year and 800 hours per equipment year.

As Figure 10 shows the results for 1 year support at 400 operating hours, we shall complete this series of analysis by looking at the 2 Year, 5 Year and 10 years support.

It should be noted in Figures 11 to 21 the cumulative expected in-service repairs are only calculated to the end of the support period for the modelled scenario but for convenience are plotted against a fixed duration x-axis. This results in the appearance of the graph flattening out.

In Figure 11 we can see that changing the support period to encompass the first two years in-service results in the reliability growth profile driving the repair costs towards the upper repair quantity confidence limit compared to the simulation of risks. This could be a potential cost driver and making it more difficult to secure longer term support contracts

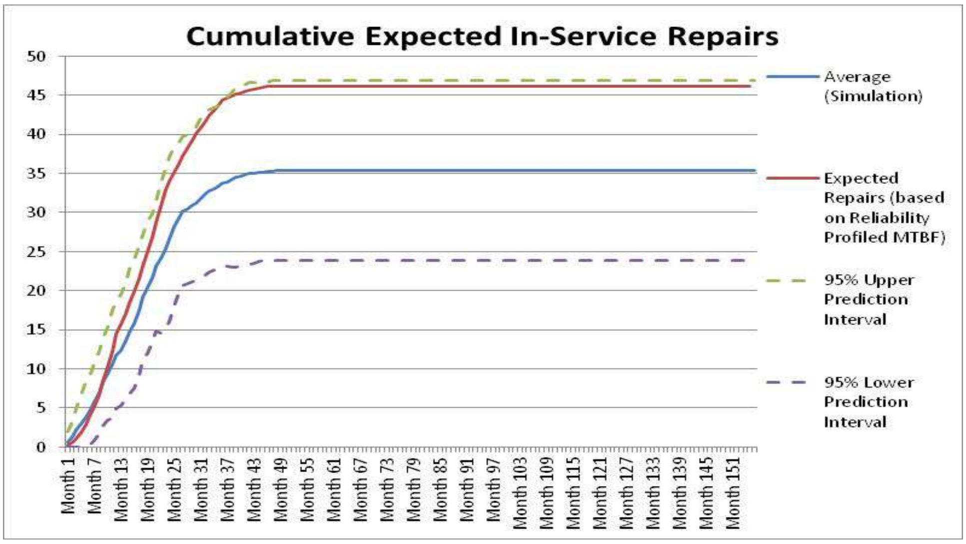


Figure 11. Support period increased to 2 years @ 400 operating hours per year

In Figure 12 when we look at the 5 year in-service support, we can see the reliability profile is still tending towards the upper confidence limit of the simulation and so drives up higher cost when offering support services.

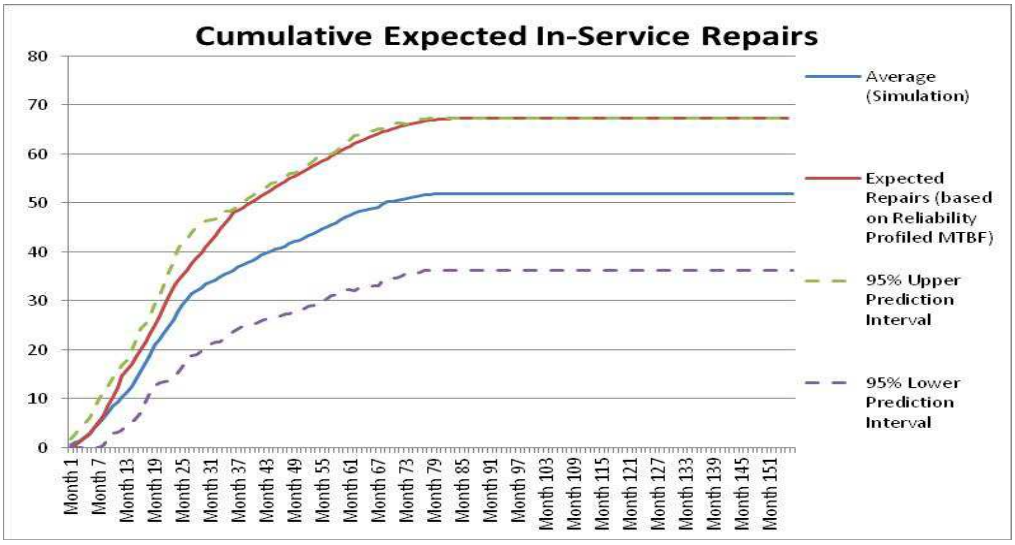


Figure 12. Support period increased to 5 years @ 400 operating hours per year

Figure 13 shows that extending to 10 years in-service support the wear out failure risks start to take effect and we get an increase in repair rate toward the end of the support contract.

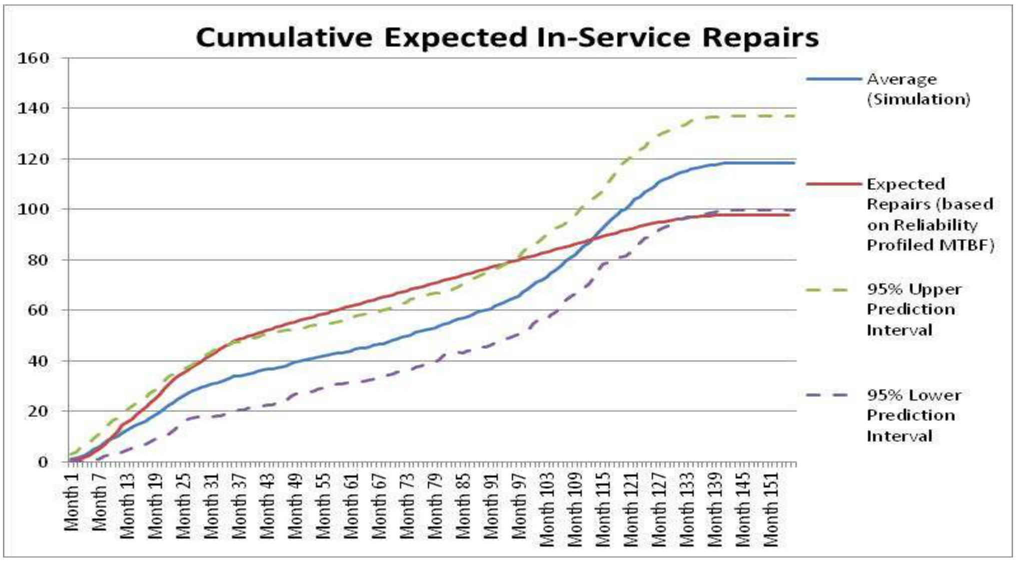


Figure 13. Support period increased to 10 years @ 400 operating hours per year

In Figure 14 we reset the operating hour to 200 per equipment per year and the support period to 1 year. With this combination of key operational parameters, we see that our old method results in a much lower cost than the simulation. I expect this is due to the reliability profile being based on data from products operating between 350–450 hours per year. Reducing the operating hours reduces the scaling we get from the reliability growth profile, but the higher ramp rate of the risk profile is more pronounced at lower operating hours (e.g. early life failures).

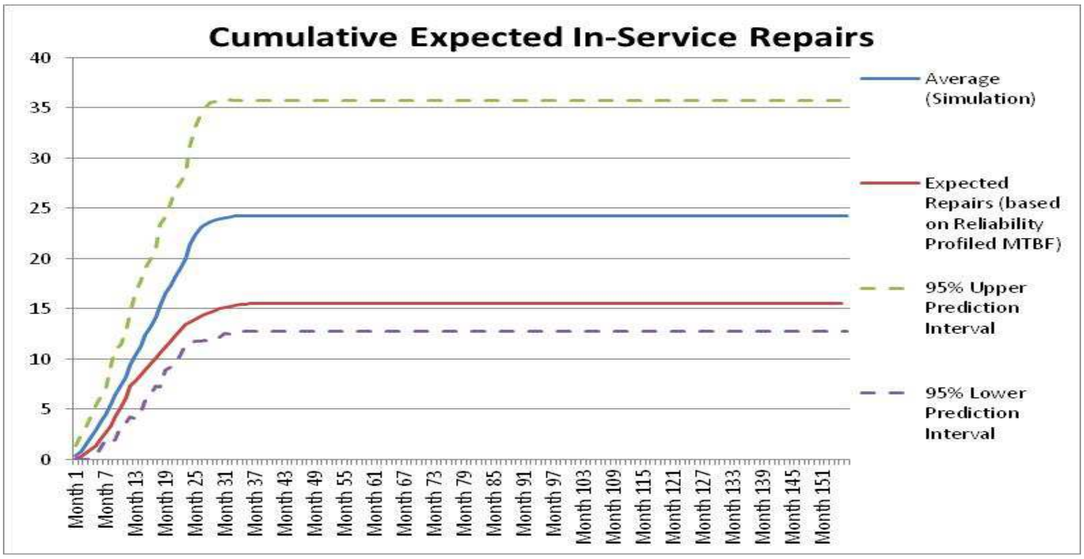


Figure 14. Support period of 1 year @ 200 operating hours per year

In Figure 15 the increase in duration to two years has allowed for a bit of averaging out and the costs are much closer again.

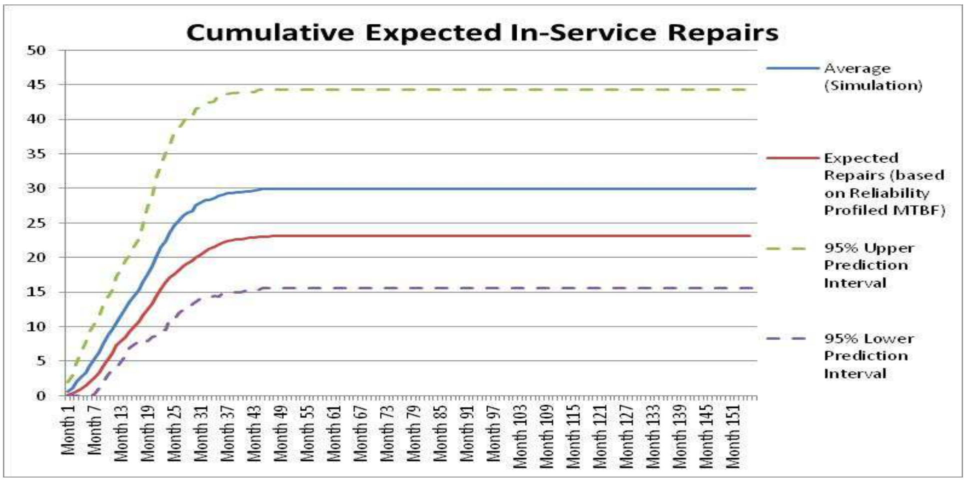


Figure 15. Support period increased to 2 years @ 200 operating hours per year

As we increase out to 5 years in Figure 16, the costs continue to converge due to the averaging effects of the reliability profile.

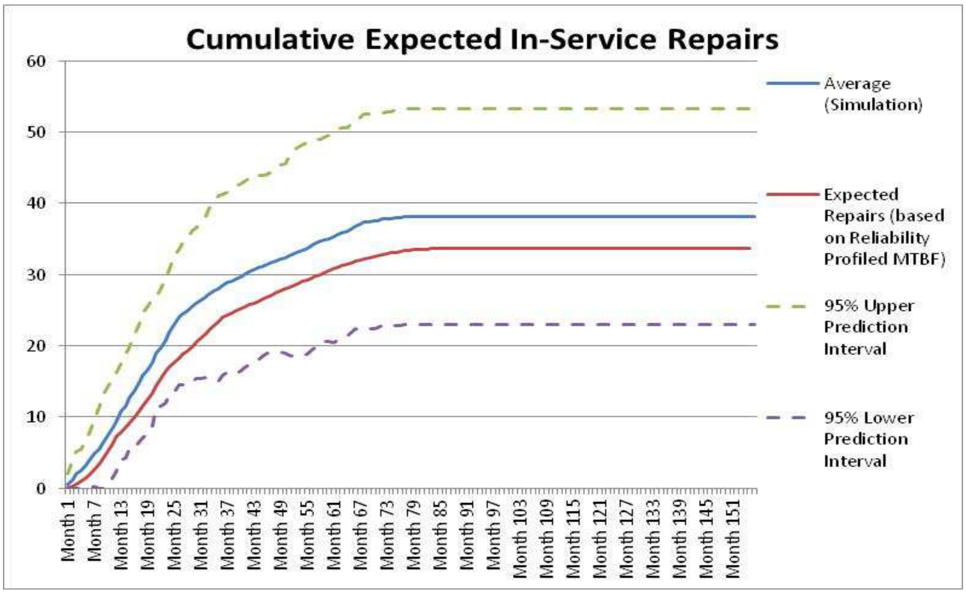


Figure 16. Support period increased to 5 years @ 200 operating hours per year

In Figure 17 covering 10 years at 200 operating hours per equipment the results a very close, but throughout all these models, the simulation has been predicting higher than we would previously have modelled and certainly our loading and cost profiles for business planning and cash flow would be different.

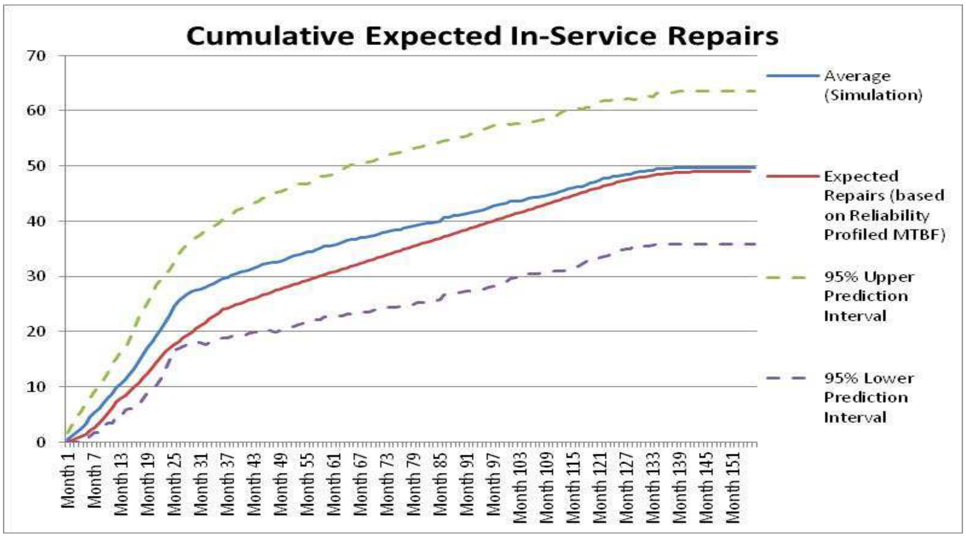


Figure 17. Support period increased to 10 years @ 200 operating hours per year

In Figure 18 we reset again to 1 year support but at the higher flying rate of 800 hours per equipment per year. Again we see the large impact of having a fixed multiplier over a fixed period for reliability growth and not looking at the way the failure manifests its self in terms of the propagation profile or failure distribution, based on actual operating hours experienced by the equipment. As the flying hours increase our fixed multiplier create proportionally more early life repairs than the risks would suggest. This would almost double our estimate of support costs in this short period (warranty) contract.

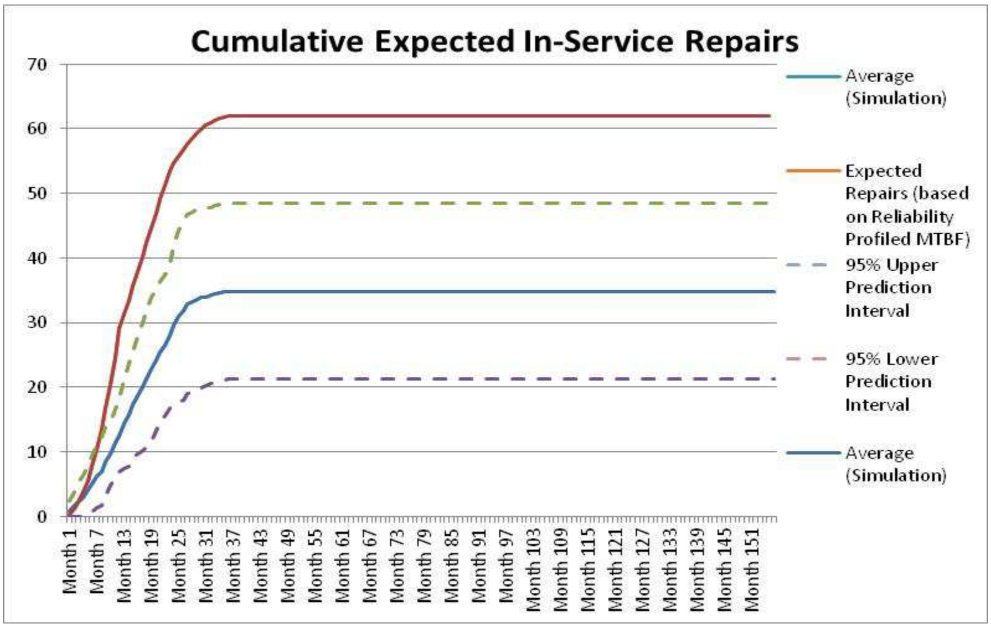


Figure 18. Support period of 1 year @ 800 operating hours per year

In Figure 19, covering 2 years support at 800 operating hours, we are still significantly above the upper confidence limit of the simulation. This identified a potential problem with the old process, in extrapolating away from the key operational parameters of the historical data. This was a modelling based risk we had not considered before.

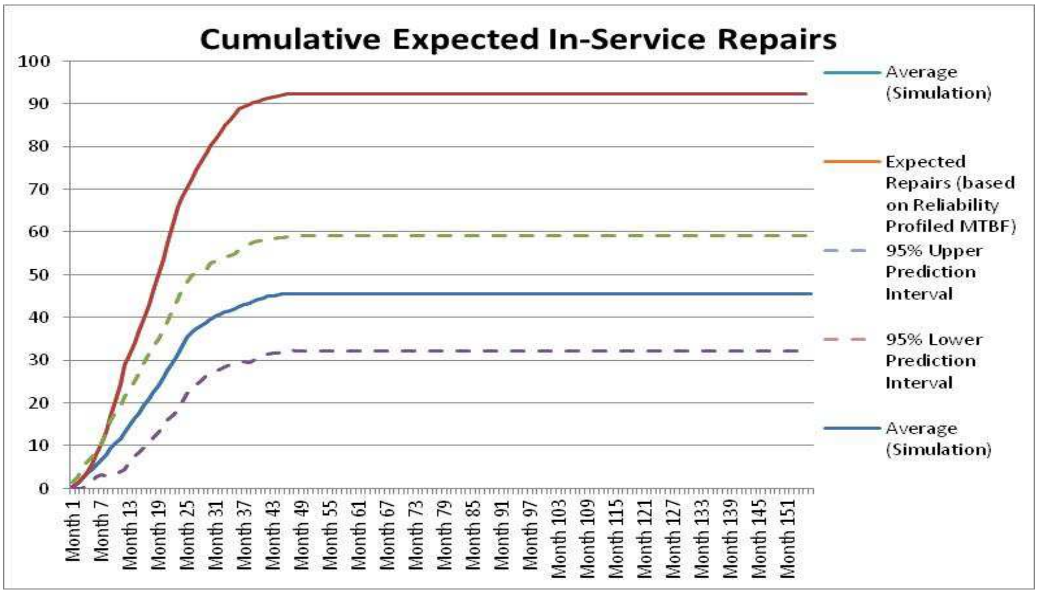


Figure 19. Support period increased to 2 years @ 800 operating hours per year

Figure 20 shows the same characteristic step increase in repairs we saw in the 10 year support at 400 operating hours per year, but this time coming in much earlier (double the operating, half the time to witness the effect). This helps difference between the two models as the averaging effect of the reliability growth factor takes effect again, but the profile of spend is significantly different.

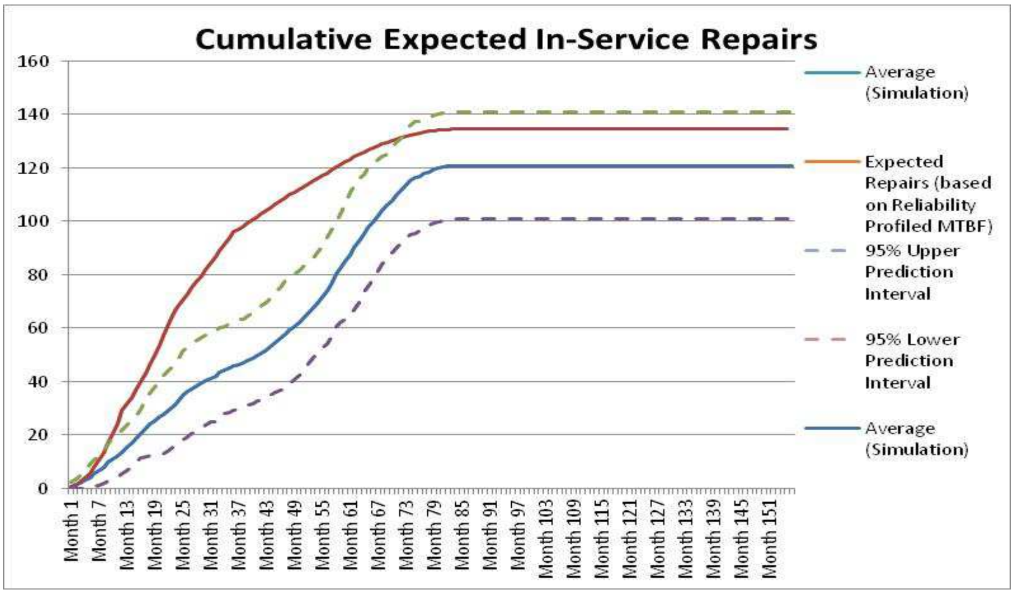


Figure 20. Support period increased to 5 years @ 800 operating hours per year

Finally Figure 21 shows the 10 years support and 800 operating hours per year. This time we see a second increase in the repair rate from the simulation that we had not seen previously. This is because we have a predicted failure mechanism with an expected time to failure of 7572 hours and a life profile of 6.3. Although this may look like a wear out mechanism, it is actually the effect of the graceful degradation of part of the equipment. This start to impact equipment that begin to approach 7500 hours and with 10 years at 800 hours per year some of the equipment will begin to fail due to this mechanism in this support period. If we had remembered we could have added another set of factors into the reliability growth profile. But there is the key point in using the reliability risks and profiles we did not need to consider these fudge factors as the profile provides the input directly to the model.

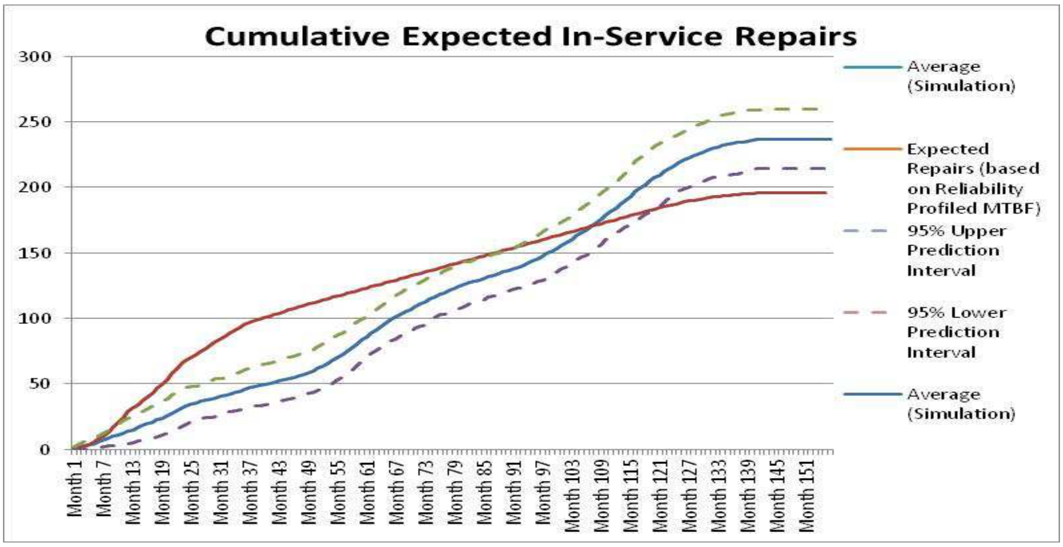


Figure 21. Support period increased to 10 years @ 800 operating hours per year

Another very useful and intriguing product of using the simulation model is the ability to look at how the failure mechanisms influence on the repairs quantities changes as their life profiles wax and wane (See Figure 22). This can help us understand how pattern faults and repair content may vary with time and also provides a baseline that can be assessed against our future FRACA data, to hopefully refine our knowledge of these contributory failure mechanisms and their parameters.

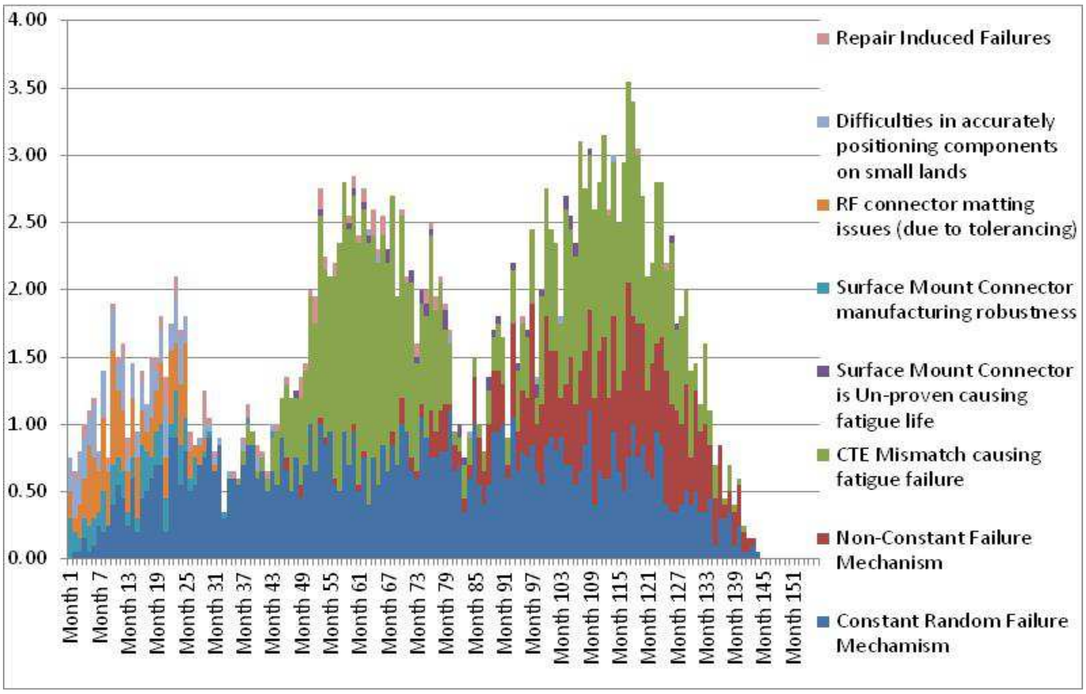


Figure 22. Impact of failure mechanisms on repair quantities

Conclusion

This exploration into two different approaches to reliability modelling has shown me that it could be very costly to our businesses trying to extrapolate from models that are too simplistic for the reliability characteristics they are trying to replicate. For years in trying to correct for this model shortfall we hid the truth behind the fudge or reliability growth factors we used to try and make them more “realistic”. One of the problems is, these factors are also based on a fixed set of key operational parameters and so can introduce their own errors and aberrations.

In looking at the results of repairs models I have been developing over recent years, I have started to see and understand why previous support model seemed to come in and out of “focus”. Sometime they seemed to meet the requirements well with repair quantities and spares demands in line with what we had expected and then other time there seemed to be an unexpected change in demands, even correcting for operational variation. Hopefully you will be able to see some of your own reliability modelling inconsistencies in what has been shown by the examples herein and will look to enhance your understanding of why.

The initial estimates we use to drive our first pass reliability risk model, much like a prior Bayesian belief, provide only a first crude estimate of what may happen. It is now up to us as Reliability or Supportability Engineers to learn how to estimate these risk profiles better in order to refine our estimates, improve our designs, ease our manufacturing processes and therefore reduce the cost to the customer or risk to our business.
I am sure the experience I gained looking into modelling with estimates of the expected underlying failure mechanisms and trying to estimate their shape and life profile better, has

provided me and my team with a much better tool to explore **the shape (or should I say cost) of things to come.**

Acknowledgements

I would like to thank my fellow Supportability Engineers at Finmeccanica in Edinburgh for their help in sourcing the historical data and elicitation process data required to undertake this study of modelling techniques.

I would also like to thank Professor John Quigley and Dr Matthew Revie of the University of Strathclyde for their help in applying their risk elicitation process and their support through the Risk Consortium.

Finally, I would like to make a special note of thanks to Dr Jezdimir Knezevic of the MIRCE Akademy for his support, teaching and mentoring me over the last 15 years as I have fought with my understanding of how to even begin trying to model the complexities of the underlying failure mechanisms through the life of our products

References

Barlow, Richard E & Proschan, Frank 1996. *Mathematical Theory of Reliability*. Philadelphia, Society for Industrial and Applied Mathematics (SIAM)

Department of Defense 1991 *Military Handbook 217F Reliability Prediction of Electronic Equipment*, Washington DC, Department of Defense

Walls L, Quigley J and Marshall J 2006 *Modelling to Support Reliability Enhancement during Product Development with Applications in the UK Aerospace Industry*, IEEE Transactions on Engineering Management 53 (2) pp 263-274.

Mirce Profitability Equation

Jezdimir KNEZEVIC,
MIRCE Akademy, Woodbury Park,
Exeter, EX5 1JJ, Great Britain

ABSTRACT

Commonly, maintenance is perceived as "fixing broken things". As such, it is associated with failure consequences and unplanned expenses, both of which negatively impact business plans or customer satisfaction. However, as failures are an inevitability of the life of any technological system, it would be worthwhile to start looking at maintenance as opportunity for dealing with them and making t positive impact on business plans or customer satisfaction, while generating profit. Thus, the main objective of this paper is to present the Mirce-mechanics approach to maintenance that is focused on the way that failures, once scientifically understood, could be managed in the way that reduces the number of in-service interruptions and operational costs, which in turn will generate profit for private companies or increases the effectiveness of public services like health, transportation, tourism up to the national defence. Finally, the development of the Mirce Profitability Equation has been presented in the paper, which is the bed rock of this approach.

INTRODUCTION

The main business of business is to stay in business. To stay in business the expected "business function" must be provided through time at minimum investment in resources. Hence, the generated profit is equal to the revenue generated by the monetary value of the "business function", R, minus the cost of the resources used to run the business, C, during a given interval of time T, $P(T)=R(T)-C(T)$. Hence, the main concerns of the owners and users of industrial systems are related to how much of the "business function" will be delivered during the life time of a system and how much maintenance and support efforts are expected from them to keep the system going[18.] For example, the business function of a passenger aircraft is to transport a passenger and cargo trough air over a life time of 25-30 years. To stay in business an airline is required to maintain it in airworthy condition. Hence, for each of the business processes these two main factors are obtained at the end of each financial year or at the end of the industrial system. [1]

This, type of performance, of industrial/business systems is known as functionability[19] performance. Regrettably, producers/constructors of industrial systems do not provide answers to this type of performance on the delivery day. Instead, years later the statistics for various functionability measures become available. The reason for this is the fact that in-

---

[18] Boeing 747, registration number N747PA, which belonged to Pan Am transportation system, have delivered the work of 80,000 flying hours and received 806,000 maintenance man-hours, during the 22 years of in-service life

[19] Functionability, n, defined as the ability of being functional through life, in the book Reliability, Maintainability and Supportability – A probabilistic Approach, by J. Knezevic, pp. 291, McGraw Hill, London 1993. ISBN 0-07-707691-5

service behaviour of industrial systems is governed by the complex processes that are governed by the laws of science, human rules and environmental impacts, which are characterised by indeterminism, irreversibility, inseparability, and dependence on time, location and humans.

Consequently, the main objective of this paper is to present the Mirce-mechanics approach to functionability, as scientific foundation of keeping system in business through failure management. It is focused on the way that failures, once scientifically understood, could be managed in the way to maximise the time in operation and minimise the time in maintenance, which in turn will generate profit for private businesses or increase public satisfaction for common services like health, transportation, education, tourism all way up to the national defence.

The paper is also showing the development process of the Mirce Profitability Equation, as a scientific foundation of a rational to maintenance based on Mirce-mechanics which should increase business competitiveness or public satisfaction f any organisation that is willing to apply it to the process of managing business processes, from reliability, cost and profitability point of view.

2. FUNCTIONABILITY QUESTIONS

One of the major concerns of design engineers and project managers are predictions of operation, maintenance and support resources required for maintaining systems in "business as usual" state through their lives. These include diagnostic equipment, skilled and trained maintenance personnel, maintenance facilities, spare parts, inspection tools, technical data, storage facilities, means of transportations and so forth. Often the cost of these resources considerably exceeds the purchase cost of system itself. Equally, the lack of maintenance resources causes further delays in keeping systems in the "out of business" state. Hence, some balance between investment in the resources and the time delays incurred by their deficiency is required. To make that trade off, engineers and managers, need to find the answer to the following functionability related questions:

- How many Failures are going to occur?
- What types of Failures are going to occur?
- What frequencies of Failures are going to be?
- How Failures will be detected?
- How long systems are going to be "out of business"?
- What resources are needed to return it to the "business"?

Unlike the functionality questions to which existing laws of science readily provide the answers, the above raised functionability questions stayed unanswered. Existing equations of motion are not able to even the address the above questions, not because they are incorrect, but because they are not created to address these phenomena.

In summary, without ability to provide accurate answers to functionability questions design engineering and project manager are not in the position make the trade off between the cost of resources required to maintain systems in "business as usual" state and the consequential losses while the system is "out of business" state, also know as the "failed state".

3. TYPES OF FAILURES

In order to better manage failure, it helps to understand that there are two consequences of failure: those affecting safety and those affecting the economics of business (revenue, profit, reputation, etc.). Thus:

- Safety related failures are those that jeopardises the safety of the industrial system or places in peril environment or humans must be prevented. Safety significant industrial systems, like aircraft, submarine, train, nuclear reactor and similar can not be of such design that any single failure of the device will have catastrophic results. This is safety engineering dogma. Today's industrial systems of this type are subject to very few critical failure modes. This safety-related reliability is attributed to the design requirements of the relevant governmental regulations as well as the specifications of operating organizations and manufacturers. Current design practice ensures that vital functions are protected, which means, that, if there is failure, a given function will remain available from other sources to insure a safe completion of operation.
- Economic related failures are those where the loss or deterioration of a particular function neither endangers the industrial system nor its environment, but it affects the "business" state of a system. Examples include systems, components, or features in a design that are not specifically required to demonstrate conformity to the basis of safety certifications. However, a failure of a single components or module can cause the loss of functionability of the industrial system and causes a loss of business until repair or replacement is accomplished.

Based on the above, it possible to conclude that one of the fundamental "business" questions is how to manage failures that take a "business out of business" at the most cost effective manner?

4. MANAGEMNT OF FAILURES

The most effective way of managing failures is to address them at the early stages of design. Generally speaking there are two main design solutions for minimising the amount of time during which the system is in "not in business" state. Thus:

- The components and systems to be designed to an exceptional degree of reliability by selecting "exotic materials", high kevel of tolerances, extensive testing and similar solutions. This could be an inordinately costly strategy. Cost-effective design trades must be made between the loss of functionability arising from a system being in "not in business" state situations and the cost of exceptionally reliable components.
- Minimising the time that a system spends in "not in business" state. The design approach embraces the incorporation of features that are extra to those required for safety certifications. These include:
    - redundancy,
    - fault tolerance
    - fail safe,
    - fail passive features
    - group replacement.

  It is necessary to stress that all of these efforts are beyond those required to certify the safe design of industrial system. Of course, this is not without its price, however. It increases the number of failure possibilities, adds more items that can fail, and results

> in equipment that is more complex and integrated — making fault isolation more difficult. It adds to the cost of the industrial system, so it must be done carefully to keep costs under control.

Regarding this fundamental design options, Jack Hessburg[20], the Chief Mechanic of the Boeing New Airplanes (1990-1999), has said "*I as a designer I have to fill my customer in as well, I have to decide where I'm going to put economic redundancy into my design, because it costs money. If you have the full answer to that, would you please see me after this meeting! There's a Nobel Prize in it. We have really not developed the discipline where we know how to normalise that, yet.*"

5. THE MIRCE-MECHANICS

The author of the paper could not have seen how to proceed with his research, challenge initiated by Jack Hessburg, within departmentalised academic institutions and training processes. Hence, he left the School of Engineering at Exeter University in UK and established an independent research, education and training organisation, named the MIRCE Akademy at Woodbury Park, Exeter, UK, in 1999, with only one clear statement of intent "Never to departmentalise any research activities." Staff, Fellows, Members and students of the Akademy have endeavoured to subject in-service behaviour of industrial systems to the laws of science and mathematics to:

- Determine the trajectory of the motion of industrial system through functionability states, which is defined by the sequence of occurrences of positive and negative functionability events, resulting from the atomic, environmental and human actions. Understand mechanisms that lead to the occurrence of functionability events starting from atomic structure that drives the behaviour of matter, up to the solar system that drives the energy conversions (a physical scale ranging from 10^{-10} to 10^{10} metre).
- Define a mathematical scheme for predicting expected in-service functionability measures of a given industrial system together with the expected work done on the system under a given maintenance policies and planned support strategy.

While in classical mechanics a force is said to do work if, when acting on a body, there is a displacement of the point of application in the direction of the force, in Mirce-mechanics a given system is said to do work, if there is a provision of measurable functions in the direction of time, which is exactly what is expected from a business. In summary, the body of knowledge comprising of axioms, mathematical equations and methods that enable engineering, predicting and managing the functionability performance of industrial systems, based on the scientific understanding of the mechanisms that drive an industrial system through states "business as usual" and "out of business" through the life, constitutes Mirce-mechanics.

6. THE CONCEPT OF MOTION IN MIRCE-MECHANICS

Motion is one of the most complex concepts of science. The images it creates in our minds are diverse as the "jiggling" of atoms and molecules to the movement of planets, and beyond. Since the earliest years of science the only idea of motion imagined was that of mechanical motion, so there is a tendency to view all other kinds of motion in terms of the concept of trajectory. As the science progressed, this naturally became impossible, for instance when the

---

[20] Jack Hessburg 27th January 1998, M.I.R.C.E. Industrial Lecture, Exeter University, UK.

attempt was made to conceive the electrical motion. It could be possible, of course, to think in the case of a high-voltage transmission line that wire is the "trajectory" of the electric signals. However, such a mental picture would have no practical purpose, as the electromagnetic waves could not have been viewed as a liquid flowing through the wires.

Consequently, the question by which the motion of industrial systems through functionability/business states through time must contain only those quantities that can be measured physically. Research performed shown that a life of any industrial system could be viewed as a sequence of occurrences of positive and negative functionability events that "move" systems through functionability/business states.
Functionability state variables uniquely determine the functionability states of a system.

The motion of Industrial Systems through functionability states stays is result of imposing physical processes or human decisions, jointly called imposing actions. To understand the mechanisms that generate those actions analysis of tens of thousands of components, modules and assemblies of systems in defence, aerospace, nuclear, transportation, motorsport, communication and other industries, had been studied at the MIRCE Akademy. As it has a profound impact on all aspects of the in-service life on any industrial system, several research studies have been performed by the Master and Doctoral students of the MIRCE Akademy [2,3,4]. All physical phenomena that cause the motion of a system from the positive to negative functionability states are known as negative functionability events. Actions that generate negative functionability events belong to the following categories:

- **Inherent actions,** generated by mechanical, electrical, thermal, radiation, chemical and other types of energy, that have been introduced into system prior to the operation process through activates associated with manufacturing, transportation, maintenance, storage and similar processes.
- **Potential actions,** generated by mechanical, electrical, thermal, radiation, chemical and other types of energy, that exceed the strength of components and systems subjected, resulting from phenomena like foreign object damage (birds, hail, rain, snow), lightening, abuse by operator (pilots, driver and user errors), single event upset [3] and similar.
- **Continuous actions,** generated by mechanical, electrical, thermal, radiation, chemical and other type of energy, that continuously act on a system through in-service life of systems and generate processes like, corrosion, fatigue, creep, wear and similar, which are result of natural decay of matter.

All physical actions that cause the motion of a component or a module from the negative to positive functionability states are known as positive functionability events. Mechanisms that generate positive events belong to the following categories [6]:

- Servicing: replenishment of consumable fluids, cleaning, washing and similar.
- Lubrication: installing or replenishing lubricant.
- Inspection: Examination of an item against a defined physical standard.
    - General visual inspection: performed to detect obvious unsatisfactory conditions. It may require the removal of panels and access doors, work stands, ladders, and may be required to gain access.
    - Detailed visual inspection: consists of intensive visual search for evidence of any irregularity. Inspection aids, like mirrors, special lighting, hand lens, boroscopes, etc. are usually required. Surface cleaning may be required, as well as elaborate access procedure.

  - Special visual inspection: an intensive examination of specific area using special inspection equipment such as radiography, thermography, dye penetrant, eddies current, high power magnification or other NDT. Elaborate access and detailed disassembly may be required.
  - Check: a qualitative or quantitative assessment of function.
- Examination: a quantitative assessment of one/more functions on an item to determine whether it performs within acceptable limits.
- Operational: a qualitative assessment to determine whether an item is fulfilling its intended function. It does not require quantitative tolerances.
- Restoration: perform to return an item to a specific standard. This may involve cleaning, repair, replacement or overhaul.
- Discard: removal of from service.

All of the above listed mechanisms of the motion of systems through positive and negative functionability states are observable physical processes or recognisable human actions. [5]

7. MIRCE FUNCTIONABILITY EQUATION

Results of experiments and observations performed over several decades by the author unquestionably lead to conclusion that the deterministic regularity found in the predictions based on continuous motion through time, such as speed, acceleration and similar, studied by classical mechanics, cannot be found in respect to the motion of functionability through time. Thus, trajectories, generated by the motion of individual copies of a given system type, under similar in-service conditions, demonstrate variability, to the degree that no two trajectories are identical. Therefore, the proven formulas of Newtonian mechanics that govern the motion of macroscopic bodies through time cannot be used for predicting the motion of functionability through time, as far as the functionability trajectory is concerned Thus, Mirce-mechanics Formulas, developed at the MIRCE Akademy, by D Knezevic, are mathematical expressions of the physically observed processes of the motion of industrial systems through functionability states and they define and predict physically measurable properties of system functionability performance in the probabilistic terms.

The laws of probability are just as rigorous as other mathematical laws. However, they do have certain unusual features and clearly delineated domain of application. For example, it can be readily verify that in the case of a large number of systems failure phenomena will occur in a specific number of the cases, and the law is more accurate the more systems are observed. However, this accurate knowledge will be of no help in predicting the occurrence of functionability events in each individual case.

The unusual features of the laws of probability have a natural explanation. In fact, most probabilistic events are results of quite complex physical processes, which in many cases cannot be studied or understood in all of its intricacy. Such inability takes its toll, as it is only possible to predict with certainty the average result of numerous identical tests.. Probabilistic predictions of the functionability trajectory are based on the framework of the sequence of occurrences of functionability events, positive and negative, which are occurring with a probabilistic regularity.

Having determined the probability distribution and its governing parameters of the times to subsequent functionability events, it is possible to develop a mathematical scheme that will provide opportunity to predict the future sequence of functionability events for any given industrial system. This is the essence of the Mirce-mechanics, which is the only theory available to design engineers and project managers to quantitatively predict the consequences of all of their decisions on in-service behaviour of their future systems and their “business” performances.

The trajectory of the motion of an industrial/business system through functionability states is uniquely defined by the sequence of occurrences of functionability events, from the birth of the system to its decommissioning. Thus, the fundamental equation of Mirce-mechanics, the Mirce Functionability Equation [7] and it defines the probability of an industrial system being in positive functionability state or “business as usual” state, at a given instant of time t, thus::

$$y(t) = P(PFS \,@\, t) = 1 - \varphi(t) + \mu(t)$$

where: $\varphi(t) = \sum_{i=1}^{\infty} P(TNE^i \le t)$ is the expected number of negative functionability events that will take place from the birth of a system and a given instant of time t and $\mu(t) = \sum_{i=1}^{\infty} P(TPE^i \le t)$ is the expected number of positive functionability events that will take place from the birth of a system and a given instant of time t.

Finally, the work done by an industrial system during the stated interval of time T, $W_{by}(T)$, can be calculated by making a use of the following expression:

$$W_{by}(T) = \int_0^T y(t)dt \qquad [\mathrm{Hr}]$$

Hence, the numerical value of the above expression presents the amount of time during which a given industrial system will be in the state of ”business as usual” during the stated calendar time T

For the most generic case, where the business can be only in the state of “business as usual” and the “not in business”, the work done to the system is determined by the following expression:

$$W_{to}(T) = T - W_{by}(T) \qquad [\mathrm{Hr}]$$

8. MIRCE PROFITABILITY EQUATION

The creation of Mirce Functionability Equation enabled calculation of the work done by the system, during a stated period of time T. That enabled the development of the Mirce Profitability Equation that links the revenue and cost sides of business at one place as a function of the engineering configurations of a system, adopted business methods associated with the relevant project management decisions and characteristics.

Thus the expected revenue of a given industrial system, during the stated interval of time, *R(T),* expressed in the monetary units, MU, is equal to the product of the Hourly Income generated by the provision of business function, HI and the amount of the work done by the system, thus:

$$R(T) = HI \times W_{by}(T) \qquad [MU]$$

In general term, the cost of doing business during the state period of time, is equal to the sum of the cost of operation, *CO(T)*, which is equal to the sum of the fix cost of operation, $CO_{fix}(T)$ and variable cost of operation that is equal to the product of the Hourly Cost of Operation, HC_{op} and the work done by the system, hence

$$CO(T) = CO_{fix}(T) + HC_{op} \times W_{by}(T) \qquad [MU]$$

Equivalent cost for maintaining a system in the "business as usual" state, during the stated period of time, *CM(T)*, which is equal to the sum of the fix cost of maintenance, $CM_{fix}(T)$ and variable cost of maintenance that is equal to the product of the Hourly Cost of Maintenance, HC_{mt} and the work done to the system, hence:

$$CM(T) = CM_{fix}(T) + HC_{mt} \times W_{to}(T) \qquad [MU]$$

Finally, the profit expected to be generated by a given industrial system, during the stated period of time, could be calculated by making use of the Mirce Profitability Equation, thus:

$$\begin{aligned} P(T) &= R(T) - C(T) \qquad [MU] \\ &= \left\{HI \times W_{by}(T)\right\} - \left[CO(T) + CM(T)\right] \\ &= HI \times W_{by}(T) - \left\{\left[CO_{fix}(T) + HC_{op} \times W_{by}(T)\right] + \left[CM_{fix}(T) + HC_{mt} \times W_{to}(T)\right]\right\} \end{aligned}$$

In summary the above equation is the only one, known to the author, which unifies all aspects of in-service performance of an industrial/business system. It enables the accurate predictions of the expected profit to be made for each operational scenario, maintenance policy and support strategy. The above equation "unites" the whole organisation into an analytical scheme, rather than to be a collection of a large number of self standing models that address a few components of the time, or a few performance parameters of the system.

System effectiveness is an emerging property of a in-service life of a system generated by the complex and time dependent interactions of the following properties:

- Functionality principles of a system (mechanical, electronic, thermal, electrical, nuclear, etc.)
- Structure/construction of a system (dependencies and redundancies)
- Operational concepts and scenarios (continuous, seasonal, one off)
- Maintenance rules (schedule inspections, replacement, testing and so forth)
- Support Strategies (training, spares, facilities, tools, equipment, etc.)
- Environmental conditions (climate and weather)

10. THE IMPACT OF MAINTENNACE ON PROFITABILITY

Although science has to be truthful, rather then useful, the body of knowledge of Mirce-mechanics is essential for scientists, mathematicians, engineers, managers, technicians and analysts in industry, government and academia to predict the work done by the system and to the system , for a given configurations, in-service rules and conditions, in order to manage failures in the way that the functionability performance is delivered through the life of system, at least investment in resources and environmental impact. For that to happened, the science proven method is needed, very much different from the classical scientific knowledge, because functionability performance is defined in the following way:

- Every scheduled flight will leave on time with a probability of at least 0.97 or in other words, it is acceptable to have no more than three delays, on average, out of 100 flights;
- The direct maintenance cost during the first 10 years will not exceed 25 % of the purchase cost with a probability of 0.95;
- The probability that the production line will be fully operational during the specified in-service time will be not less than 0.91;
- In system consisting of several systems, at least 90% of them will be operational at all times with a probability not less than 0.925;
- The mission reliability will be greater than 0.98 for missions up to 500 hours;
- Each 10-hour flight will be successfully completed with probability of 0.995, during the first 20 years of operation

Consequently, the only way to address functionability performance targets formulated in the way above is to use concept and principles of Mirce-mechanics to evaluate engineering and management options, at the time when fundamental and irreversible decision are made regarding the management of failures of future industrial systems.

10. CONCLUSION

The main objective of this presentation is to present the Mirce-mechanics approach to failure management process regarding the increase in profitability of industrial systems, as a new approach to maintenance. It is focused on the way that failures, once scientifically understood, could be managed in the way to maximise the time in operation and minimise the time in maintenance, which in turn will generate profit for private businesses or increase public satisfaction for common services like health, transportation, education, tourism all way up to the national defence.

Unlike the classical mechanics, where the continuous uniform motion is natural state of the macro world that is fully defined and predictable by Newton’s equations, in Mirce-mechanics continuous change in the functionability states is a natural state of industrial systems during their in-service life, which is fully defined and predictable by Mirce Functionability Equation. Finally, Mirce Profitability Equation is presented as the scientific foundation of the System Engineering and Management predictions and analysis that brings together the revenue and cost elements of businesses that are dependent on the behaviour of industrial systems.

11. REFERENCES

[1] J. Knezevic, *Functionability in Motion,* Proceedings 10th International Conference on Dependability and Quality, DQM Institute, 2010, Belgrade, Serbia.
[2] J. Knezevic, *Scientific Scale of Reliability*, Proceedings of International Conference on Reliability, Safety and Hazard, Bhabha Atomic Research Centre, 2010, Mumbai, India.
[3] I, Zaczyk, J. Knezevic, *Cosmic Phenomena in Mirce-mechanics Approach to Reliability and Safety*, International Journal of Life Cycle Reliability and safety, Vol 2, Issue No 2, 2013, ISSn-2250 0820, Society for Reliability and Safety, India.

[4] J. Knezevic, *Atoms and Molecules in Mirce-mechanics Approach to Reliability,* SRESA Journal of Life Cycle Reliability and Safety Engineering, Vol 1, Issue 1, pp 15-25, Mumbai, India, 2012. ISSN-22500820
[5] C, Hirtz, *Impact of Environment and Human factors on Duration of Maintenance Task*, Doctoral Diploma Dissertation, MIRCE Akademy, Exeter, UK, May, 2012.
[6] Ben-Daya, Duffuaa, Raouf, Knezevic and Ait-Kadi, D. (2009), *Handbook of Maintenance Management and Engineering,* Springer, Dordrecht, Heidelberg, London and New York, NY.
[7] J, Knezevic, Mirce Functionability Equation, Journal of Engineering Research and Applications, ISSN: 2248-9622, Vol. 4, Issue 8, August 2014, pp 93-100.

Prognostic Engineering Science
- the attributes of decay that affect functionability -

Chris Burden BSc, MINDT, Science Fellow MIRCE, Director AePS.

Abstract

Condition monitoring of engineered operational products/systems has been a life time career for me. Having commenced employment in September 1971, starting as a 16 year old engineering apprentice by Rolls-Royce (1971) Defence Engine Division at Bristol through 43 years in the same company seriously involved in product measurement engineering, I hold enormous knowledge of the 'science' discipline.
I have completed an engineering apprenticeship with a Higher National Certificate in Engineering followed by a personal Technology/Science education through the Open University. These educations and operations started the association of how many engineered products with a different operational analysis can map to an understanding of how functional decay can be detected and understood.

My vision for condition monitoring, as the human race advances in science and requirements for the future, is that it will be absolutely essential that a discrete condition/health monitoring system integrated into the product/system as a prime consideration of the product/system design, is not treated as an 'add on', as currently considered.

The decay in the operation of an engineered product/system will gradually affect the functionability of the product/system and consequently start to define the probability routes to an ultimate failure mode manifestation. However the definitions for the probability routes that lead to the failure modes are far more complicated than expected, envisaged and perhaps understood and these issues I hope to express in this document for prosperity.

*For example, one of the key witnesses to a failure mode probability route maturing is the '**increase'** in ascertainable 'change' 'seen' and reported in the monitoring of the operational device, by for example a vibration transducer.*

*In vibration monitoring the most common understanding is that an 'increase' in monitored vibration levels point at the 'operational functionability change' and define the precursory view of decay onset, commencing the countdown to system ultimate failure. This is not necessarily the case as 'elastic stress' wave sensors can/do experience a '**decrease'** in the signature levels as the functionability changes, let's explore, within the realms of the title Condition Monitoring.*

Virtually all operational products / systems demonstrate a phenomenon of operational witness. For example, a living human operating normally will demonstrate a heartbeat and a breathing action detectable via the 'feature' witnesses of a pulse, the expansion of the chest and usually structural movements. These three functions/operations portray large variance in ‘feature’ perception; typical describing nomenclature from the ‘professions’ and the normal public includes ‘heart rate’, ‘fluctuations of beat’, ‘deep breathing’, ‘shallow breathing’, ‘panting’, ‘shortness of breath’, ‘wheezing’, ‘chest pain’, ‘angina’ , ‘twitches’, etc.

Words that describe the ‘state’ of the humans three prime ‘functionality’ to which understanding of ‘condition’ can be applied, but clearly these statements lack key information as to the functionability, most of which is taken for granted.
This metric of detail to support functionability in modern science, engineering and condition monitoring (all types) demands and requires to be taken more seriously than at present and it is essential that the functionability features and phenomena are better evaluated and built on.

These ‘conditions’ supported by the ‘witness’ of just heartbeat, breathing and motion offer understanding of the human condition. However, these conditions are just the ‘tip of the iceberg’ in world of condition monitoring as there are so many more ‘features’ that an operational product/system is affected by.

These ‘conditions’ and the ‘features’ are the key ‘witness’ to the functionality and the functionability of the product/system and will hold a certain series of signatures of operation throughout the products/systems functional life, only deviating from the ‘normal’ signature when ‘features’ manifest to invoke product/system operational ‘change’.

The problem with the current condition monitoring philosophy is that the observed onset of final operational functionability is very weak, a philosophy usually driven by the monitoring systems inability to detect ‘change’ with which to attribute a ‘feature’ witness and no perceived ‘business’ requirement needed to increase that fidelity of detection.

The evolution of the engineering monitoring capability has provided many operational questions in my experience. The questions posed demanded investigation and as the transition from a measurement engineering occupation to an engineering health monitoring occupation resulted in deep investigations to better explain, with evidence, the nature of ascertainable operational monitored events with their associated ‘features’.

This drove the idea of how to best comparator ‘change’ in operational ‘features’ with all associated phenomena surrounding the product/system operational environment.
The first issue (in my personal history) in this campaign was the improvement in the ‘change’ detection and occurred in the middle to late 1980’s when engineering research was still a prime function of forward looking manufacturers and before engineering measurement degraded to ‘not core business’. In my quest for better capability at the time, frequency bandwidth was and still is the main issue of recording media. In those days broad band tape speeds on tape decks (up to 20 kHz) enable certain measurement technologies to progress, like vibration, pressure transducers, pulse probes for speeds, strain gauges, pulse modulation like FM grids and thermocouples for temperature capture. In today’s engineering measurement recording requirements the same issue still exists, for example when instrumentation stimulus bandwidth requirements exceed 60 kHz, because the digitisers (just like magnetic tape) cannot capture spectra with the necessary fidelity, event recording is compromised, missed altogether and the event magnitude degraded in severity.
So the hunt was on for a dedicated system with fidelity and data capture that focused on a new idea. The rational I arrived at was the need to move up the frequency spectra away from the low frequency range to find evidence of ‘higher frequencies’ that manifest during product/system operation, usually portraying a picture evidence of ‘normal’ that when

‘change’ occurred could be distinguished and build a knowledge data base of ‘Cause and Effect’. I discovered the world of Acoustic Emission base on personal studies of Raleigh Waves, Elastic Stress waves, and Lamb waves and very quickly realised that these were the prime drives to the engineering measurement world I needed to be able to express to peers my experiences and findings,.

However due to many facets of the business world, vested interests, complexities and other strange cultures and following a presentation and a runner up commendation at the 2003 National Measurement Awards for my Acoustic Emission science studies, pushing the ideas forward is harder than running the many marathons I have completed.

However I did not acquiesce to the negative pressures because my ideas are key to the future of product/system health and condition monitoring. Fortunately the Acoustic monitoring measurement system moved to a productionised/development system. I saw the need to investigate the capability as I had many personal examples of ‘intuitive change’ events while conducting engineering test experiments that I could not explain but more importantly capture in a format that I could portray to others to create discussion.

The program of investigations were a personal campaign to demonstrate capability from discrete components through to complex high power engines, all of which grew in confidence that the capability does map detection of ‘change’ during operation and gradually started to relate detection to ‘features’ and probability routes to failure modes.

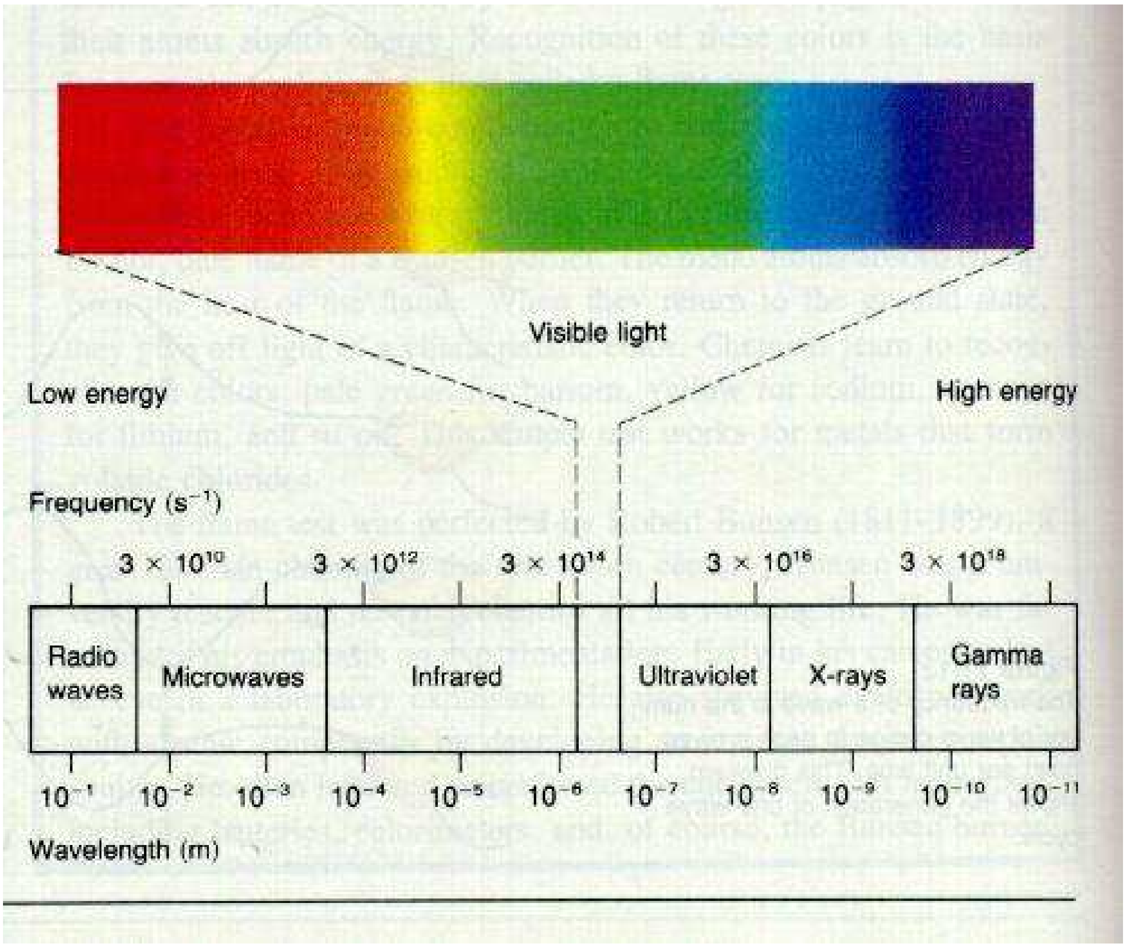
One major problem was the name of the technology. Acoustic emission technology insinuates an ‘air borne’ transfer of energy to a sensor. This is not the case and my renaming of the technology was to better define the location in science where the technology sits.

The technology operates in the medium frequency domain between 60 kHz and 700 kHz, it captures the energy in the product/system as it operates and transfers it to the sensor (piezo crystal) from which the computer and software create an instance presentation of the spectra, thus the Medium Frequency Energy Transfer, **MFET** acronym was created. In the creation of the MFET acronym a period of ‘seismic emission’ was adopted but as seismology applies to geology the name was always contestable. This is a very brief back ground into my condition monitoring engineering history (1971 to 2003). There are many more aspects to this history which are very important dimensions to add to the feature clarity, but they are deeper and very complex for this abstract, now back to the science.

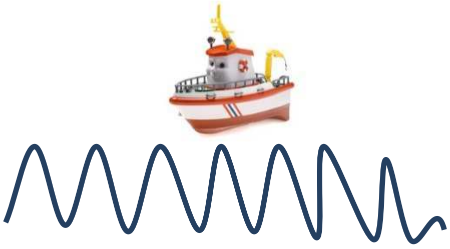
Energies exist in all products /systems, all are quantum related in the atom and sub atom forms moving to multi atomic, molecular, Newtonian structures of all types. These energies that exist in the product/system invariably operate over regions of the frequency spectra from dc to gamma rays and this formed my common denominator from which to mount my sensor suit against and to allocate ‘features’ of functionality for the product/system operation.

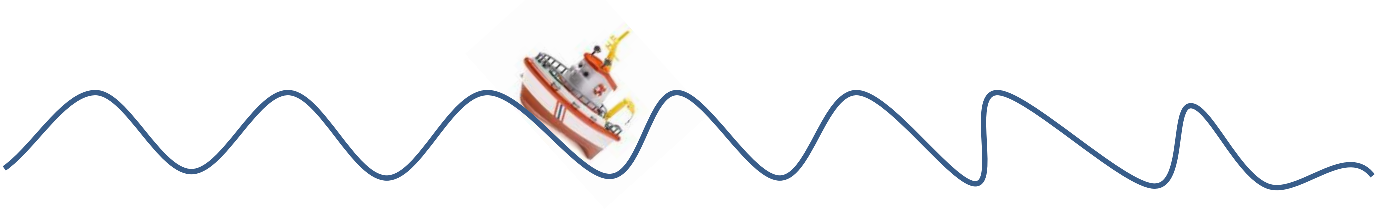
Clearly frequencies of operation that are monitored in the low frequency spectra like vibration are easy to capture both with vibration/acceleration transducers, the ‘pulse’ of sense by the human body, a glass of water, a moving article on a shaking structure, etc., usually the repetitive sound pulse can be audibly heard and ‘change’ detection easily discernible. However the eye captures the motion of the water ripple and the eye operates in the visual light spectra and always has; the frequency (range) is in the sub atomic particle region where photons and phonons are created so our eyes work in the quantum field

The main issue with these very low frequencies are that determinable ‘change’ usually associates with serious degradation of the product/system functionality, potentially moving towards a failure mode rapidly.

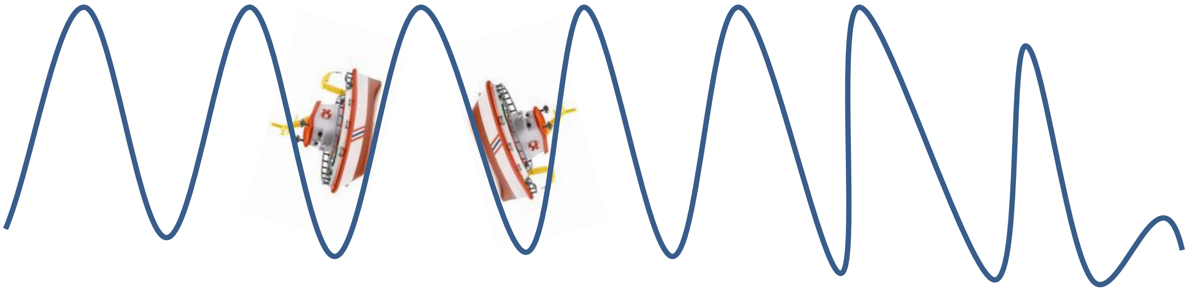


Imagine a boat riding the waves, the frequency is high the wave lengths are short; therefore the waves under the boat are tight together making the boat surf on a flat surface so things are “good”. Now stretch the wave lengths out so they are long the frequency is low and the boat is now experiencing a very rough sea and things are “bad”. This is exactly the way that vibration works, but the real problem is the short period of time in the transition from the higher frequency short wave length to the lower frequency long wave length.



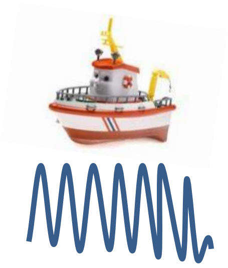


In this very short time duration because the change is so small, decay modes occur rapidly giving very little chance to “capture” the operational product/system operation, shut it down and save a major failure.



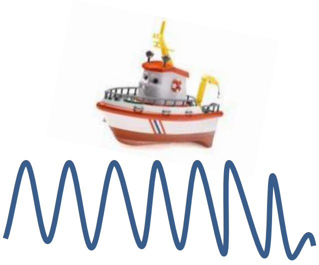
Also the change in amplitude occurs usually because of the decay in frequency and it is this enlarged stimulus that excites the vibration transducer to incite the ‘increase’ in vibration levels, trigger alarms and raise concerns.

If however the system detection monitored in a higher frequency domain and captured changes in the high frequency moving to a slightly lower frequency the boat would still be “good” but a “change” has been detected and we are on alert.



Feature 1“normal”

Feature 2 “First change”



Feature 3 “Second Change”

This is a very ‘simple’ demonstration of wave capture because the actual wave forms are also generated at various angles to the ‘main’ wave and are the cause of ‘side bands’. Unfortunately these witness bands usually fall outside ‘normal’ operational vibration monitoring for event/witness capture and key witness/evidence is lost/ignored for product/system decay/safety monitoring.

The MFET (Elastic Stress Wave) sensor capability moves the frequency domain up into frequencies that are above the low Hz values and in my experience into the medium wave frequency region where ‘change’ effects clearly have longer periods of time to mature before a failure mode is created, hours , months, years. These medium wave frequencies exist with full spectra frequencies and offer a total insight to the ‘status’ of the product/system if we bother to understand it!

So let’s examine key elements of the science we are discussing here.
The expressions of the frequency range then expanded to the obvious, my eyes operate in the Quantum field! This acceptance, discovery, fact call it what you will is so obvious that immediately I had taken the frequency spectrum from DC to visual light and to take it to

gamma was a formality when discussed with fellows of the X-Ray world. So I now had the **denominator** to assimilate the witness phenomena of prognostic understanding against, frequency and therefore wave length.

This denominator also has a ‘cross over’ point where ‘Newtonian Physics’ integrates with ‘Quantum Physics’ for the frequencies defined. This cross over point in the Newtonian field of molecule displacement to electromagnetic field excitement and displacement is very important, but essentially just to understand.

So getting back to presentations of the denominator idea, the magnitude of the denominator is massive when the range of frequencies are applied, so to represent this on an A3 sheet of paper was impossible when clarity around the 700kHz bandwidth over the full frequency spectra resulted in the time period the width of my pencil!

Clearly the ‘Newtonian’ frequency features needed to be frequency ‘banded’, as would the ‘Quantum’ features to enable clarity of all presentations. The problem is that for decay/prognostics/functionality/functionability/witness etc. the dissections of the product/system to component parts, to best define frequency phenomena, can interfere with the ‘total’ product/system understanding.

This is where and why the current ideology of prognostics does not deliver, resulting in the culture of ‘normalisation of deviance’, basically it’s been ok before therefore it will be ok (Professor D.Vaughan Columbia University on the Challenger Shuttle Disaster). This disaster was ‘O’ ring seal related, a physical component part, not even condition monitored signatures from sensors. So how can subjective sensor data drive safety, by being accepted as creditable, believed, understood and engaged in our culture of science.

This stance is unacceptable to me and the prime reasons for the need to look across the frequency spectrum as a whole and link all product/system operational phenomena together to ‘lock down’ ‘change events’ and define all the witness occurrences that could have caused that or the ‘change event instance’.

The need for this pedantic attitude to prognostics and decay/change/witness management is to be ahead of the failure mode game and be professional in the detection of the functionability change.

When we (the human race) move to more complex products/systems that are essentially monitored to prevent loss of life, the product/system integrity must match the expectation of product/system operational success to as near 100% as possible.
I think this is a good point to close the rationale behind my prognostic theorems and the first of many papers/abstracts for the Science.

Call for Papers.. Call for Papers.. Call for..

2017 Annals of Mirce-mechanics

Published by the MIRCE Akademy to facilitate exchanges of knowledge and experience between: scientific, engineering and management professionals, which are interested in Mirce-mechanics.

The Annals welcomes the following types of original contributions:

- Presentations of the research results related to all aspects of Mirce-mechanics
- Applications of existing Mirce-mechanics knowledge
- Observational knowledge that could be beneficial for further developments of Mirce-mechanics
- Reports, book reviews and short news that are of a general benefit to Mirce-mechanics

Potential authors please see: Guidance for Authors at http://www.mirceakademy.com

Papers..Call for Papers..Call for Papers...

Please send your paper to:

Dr Jezdimir Knezevic By:

Email: jk@mirecakademy.com

Post: MIRCE Akademy, Woodbury Park, Exeter, EX5 1 JJ, UK