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2021 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

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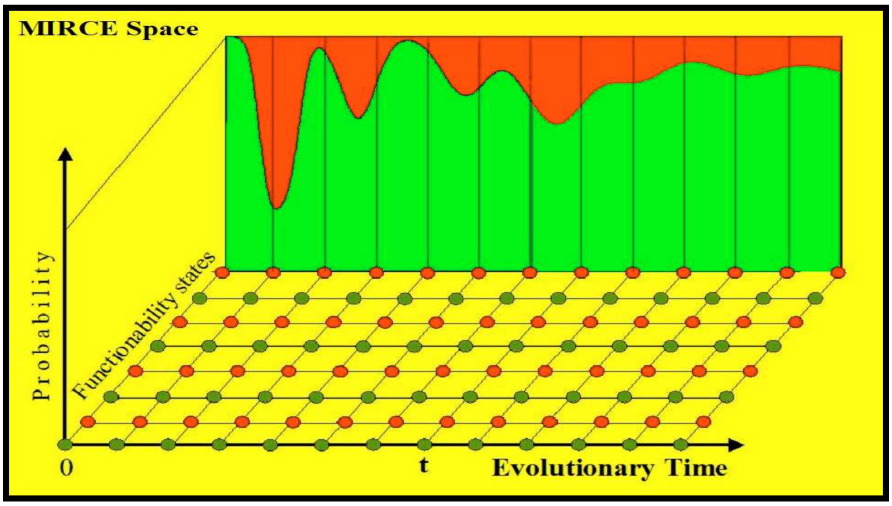
MIRCE Science

The philosophy of MIRCE Science is based on the premise that the purpose of existence of any functionable system[1] *is to do functionability work, which is considered to be done when the expected measurable function is performed through time, like miles travelled, units produced, energy supplied and similar. However, experience teaches us that at any instant of in-service life there is a probability of work being interrupted by occurrences of negative functionability events, resulting from failures of consisting components, natural causes, human actions or their interactions. For the work to be continued, humans undertake appropriate positive functionability actions, like: maintenance tasks, change of the mode of operation and similar must be performed. Thus, the life of functionable systems is a sequence of transitions through functionability states. Typically, functionability performance (the amount of work done and resources consumed to support operation and maintenance) becomes known through the end of the life statistics*[2]*, which c ertainly could be change at that stage..*

After five decades of systematic studies (practical and observational) of in-service behaviour of functionability systems and their performance Knezevic [1] has generated a body of knowledge, named MIRCE Science, which describes the motion of functionable systems through MIRCE Space[3]*. Its axioms, equations and computational methods enable predictions of expected performance to be done, well before the design has been finalised, for each of physically feasible alternative. It is based on the scientific understanding of the physical mechanisms that generates the occurrences of functionability events, considered within a physical scale between* 10^{-10} *m (atomic scale) and* 10^{10} *m (solar system scale). These mechanisms, together with the human imposed rules, quantitatively define the expected functionability performance.*



Reference: [1] Knezevic, J., The Origin of MIRCE Science, pp. 232, MIRCE Science, Exeter, UK, 2017, ISBN 978-1-904848-06-6

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[1] Functionable system is a set of the constituent things from natural and human worlds arranged to deliver at least one measurable function. [1]

[2] Pan Am's Boeing 747, registration number N747PA, during the 22 years of in-service life, has delivered 80,000 hours of positive work (transported 4,000,000 passengers, burned 271,000,000 gallons of fuel) while receiving 806,000 man-hours of maintenance work (consuming: 2,100 tyres, 350 brake systems, 125 engines, among other parts.

[3] MIRCE Space**:** a conceptual 3-dimentional space containing MIRCE Functionability Field, which is an infinite but countable set of all possible functionability states that a functionable system could be found in at any instance of calendar time and the corresponding probability of being in those states. [1]

Content

MIRCE Science Approach to Maintenance of Microbial Contamination of Fuel Tanks in COVID-19 Grounded Aircraft

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Microbial contamination of aviation fuel tanks is a known physical phenomena to airlines that are dealing with it in accordance to manufacturer guidelines. However, as the disastrous COVID-19 pandemic has left aircraft grounded and scattered across airfields around the world there is a danger that contaminated fuel could cause undesirable consequences to a fuel system like:
clogging of fuel filters, corroding tanks, performance degrading combustion quality, as well as damaging the rubber components specific to the fuel tank, thus impacting the functionability performance of an aircraft. A full understanding of these mechanisms is essential for the determination of the most effective maintenance policy for testing the fuel of grounded aircraft. Thus, the main objective of this paper is to address microbial contamination of fuel tanks in COVID-19 grounded aircraft as a potential mechanism of the motion of an aircraft through MIRCE Space. Recommendations for the fuel contamination testing maintenance programme are presented in the paper, which should assist airlines to ensure that fuel systems of over 20,000 temporarily grounded aircraft are safe when the time comes for them to resume operations.

Kay words: MIRCE Science, microbial contamination, aviation fuel tanks, CODIV-19 grounded aircraft, fuel testing maintenance programme

1. Introduction

The principal function of aircraft fuel tanks is to function as a wing and then as a fuel tank. Thus, the design of a wing structure does not allow a single simple sump, but it creates lots of difficult to drain water traps. While an aircraft is in regular operation, a system of specially shaped pipes is designed in the fuel tanks that mix any water back in with the fuel to prevent microbes accumulating.

Due to the global pandemic of corona virus COVID-19, around 80% of the world's fleet of commercial aircraft were grounded during most of 2020 creating conditions for the water accumulation in their tanks. The situation is even more critical during the summer months when the rising temperatures create conditions ideal for the growth of microbes. During the pandemic aircraft are on the ground all the time. Hence, the fuel system, the fuel, and the water get to an ambient temperature, which in most parts of the world in summer is over 30° C. In fleets that have not been treated with biocide the first signs of microbial growth begin to show after two to three months of storage.

The reduction in movement of aircraft during the COVID-19 outbreak has raised concerns over microbial contamination and the damage this can do to aircraft fuel systems, especially when they are in hot, humid regions that facilitate the rapid growth of micro-organisms.

Many of these aircraft have been in "active storage" with some fuel remaining in the tanks. Although that fuel is often treated with biocide, the threat of microbial contamination still exists. This is because fuel is warm for extended periods without being in flight and fuel is also static, so “hotspots” of contamination may occur that are very difficult to detect.

Experience teaches us that the storage and distribution of aviation fuel has “challenges” regarding the control and prevention of the growth of microbes (bacteria and fungi) in fuel tanks. Presence of water enables microbes to grow and multiply in the fuel tank, and then to get transferred to other tanks and continue propagating. The contaminated fuel could cause undesirable consequences like: clogging of fuel filters, corroding tanks and performance degrading build up of deposits caused by the acids the microbes excrete which cause fuel to break apart and lose combustion quality. Thus, the main objective of this paper is to address microbial contamination of fuel tanks in COVID-19 grounded aircraft as a potential mechanism of the motion of an aircraft through MIRCE Space. Recommendations for the contamination testing maintenance programmes for aircraft scattered over airfields away from usual lab testing facilities are presented in the paper in order for operators to ensure that fuel systems of over 20,000 aircraft are safe when the time comes for them to resume operations.

2. MIRCE Science Fundamentals

According to MIRCE Science[4], at any instant of calendar time, a given functionable system[5] could be in one of the following two states [1]:

- Positive Functionability State (PFS), a generic name for a state in which a functionable system is able to deliver the expected function, performance and attributes.
- Negative Functionability State (NFS), a generic name for a state in which a functionable system is unable to deliver the expected function, performance or attributes.

In MIRCE Science a functionability performance of a functionable system is defined by the trajectory of its motion through MIRCE Space. Mathematically, it is three dimensional space containing functionability points. Each point is defined by:

- a functionability state that a functionable system could be found in,
- a probability of being in each of these states
- the instant of the calendar time considered.

The motion of a functionable system through MIRCE Space is generated by natural or human functionability actions, which are classified as:

- Positive Functionability Action (PFA), a generic name for any mechanism whatsoever that compels a system to move to a PFS.

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[4] MIRCE Science is a body of knowledge that computs the time evolution of opertionally defined functionable systems by subjecting natural and human actions to the laws of mathematics. www.mirceakademy.com (assessed 18.09.2020)

[5] According to Knezevic, a functionable system is “a set of mutually related entities required for delivering work that is considered done when a measurable function is performed through time.” [1]

- Negative Functionability Action (NFA), a generic name for any mechanism whatsoever that compels a system to move to a NFS.

MIRCE Science focuses on the scientific understanding of the mechanisms that generate functionability actions, positive and negative, which govern the motion of functionable systems through MIRCE Space [1]. The understanding of these processes, in MIRCE Science, is placed within the physical scale that provides the necessary level of understanding. That scale is ranging from the size of 10^{-10} m (Atomic System) to 10^{10} m (Solar System). Analysis and research performed in any "smaller scale" would not give sufficient granularity of observations, which could lead to the prediction errors.

Microbial contamination impacts the functionability of aviation systems through mechanisms such as microbiologically influenced corrosion (MIC), clogging of fuel filtration components, fuel deterioration, failure of aircraft fuel system instrumentation, and even stopping the fuel supply to the engines during flight. The study conducted by Hu, D., et al [3], concluded that, "the aircraft fuel tanks harboured various micro organisms, which utilised the aviation fuel as a source of carbon and energy."

Microbial contaminated aviation fuel, if left untreated, can lead to costly damage to structures, potentially cost millions of dollars or a complete write-off in extreme cases. In normal operation, unscheduled aircraft downtime equates to loss of precious revenue, but also the possible additional pay-out for passenger compensation if flights are significantly delayed or cancelled.

3. Types of aviation fuel contamination

The three main types of contamination are:
- Water
- Particulate
- Microbial growth

Each of the above will be briefly addressed below.

3.1 Water

The chemical composition of aviation fuel allows water to be absorbed and held in suspension, either as suspended particles or in liquid form. The amount of suspended particles varies with the temperature of the fuel. Physical processes draw out some of the water molecules that are suspended in the fuel and slowly accumulate them in the bottom of the fuel tank, whenever the temperature of the fuel decreases. However, whenever the temperature of the fuel increases, it draws moisture from the atmosphere to maintain a saturated solution. Consequently, temperature changes result in a continuous accumulation of water.

Water promotes corrosion in some components of a fuel system. If enough water is present, it can form ice crystals in low temperatures and clog fuel lines, filters, or components. This could interrupt or even stop the fuel supply to the engine. To prevent this, some aircraft fuel systems employ heated fuel filters or fuel heaters to eliminate the problem of ice crystal accumulation and others rely on anti-icing fuel additives.

3.2 Particulates

Almost anything can cause particulate contamination from rags and bugs to deterioration of fuel system components like corroded metal parts or deteriorated rubber of fuel cells and lines. Dust and sand can be introduced through openings in tanks and from the use of fuelling equipment that is not clean. Rust can be introduced through pipelines, storage tanks, fuel trucks and drum containers.

Other sources of particulates include airborne solids that enter through tank vents or slip past the seals of floating roof tanks, like pollen or solids entering through damaged hoses and filters (rubber particles and fibres).

3.3 Microbial growth

A microbial contamination of fuel could be caused by numerous different types and species of microorganisms. However, the following three are the main categories:

- bacteria that are typically small (1–5 microns) rod shaped or spherical cells; some can produce slimy extra cellular polymers;
- moulds that are filamentous micro-organisms that produce mats of growth at the fuel/water interface and on surfaces: they also produce resistant spores that enable the spread of contamination in the fuel phase;
- yeasts that are either filamentous or ovoid cells (typically 5 -10 microns across).

Moulds and yeasts belong to a group of microorganisms collectively known as fungi. All of these organisms are present in the natural environment and therefore can easily access the whole fuel supply chain. The microorganisms grow in water and feed off the hydrocarbons in the fuel.

The essential constituents that are necessary for the existence of microbes are:

- water, as essential surrounding for living
- fuel, as essential food source
- oxygen, as essential element for growth

Certain bacteria and fungi are capable of existing in water where it interfaces with the fuel. These micro-organisms use alkanes[6] and additives in fuel as food. They can propagate rapidly, while generating a sludge-like substance as a by-product.

The most destructive of the microbes that grow in the aircraft fuel environment is the fungus Hormoconis resinae[7], due to its size. Compared to single-cell yeasts and moulds,

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[6] Alkanes are functional saturated hydrocarbons that form a chain with single bonds between atoms.

[7] Commonly known as the kerosene fungus. It utilises aliphatic and aromatic hydrocarbons, as well as alcohols and acids. Its growth can lead to serious bio deterioration of the fuel quality, the formation of sludge, and deterioration of pipe work and storage tanks, both in the refinery and at the end-user facility. [4]

it produces far more biomass. It is the most common cause of microbial corrosion in aircraft fuel tanks.

4. Mechanisms of attack by microorganisms

Hendey [4] coined the name ‘kerosene fungus’ for the fungus that had been known as the ‘creosote fungus’ because of its association with creosoted timbers. It is usually referred to as Cladosporium resinae because this is the state in which it normally occurs in kerosene and soil. Interest in this fungus was first aroused, in the early 1960's, by reports of its occurrence in storage and aircraft fuel tanks containing aviation fuel. [5]

Lansdown [6] has specified problems related to the microbial growth in aviation fuel. These include filter clogging, fuel tank corrosion and failures of fuel pumps due to corrosion. Even, at that time, he concluded that, “It has now become apparent that microbial contamination is widespread in aircraft fuel supply systems, both on land and in aircraft carriers, where serious clogging of fuel system filters has occurred.” The observed problems were spread worldwide, although the worse cases were experienced in the tropics.

Hazzard [7] reported that in 78% of all fuel samples from aircraft tanks tested in Australia the ‘kerosene fungus’ is the organism most frequently observed, whereas Engel and Swatek [8] stated that it was in 80% of all fuel samples examined in California, USA.

Aviation fuel is mainly composed of hydrocarbons[8] with some traces of contaminants and additives. The major additive, found in high-octane aviation fuel, is a lead compound. Typically, it is a lead tetraethyl with an organic bromide used to prevent lead fouling. Other additives that are present in aviation fuel, but in much smaller quantities, are:

- anti-oxidants, which extend storage life and protect fuel systems by increasing resistance to oxidation
- anti-icing, which prevents icing of water in non heated aircraft fuel systems
- anti-static, which ensures that aviation fuel will not become charged.

Jet aircraft today use aviation turbine kerosene that in its natural state can dissolve up to 75 ppm of water, which extracts constituents from the fuel and might, for example, contain a few ppm of hydrocarbons and several per cent of anti-icing additive. These water extracts constituents from the fuel might contain a few ppm of hydrocarbons and several per cent of anti-icing additive, for example. Due to condensation, the actual amount of water present in fuel depends on variations of temperature and atmospheric humidity.

Different classes of hydrocarbons attack different microorganisms. For example, the ‘kerosene fungus’ can use kerosene as its sole carbon source. Between 20 and 50 percent of the carbon assimilated by bacteria and fungi is converted into cell substance, whereas the remainder of the carbon is converted to more highly oxidised compounds

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[8] Compounds containing only carbon and hydrogen

including carbon dioxide, organic acids, alcohols and esters. These compounds modify the environment. For example:

- the lowering molecular weight fatty acids would lower the pH of the aqueous phase making it more corrosive to metals.
- alcohols and esters increase the solubility of fuel in the aqueous phase., resulting in extension of the zone for optimum microbial growth. Consequently, micro-organisms that meanwhile had remained dormant, may now find conditions suitable for their growth, which is now rapid and oxygen is all consumed leading to anaerobic conditions.
- the presence of sulphate creates favourable conditions for the growth of sulphate-reducing bacteria, which produce fuel-soluble corrosive sulphide that can be carried with the fuel and cause corrosion of components of an aircraft fuel system.

Microbial attack is also manifested by the formation of sludge or solid matter that may clog downstream parts of the fuel system, particularly filters and screens. Although there is some doubt as to whether bacterial slime has sufficient mechanical strength to block filters, there is a little doubt that fungal mycelium can block filters, screens and even the drain points of fuel tanks.

Fungal growth may also become attached to the fuel tank walls and prove difficult to remove during cleaning maintenance tasks. Some rust inhibitors appear to function as nutrients for bacteria. The surface-active rust inhibitors reduce the interfacial tension of water and hydrocarbon, and thus increase the availability of hydrocarbon to bacteria that encourage rust and make slimes. Slimes generated hold rust in suspension that encourages bacteria, which encourage rust to make more slime.

5. Impact of Microbial Growth of Aircraft fuel system

The wide variety of environments and microbes means that every infestation is different and can cause a wide range of problems. For example:

- Bacterial films can interfere with sensors,
- Microbial mats can clog filters and pumps,
- Microbial growth can extract the plasticiser contained in seals, making them less flexible and leading to leaks,
- Fungi can spread filaments below the epoxy layer that lines the bottom of some fuel tanks, breaking it apart and creating debris that can block fuel filters.

All of these microbes tend to form by-products of metabolism that are generally acidic. Some of these organic acids are capable of attacking the aluminium structures aircraft are made of, whereas the other microbes can create sulphuric acid and sulphide ions capable of eating away at steel and copper.

5.1 Microbially Influenced Corrosion of Alloys used in Aircraft Fuel Tanks

Microbes have a preference to thrive on surfaces in a film of slimy growth, known as a biofilm. The action of microbes within biofilms on metal surfaces can result in Microbiologically Influenced Corrosion (MIC) of aluminium alloys in aircraft wing tanks. Typically, it is due to the accumulation of microbially produced acids, such as isocitric acid[9], within biofilms that have developed on the tank surface. MIC of aluminium alloys in aircraft wing tanks is manifested by etching and/or pitting corrosion, both of which may progress at rapid rates.

The water permeability of epoxy-based coatings and primers, can also increase by microbially generated acids, exposing the underlying metal to corrosive attack. In the past, coatings and primers have incorporated chromates[10] to help prevent corrosion and some anti-microbial activities. Due to the current environmental consideration, chromates are not acceptable and are not used in modern aircraft.

5.2 Impact of microbial contamination on filters in the aviation fuel supply chain

Filters are used throughout the aviation fuel supply chain and on aircraft to ensure the fuel that reaches the aircraft engine is clean and dry. Filter Water Separators (FWS) are widely used in the supply and distribution of aviation fuel to remove both particulates and water. In under-used FWS units, microbes may proliferate in any water that remains on the outer sock of coalescer elements resulting in the formation of brown spots of microbial growth, commonly known as “leopard spotting”. As this microbial growth develops on the downstream side of the coalescer, it can contaminate clean fuel passing through the filter. Even more, if heavy microbial growth develops on the surface of the filter, the biosurfactants produced by the microbes can impact the ability of the coalescer to remove water from fuel and thus disarm the coalescer.

Although microbial growth tends to be the most predominant at the bottom of the tanks at the interface between fuel and any water or as a slimy film of growth on tank surfaces, turbulence in a contaminated tank can disperse particles of biomass into the fuel. In severe cases this can result in unacceptable differential pressure, as filters become clogged. A major industry development was the decision of the Energy Institute[11] to withdraw EI 1583 Report[12]. A number of alternative technologies have been proposed as replacement, including FWS or Water barrier filters, combined with enhanced particulate monitoring. The long-term implications of this change on the occurrences of microbial growth and contamination remain to be seen.

5.3 Impact of microbiological contaminants on the quality of aviation fuel

Microbial growth may occur wherever any water accumulates in aviation fuel tanks and systems. The presence of water allows heavy microbial growth to take place affecting the quality of the fuel due to particulate contamination of fuel with microbial biomass, and contamination with by-products of microbial growth such as biosurfactants and sulphide.

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[9] Isocitric acid, defined by a chemical formula $C_6H_8O_7$, is a structural isomer of citric acid, It is an intermediate in the citric acid cycle, which occurs in the metabolism of all aerobic organisms.

[10] Chromates are harmful when powdered because the dust is carcinogenic.

[11] The Energy Institute is an independent professional organisation for engineers and other professionals in energy related fields established in 2003 in London, UK.

[12] EI 1583: Laboratory tests and minimum performance levels for aviation fuel monitors to be withdrawn at the end of 2020.

If microbiologically contaminated fuel is loaded onto aircraft there is a possibility of serious operational problems. Consequently, industry best practices places a strong emphasis on the prevention of microbial growth in the fuel supply chain and in aircraft fuel tanks before it causes operational problems.

6. Impact of the COVID-19 on the contamination of fuel and fuel tanks in grounded aircraft

In the COVID-19 pandemic environment, thousands of aircraft are parked and the probability of fuel contamination is higher than normal. Fuel microbes thrive in heat and humidity, and if fuel becomes contaminated it can corrode fuel tanks and cause wing structure damage. Hence, fuel testing must be carried out more frequently in the current circumstances, especially on those aircraft standing idle in hot and humid places. [2]

Aircraft in tropical areas, much of Latin America, Africa, the Middle East, Southeast Asia and Australasia, are considered to be at higher risk of microbiological contamination, according to the International Air Transport Association (IATA). Tests that used to be done at least once per year now need to be done about every other week, according to Conidia Bioscience corporation[13], which develops fuel tests for various industries. In addition to increased testing, operators are ramping-up fuel tank borescope or visual inspections for aircraft in a temporary parked situation.

While operators or maintenance organisations run a grounded aircraft to make sure the systems are working, the aircraft uses some fuel. This can leave residue in the tanks, which can cause problems. Any moisture in the fuel tank, due to heat or humidity, can cause contamination, The fungi has the ability to stick to the tank, so even if the fuel is free of contamination, parked aircraft in hot or humid areas face increased microbial contamination, which requires extra inspections.

As the duration of the COVID-19 pandemic is unknown, ultimately the point could be reached where de-fuelling is required, especially if it's for disposal because it's been contaminated. In those cases some additional maintenance actions will be required because disposal of contaminated fuel is not something that is routinely done at airports. [2] The logistics of this process is rather challenging regarding the availability of resources like: injection carts, additives and the access to aircraft that are parked nose to tail on taxiways.

7. Microbial contamination related maintenance tasks

The best and most effective way of managing microbial contamination in aviation is prevention. Essentially, keeping fuel tanks clean is one of the best methods to avoid contamination. This prevention process can be divided into three parts namely[14]:

- Fuel monitoring program for the microbes: it involves periodic testing and sampling of the fuel, with the objective to minimise the problems through early

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[13] https://conidia.com/industries/aviation/

[14] https://fuelandfriction.com/trucking-pro/microbial-growth-in-fuel-prevent/#:~:text=%E2%80%9C%20Fuel%20tanks%20and%20other%20storage%20systems%20are,can%20also%20cause%20tank%20corrosion%20and%20fuel%20spoiling (accessed 5.8.2020)

detection of microbial growth. The appropriate industrial standards outline monitoring procedures that should be followed in test laboratories.

- Fuel system maintenance: the best way to prevent microbial growth in aviation fuel tasks is to reduce the exposure of the fuel to water. There are various ways this could be achieved[9].
- Fuel treatment: a set of activities that should control the spreading of microbial growth. Removal of the biomass or the sludge that has already developed is also needed. When choosing a remover, several factors should be considered, namely:
    - solubility of the fuel/water,
    - compatibility with system components,
    - compatibility with fuel and other additives,
    - time required to kill the microbes, in accordance to regulatory approvals.

7.1 Fuel sampling

Regular fuel sampling can help reduce problems with microbial growth and freezing associated with water in the system. It also can also help identify particulate contamination.
The actual process of fuel sampling is a routine operation. Fuel is drained into a clear container filling it half way to two-thirds full. Holding it up to the light, it becomes possible to see any water or particulate contamination it contains at the bottom. Swirling the sample around to create a tornado-shaped vortex in the container can also help isolation of any contaminates. Any water or particulates will accumulate at the bottom of this vortex.

A simple way to detect the water in the fuel is to add a few drops of food colouring to the sample. The food colouring will not mix with the fuel but will mix with water. If water is present, the colouring will mix with it. If no water is present, the dye will just settle in the bottom of the container. This is a good test to ensure that the whole jar is not just full of water.

Fuel samples taken should be clear and clean. A fuel sample should never be taken immediately after an aircraft is fuelled, as the fuelling action causes the water and particulates to become temporarily suspended in the fuel. A good time to take a fuel sample is prior to the first flight of the day.

7.2 Topping up fuel tanks

A good practice for operational aircraft is to top up aircraft tanks at the end of each flying day. Aviation fuel has a tendency to absorb moisture from the atmosphere. Hence, with less air in the fuel cells, the lower rate of absorption.

A good practice for grounded aircraft it to ensure for the entire parking period a fuel quantity in each tank of minimum 10% of the tank capacity. However, sometimes to prevent aircraft from leaving its parked position under the effect of high winds the weight of parked aircraft is increased by uploading a higher fuel quantity in the tanks. [11]

7.3 Inspection of fuel system screens and filters

Screens and filters within a fuel system should be inspected and cleaned on a regular basis, as this action ensures that any excessive particulate presence is investigated to the source of the contamination. Regular cleaning ensures that the filter elements do not become clogged.

The following two possibilities exist with clogged fuel filters, thus:

- In filters with a bypass system, once the filter is clogged enough to cause the differential pressure to activate the spring mechanism, the fuel will no longer be filtered, but will instead bypass the filter altogether, which could cause failures of components down the line.
- In non-bypass filters, the differential pressure that is built up could rupture the filter element and possibly generate even more particulate contamination.

8. Frequency of fuel testing for microbial contamination

In normal operation, aircraft may fly up to eight times per day. At altitude, temperatures way below 20 degrees C stop microbiological growth. However, the frequency of flights during the COVID-19 outbreak has dropped significantly and subsequently, the risk of microbial contamination has greatly increased for aircraft in active storage with some fuel still in their tanks.

Accurate testing at the regular intervals enable maintenance engineers to determine the correct testing frequencies, with the objective of being able to intervene at the earliest and least costly opportunity, well before the contamination is classified as “heavy” and requires intensive remedial actions. [10]

According to [11], if heavy contamination levels are reached, a full clean of a three-tank aircraft can cost in excess of $100,000 plus three or four days of lost revenue while the aircraft is on the ground. In total this could be anywhere up to around $2 million.

Airlines manage the risk of contamination through periodic testing of fuel. The interval between tests will depend on the aircraft manufacturer’s guidelines and a risk assessment carried out by the airline. The risk is higher for aircraft located in hot, humid regions where the micro-organisms can really thrive.

In the Asia-Pacific region, for example, the time from cleaning a fuel tank to heavy contamination can be as little as three months. Therefore, testing every month is not uncommon. At the same time, in colder regions, such as Scandinavia, the risk assessment may mean testing once every 12 to 18 months may be sufficient.

Normally, EasyJet is testing aircraft fuel for microbial contamination once per year, but that frequency for the COVID-19 grounded aircraft has been increased to once every 14 days, for each of the 21 currently grounded locations instead of one. For all operators, the COVID-19 grounded aircraft require more frequent testing that means more samples to be sent to well established laboratories, which is where many test providers test fuel samples. To take fuel test samples, send them to labs, and wait for the results typically takes 4-10 days. Today, in the COVID-19 driven environment forces aircraft to be scattered around airfields away from home bases, the process inevitably takes longer and requires more resources. Also, it is a logistical problem, as these samples also need to be transported in a controlled environment so that micro organisms present in the sample are not compromised, leading to a false test result. Even further this is compounded by travel restrictions in various countries due to the pandemic.

In summary, many airlines are finding that the increased frequency of testing the fuel of grounded aircraft across multiple airfields very difficult or even physically or financially impossible. Even if fuel has been treated with biocide, the biocide is only effective on the amount of fuel actually in the tank, which may be only 10 percent of full payload, contamination levels still need to be monitored to ensure it is still working.

9. Conclusions

Microbial contamination of aviation fuel tanks is a known physical phenomenon to airlines that are dealing with it in accordance to manufacturer guidelines. However, as the disastrous COVID-19 pandemic has left aircraft grounded and scattered across airfields around the world there is danger that contaminated fuel could cause undesirable consequences for a fuel system. Thus, a full understanding of these mechanisms is essential for the determination of the most effective maintenance policy for testing the fuel of grounded aircraft.

Microbiological contamination of fuels can cause operational problems, such as corrosion of metallic structures, fuel quantity indication problems, and blocking of the scavenge systems and fuel filters during flight. There are a number of signs that will indicate that fuel tanks are contaminated such as evidence of contamination of fuel filters, discoloration of sump sample, blocking of fuel injectors, erratic/inaccurate fuel level readings. For example erratic behaviour of the fuel quantity gauging system can be a sign of microbiological contamination, as most gauging systems are capacitance based and the microorganisms have a different capacitance than fuel.

While aircraft fuel contaminants can prove difficult to control, employing a solid fuel quality monitoring system through a series of tests will ensure that aircraft fuel stays clean. Whether in the aircraft or stored in a long-term facility, it is important to understand the potential of microbial growth, taking appropriate measures to search for it, and then removing any sludge, thereby keeping the fuel microbial free is an integral part of preventive maintenance process of any airline.

As the duration of the COVID-19 pandemic is unknown, ultimately the point could be reached where de-fuelling is required, especially if it’s for disposal because it’s been contaminated. In those cases some additional maintenance actions will be required because disposal of contaminated fuel is not something that is routinely done at temporal storage facilities. The logistics of this process is rather challenging regarding the availability of additional resources, like: injection carts, availability of the additives and also simple things like being able to access aircraft that are parked nose to tail on airports runways.

Recommendations for the fuel contamination testing maintenance programme are presented in the paper, which should assist airlines to ensure that fuel systems of over 20,000 temporarily grounded aircraft are safe when the time comes for them to resume operations.

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Cannibalisation as a functionability action of MIRCE Science

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Abstract

The main objective of this paper is to examine the cannibalisation process, removing a required component from a designated system and installing it on the unserviceable system, as a functionability action of MIRCE Science. It impacts the work done of a functionable system and resources consumed during a given interval of calendar time. Although the cannibalisation process improves profitability or readiness of functionable systems, it can also lead to increased costs and disruption by diverting resources from other activities and create additional technical and financial risks. Thus, cannibalisation is one of the drivers of profitability that could be predicted by applying MIRCE Profitability Equation, which considers the whole organisation as a single analytical scheme. It is a huge improvement in respect to current practices where the whole business process is partitioned into a large number of self standing models that address a few influential parameters at a time. Example of cannibalisation in Royal Navy is given in the paper.

Key words: cannibalisation, functionability, profitability. readiness

1. Introduction

The philosophy of MIRCE Science[15] is based on the premise that the purpose of existence of any functionable system[16] is to deliver the expected work. The work is considered to be done when measurable functionality (function, performance and attributes) is delivered through time, like: annual miles travelled, monthly units produced, daily energy supplied and similar.

The main business of any business is to stay in business by providing a revenue-generated work. Hence, the three of the least liked words in commercial aviation business are aircraft on ground (AOG). The following example is one of the possible scenarios of AOG: a passenger aircraft is due to departing, on a scheduled flight, at 16:00 with 235 fare-paying passengers. The pre flight test has shown that a safety critical avionics module has failed, which is not on Minimum Equipment List. To meet operational requirements and to dispatch the aircraft on time it is necessary to replace a defective component. The regular maintenance procedure is completed by issuing a replacement component from the inventory and releasing the aircraft into service after its installation. However, the on-line mechanics investigation has concluded that a replacement part is not available in the inventory. An interrogation of airline's available inventory reveals that module required could be delivered in 14 hours time. This means

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[15] MIRCE Science is a theory that subjects functionability phenomena to the laws of mathematics and computes time, space and human driven performances. (www.mirceakademy.com)

[16] According to Knezevic, Functionable system is operationally defined functional system. [1]

that the another aircraft has to be found to delivered the scheduled flight or that the 235 passengers and the crew have to be taken care of in local hotels till the needed component arrives. The other options to authorise cannibalisation (robbery) process. It means that the required component is removed from a designated aircraft (the donor aircraft), inspected, and installed on the unserviceable aircraft (the receiver aircraft. When the work is completed, the aircraft is dispatched into regular service. An AOG can happen at any time, anywhere in the world, and when it does, every minute the aircraft sits on the ground is critical.

The main business of any defence organisation in any country is to satisfy the defence requirements by providing operation ready weapon systems. They focus on a fleet readiness and the budget allocated for maintaining inventories of spare parts. Hence, all military services rely extensively on cannibalisation and consider it to be a normal part of fleet maintenance. A recent study identified approximately 850,000 documented US Air Force and Navy cannibalisations that consumed 5.3 million maintenance hours, during the period of five-year. [2]

While cannibalisation provides a short-term solution that makes a functionable system operational, its long-term impacts can be significant.

The main objective of this paper is to address cannibalisation as a functionability phenomenon of MIRCE Science, which uniquely determines the time emerging functionability performances, like: work done, resources consumed and consequential profitability in private sector or operational readiness in defence sectors. The body of knowledge presented here is of a generic nature, which means that is applicable to any work delivering functionable system.

2.0 Fundamentals of MIRCE Science

According to MIRCE Science, at any instant of calendar time, any functionable system could be in one of the following two functionable states:

- Positive Functionable State (PFS), a generic name for a state in which a functionable system is doing work,

- Negative Functionable State (NFS), a generic name for a state in which a functionable system is not doing work.

In MIRCE Science a work done by a functionable system is uniquely defined by the trajectory it traces thorough MIRCE Space. Mathematically, it is a continuous three-dimensional space containing discrete points, each representing a functionable state that a functionable system could be found in at any instant of time and the corresponding probabilities.

The motion of a functionable system through functionable states is governed by the following two types of actions:

- Negative Functionable Action (NFA) that causes occurrences of negative functionable events (NFE) at which functionable systems are compelled to move to NFS.

- Positive Functionable Action (PFA) that causes occurrences of positive functionable events (PFE) at which functionable systems are compelled to move to PFS.

MIRCE Mechanics is a part of MIRCE Science that focuses on the scientific understanding of the mechanisms that generate positive and negative functionable actions, which uniquely define the functionability in motion though MIRCE Space [1]. A full understanding of these mechanisms is essential for the predictions of expected performances of functionable systems using MIRCE Science Equations, like works done and resources consumed.

MIRCE Science Equations are mathematical expressions of the motion of functionable systems through MIRCE Space, developed by Knezevic [1]. They enable predictions of the expected work to be done by operationally defined functionable system, together with resources required, which when converted into monetary values present the expected cost and revenue, from the birth of the system to its retirement.

According to the MIRCE Science the probability of a functionable system being in PFS, at a given instant of time t, is defined by the MIRCE Functionability Equation [3], which defined the motion of a functionable system through MIRCE Space, thus:

$$y(t) = P(PFS,t) = \sum_{i=1}^{\infty} P(PFS^i,t) = \sum_{i=1}^{\infty}\left[O^{i-1}(t) - F^i(t)\right], \qquad t \geq 0 \qquad (1)$$

where:

$O^i(t) = P(TPE^i \leq t)$ is the probability that the time to i$^{\text{th}}$ PFE will take place between the birth of a system and a given instant of time t

$F^i(t) = P(TNE^i \leq t)$ is the probability that the time to i$^{\text{th}}$ NFE will take place between the birth of a system and a given instant of time t.

The positive work done, PW(T), by a given functionable system presents the amount of time it is expected to be in PFS consuming necessary operational resources (personnel, energy, material, facilities, equipment and similar) during the stated interval of time T, can be calculated by making a use of the following expression: [1]

$$PW(T) = \int_0^T y(t)dt \qquad [\text{Hr}] \qquad (2)$$

The numerical value of the above expression, when applied to operationally defined functional system type, presents the amount of time it is expected to be in PFS delivering expected: function, performance and attributes.

Correspondingly, the negative work done, NW(T), by a given functionable system presents the amount of time it is expected to be in NFS consuming necessary maintenance resources (personnel, material, spares, facilities, energy, equipment and similar) during the stated interval of time T, can be calculated by making a use of the following expression:

$$NW(T) = \int_0^T n(t)dt \qquad [\text{Hr}] \qquad (3)$$

where $n(t) = P(NIS, t) = \sum_{i=1}^{\infty} \left[F^i(t) - O^i(t) \right]$.

The numerical value of the above expression, when applied to operationally defined functional system type, presents the amount of time it is expected to be in NFS not delivering expected: function, performance or attributes.

3.0 Managing spare parts demands in commercial aviation

Mitigating the impact of an AOG situation is daily challenge of aviation fleet management process, which takes detailed planning, preparation and data. The following strategies are effectively used by many airlines to eliminate or reduce the impact of an AOG, regarding provisioning of spare parts[17]:

- Spare parts stock: By analysing system usage data and identifying components prone to causing AOG-related issues, inventory of spare components can be obtained to anticipate them.

- Fly-a-way kit: Some airlines maintain a flyaway kit that contains items that have demonstrated a statistically high chance of becoming faulty. They are available immediately during grounding at outstations.

- Partnerships: Airlines often develop partnerships with companies operating at stations where they have flights. The best partner is another airline based in that station or one that operates from the same country and maintains a similar fleet.

- Cannibalisation: a process consisting of removing required component from a designated aircraft (the donor aircraft), inspecting and installing it on the unserviceable aircraft (the receiver aircraft).

Although the mechanism of each strategy listed above is studied in MIRCE Science, this paper is focusing on cannibalisation only.

4. The anatomy of cannibalisation

Cannibalisation involves removing components from a donor system that could be in operation or in maintenance and transferring them to recipient system. It could involve moving an interchangeable part or more complex components through the following steps:

- Safe isolation of the part from the donor's system,

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[17] Down—But Not Out: How To Overcome An AOG, AerSale, https://www.aersale.com/media-center/down-but-not-out-how-to-overcome-an-aog (accessed 12.05.2021)

- Provision of a back-up system’s function fully to ensure the integrity,
- Removal of other components and modules to gain the access the desired part,
- Repositioning other systems and equipment to clear a path to move the cannibalised part,
- Physically movement of the part to a new location and packaging it to prevent damage during transit, when applicable
- Dispatch of the part to the recipient, which may be in the same location or elsewhere.

The recipient’s team then repeats the above describes process, while the donor is left with a defect in NFS. However, if the part remains unavailable when the donor requires it, for example to become operational or undergo specific maintenance, the cannibalisation process may have to be repeated[18].

4.1 Technical impact of cannibalisation

Cannibalisation creates additional engineering risks for both the cannibalised components and those components removed to get access to them within the donor and recipient system. The engineering teams may need to conduct additional systems testing to ensure system integrity. The resulting risks could be summarised as following:

- Defects: Some cannibalised components have been damaged while being removed, transported or reinstalled.

- Reduced service life: Repeatedly transferring the same part between systems may reduce its service life due to maintenance induced error or transport damage.

- Loss of warranties: Cannibalisation may invalidate warranties where components are used for a purpose beyond that intended, as perceived by original equipment manufacturer.

4.2 Financial impact of cannibalisation

Cannibalisation introduces the additional work of personnel who is needed to access, remove, transport, install and test the cannibalised part. This can be particularly challenging within systems like aircraft and submarines given the confined space and the need to maintain safety and operational requirements. The extent of additional work varies but can be time-consuming, diverting resources from other work such as scheduled or preventative maintenance and increasing costs.

Cannibalisation also involves additional administrative work such as producing temporary operating instructions. According to [5] the analysis of 146 events related Type 23 Frigate cannibalisations in 2012 identified that an average extra work cost £4,000. In 50% of these cases, work to remove and reinstall cannibalised components

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[18] According to [5] “We found eight instances of the same type of part being transferred between the same type of ship or submarine at least five times.”

was equal to, or greater than, the value of the part itself. In 25% of cases it was four times greater.

In summary, cannibalisation can be effective way of re-gaining functionability, but should only happen when no other solution is available, as it can lead to increased costs and disruption, divert resources from other activities and create additional technical and financial risks.

4.3 Example of equipment cannibalisation in the Royal Navy

The National Audit Office (NAO), that scrutinises public spending for Parliament and is independent of the UK government, has performed an investigation on when, why and how cannibalisation occurs across the Royal Navy and its impact. [5]. Although the Ministry of Defense recognises the adverse impact of cannibalisation, the tight budgetary constraints increase the risk of parts not being available. Hence, the removing a working part from one piece of equipment, such as a ship or submarine, to put it into another that is in greater operational need is approved practise, that has to be monitored and managed. Between April 2012 to March 2017 there were approved 3,230 instances of cannibalisation, involving 6,378 parts. This was an increase of 49% in the previous five years. [5]

In Table below are shown parts most often repeatedly transferred across ships and submarines of the same class, April 2012 to March 2017 (Source: National Audit Office analysis of Ministry of Defence data [5])

Part	Occurrences	Value (£)
Magazine torpedo launch system circuit card assembly	26	6,750
Chemical agent monitor	8	n/a
Perkins marine engine generator	8	219,956
Machine control and surveillance system display screen	6	16,793
Command support system interface	5	n/a
Low voltage electrical generator	5	286,129
Alternating current motor	5	n/a
Multi-functioning radar circuit card assembly	5	n/a

According to auditors, around 40% of ships and submarines receiving cannibalised parts needed them so they could be ready for operations or training. In these cases, equipment cannibalisation rectified issues that would have reduced the operational capability of ships and submarines. The remaining 60% of ships and submarines did not need the parts for operations or training, but were needed in order to, for example, complete planned maintenance work to schedule and cost.

In March 2017, the ships operating centre of the MoD’s arm’s-length procurement body Defence Equipment & Support met 55% of part demands from ship and submarine crews by the required date. This was against a target of 75%, while the submarine operating centre met 63% of demands against a target of 80%. [5]

5. Planning for cannibalisation

The research performed as a preparation for this paper has shown that although cannibalised components constitute a small proportion of components issued, there is a clear evidences that it has impact on profitability in private sectors and capability of functionable systems in public sector. However, there is a little evidence of systematic considerations and planning for the long-term impacts of cannibalisation when making its strategic decisions on the level of investment in spare parts. One of the possible reason for this is a fact that there is no a coherent body of knowledge that is able to concurrently address the following activities:

- quantitative assessment of the trade-offs between saving measures, such as reducing investment in spares upfront, and the longer-term value-for-money implications relating to cannibalisation,

- accurate prediction of the cost implications, such as for the maintenance of heavily cannibalised equipment, to allocate appropriate long term financial support,

- considerations of any underlying increase in technical risks and subsequent impact on testing during the operational process,

- clarification of commercial arrangements, due to a lack of clarity on the impact of cannibalisation on part warranty.

The body of knowledge contained in MIRCE Science enables many of the above listed challenges to be addressed. In the remaining part of the paper it will be shown how the impact of cannibalisation on the expecting profit can be predicted by making use of MIRCE Profitability Equation.

6. Impact of Cannibalisation on profitability

The creation of the MIRCE Functionability Equation enabled the development of the MIRCE Profitability Equation [4] that links the revenue and cost sides of business, by integrating the consequences of system engineering decisions, adopted business methods and project management decisions.

In economics a profit is defined as a financial gain quantified as the difference between the amount earned (revenue) and the amount spent in buying, operating, or producing something (cost), expressed through a monetary units (MU), thus:

$$\text{PROFIT} = \text{Revenue - Cost} \qquad [MU] \qquad (4)$$

6.1 The expected revenue

According to MIRCE Science [1], the expected revenue of a given functionable system, during the stated interval of time, *Rev(T),* expressed in the monetary units (MU), is equal to the product of the Hourly Income generated by the provision of business function, HI, expressed in monetary units, and the amount of the work done by the system, thus:

$$\text{Rev}(T) = HI \times PW(T) \qquad [MU] \qquad (5)$$

6.2 The expected cost categories in MIRCE Science

The motion of a given functionable system through MIRCE Space is driven by the execution of functionability tasks, positive and negative, is related to utilisation of physical resources, on one hand, and satisfactions of legal and organisational requirements associated with operation, maintenance and support processes, on the other. Both parts are treated as a cost and are quantifiable in monetary terms. Thus, in MIRCE Science, the following three categories of cost are recognised:

- Set up costs, which is the total investment necessary to enable operational, maintenance and support systems to be established before the introduction of a system into service. Such costs are generally non-recurring during the life of the item/system. Typically it is related to the acquisition of: test equipment, training devices, upgrade of facilities, transportation devices, initial tooling and so forth.

- Fixed costs, which is exist irrespective of the number of operational and maintenance tasks performed (eg. test equipment, ground equipment, facility costs, training of personnel and similar). Although fixed costs are assumed to remain unchanged in response to changes in the level of activities, they may change in response to other factors such as price changes.

- Variable costs, which are dependent upon the quantity of operational and maintenance tasks performed. These costs are usually related to the direct material and direct labour consumed.

6.2.1 The expected cost of positive work

Following the MIRCE Science cost structure, the cost of doing positive work during the stated period of time[19], CPW(T), is equal to the sum of the set up cost, CPW_{set}, fix cost, $CPW_{fix}(T)$ and variable cost that is equal to the product of the Hourly Cost of positive work, HC_{PW} and the duration of the time a functionable system spends in PFS (Equation 2), thus:

$$CPW(T) = CPW_{set}(T) + CPW_{fix}(T) + \left[HC_{PW} \times PW(T)\right] \qquad [MU] \quad (6)$$

6.2.2 The expected cost of negative work

Equivalent cost for doing negative work (maintenance and storage), during the stated period of time[20], CNW(T), which is equal to the sum of the set up cost, CNW_{set}, fixed cost, $CNW_{fix}(T)$ and variable cost that is equal to the product of the Hourly Cost of negative work, HC_{NW} and the duration of the time a functionable system spends in NFS (Equation 3), thus:

$$CNW(T) = CNW_{set}(T) + CNW_{fix}(T) + \left[HC_{NW} \times NW(T)\right] \qquad [MU] \quad (7)$$

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[19] Monetary value of resources used for the execution of all tasks needed for doing positive work, like: personnel, material, facilities, equipment, energy, information and so forth.

[20] Monetary value of resources used for the execution of all tasks needed for doing negative work, like: personnel, material, facilities, equipment, energy, information and so forth.

In the business orientated organisations the time spend in NFS can be translated into monetary value of the revenue lost. Hence, Knezevic [1] has introduced the concept of the cost of lost revenue, during a given interval of calendar time, *CLR(T)*. This lost cost category could be even higher than that of revenue generated due to the potential consequences of the occurrences of NFE to the business and environment. For example, after the Deep Water Horizon the offshore rig explosion that killed 11 workers and caused a 134 million gallons crude oil spillage British Petroleum (BP) was found by the court to have been "grossly negligent". As a consequence, BP was forced to pay over 20 billion dollars in settlement to cover the environmental damage and other claims by the five Gulf States and local governments[21]. Of course, it was on the top of the cost of resources used by them to recover from the disaster. Thus, the final expression for predicting the cost of negative work in MIRCE Science is as following:

$$CNW(T) = CNW_{set}(T) + CNW_{fix}(T) + \left[HC_{NW} \times NW(T)\right] + CLR(T) \qquad [MU] \quad (7)$$

The above expression can be used to predict the cost to the business in case of cannibalisation.

6.3 The expected profit

The expected profit to be generated by a given functionable system, during the stated period of time, PROFIT(T), could be calculated by making use of the MIRCE Profitability Equation [5], which also includes the cost of lost revenue, while a functionable system is in NFS, CLR(T), thus:

$$PROFIT(T) = HI \times PW(T) - \left[CPW(T) + CNW(T) + CLR(T)\right] \qquad \left[MU\right] \quad (8)$$

The above equation is the only one, known to the author, which unifies all aspects of the existence of a functionable system, including the phenomenon of cannibalisation. It unites the whole organisation into a single analytical scheme. It is a huge improvement in respect to current practices where the whole business process is addressed through a collection of a large number of self standing models that address a few influential parameters at a time.

7. Conclusions

The main objective of this paper was to examine the cannibalisation process, removing a required component from a designated system and installing it on the unserviceable system, as a mechanism of the motion of a functionable system in MIRCE Science. It impacts the functionability work done and resources consumed during a given interval of calendar time. Although the cannibalisation process improves profitability or readiness of functionable systems, it can also lead to increased costs and disruption, divert resources from other activities and create additional technical and financial risks. Thus, cannibalisation is one of the drivers of profitability that could be predicted by applying MIRCE Profitability Equation, which considers the whole organisation as a single analytical scheme. It is a huge improvement in respect to current practices where

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[21] BP oil spill: judge grants final approval for $20bn settlement, The Guardian, 4th April 2016.

the whole business process is addressed through a collection of a large number of self standing models that address a few influential parameters at a time.

The cannibalisation process must be rigorously managed and controlled to maintain regulatory and safety compliance, on one hand, and performing the trade-offs between saving measures, such as reducing investment in spares upfront, and the related longer-term value-for-money implications, on the other. Efficiency is also a priority, because the cannibalisation process is typically applied under operational pressure and tight deadlines. Finally, cannibalisation presents a challenging underlying technical risks, subsequent consequences on testing during the operational process and cost implications on the long term financial support of the maintenance of heavily cannibalised components/equipment.

8. Acknowledgement

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Mathematical and Physical Reality of Reliability

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Abstract

According to Knezevic [1] the purpose of the existence of any functionable system is to do work. The work is done when the expected functionality (function, performance and attributes) is delivered through time. However, experience teaches us that the work expected to be done is frequently beset by failures, some of which have safety consequences to: the users, the natural environment and human communities[22]*. Thus, from the late 1950s reliability models, based on a reliability function, have been used to predict the impact of the design decisions on in-service reliability and safety, before finalising the design. As the accuracy of these predictions is fundamental for the formulation of failure management policies, the author has studied the physical properties that future systems must possess, in accordance with the mathematical view of reality, firmly imbedded in their reliability block diagrams. The results of the study are presented in the first part of the text. These findings are tested through scientific studies of a large number of physically observed failures generated by operation, maintenance and support processes of defence, aerospace and nuclear power systems. The results obtained, presented in the second part of the text, show significant discrepancies between the mathematical reality of reliability based on axioms of probability imbedded in reliability function and the physical reality observed through the scientific studies of numerous in-service reliability and safety related events. Thus, the main objective of this text was to expose the reliability and safety community to the mathematical and physical realities of reliability function with the objective to focus their attention to the following question, "What is the body of knowledge on which reliability and safety modelling should be based, in order for predictions made to be confirmed by reliability measures obtained in operationally defined physical reality?"*

Key words: reliability function, mathematical reality of reliability modelling, observed failure events, physical reality of reliability modelling,

0. Dedication

This work is dedicated to the memory of Professor Arie Dubi (1945-2015), the greatest scientist I had the pleasure to collaborate with, for introducing me to the real meaning of a mathematical and physical truth and thus opening the door for the creation of MIRCE Science.

1.0 Introduction

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[22] Three Mile Island (1978 in USA), Chernobyl (1986 in USSR), Fukishima (2011 in Japan), Deepwater Horizon oil spill (2010, USA), NTPC power plant explosion (2017 in India) and numerous others.

All engineering disciplines have been developed, several decades or even centuries, after the development of the relevant discipline of science. Thus, mechanical, electrical, nuclear, chemical, aeronautical and other types of well recognised and proven engineering disciplines have grown on the foundations made of mechanics, electrodynamics, fluid mechanics, thermodynamics, quantum mechanics and similar scientific disciplines, fully defined by the proven laws and equations named after their creators like: Newton, Maxwell, Hamilton, Lagrange, Euler, Bernoulli, Boltzmann, Planck, Schrödinger, Heisenberg and other giants of science. These equations are used to make predictions of the performance of future engineering systems. However, in order to make any type of prediction a model of reality must be created, as science cannot look at the absolute reality. So, it could be safely said that all the above-mentioned equations of science are models of physical reality that predict results that are consistent with the measurements made. These measurements are the only "mechanisms" through which humans interact with physical reality. In summary, the greatest engineering "feats" like: steam engines; aircraft; power stations; communication systems; computers and numerous other systems have been designed by human ingenuity using models based on mechanical, electrical, nuclear, chemical, aeronautical and other types of well recognised and proven engineering disciplines.

With the development of advanced military, aerospace and nuclear industries, the necessity for their in-service reliability and safety became imperative. Hence, in the1950s, Reliability Engineering was "created" by these industries. To the best of this author's knowledge there was no "father" figure of reliability and safety comparable to Newton or Maxwell. Thus, for the first time in engineering history the process of the creation of an engineering profession has preceded the process of the creation of the scientifically proven theory on which relevant models are built. The focus was on the data collection related to the number of failures that took place during the operation of systems. Massive attempts were made by the reliability and safety community to utilise the collected failure data and produce some measures of reliability. Hence, a Mean Time Between Failures[23] (MTBF) and its reciprocal, a failure rate (λ), became measures of reliability. They are primarily used for contractual purposes between producers and users, mainly within defence, aerospace and nuclear industries. However, these reliability measures only quantify the past performance of systems, rather than predict their future performance.

Deterministically educated design engineers and project managers could not improve the situation as they had huge difficulties in understanding these reliability measures, as they are totally different from all other measurable physical properties known to them. For example: pressure, temperature, volume, voltage, weight and similar can be measured directly. Even further, by applying existing laws of natural sciences, accurate predictions of these physically measurable properties for the future systems could be made. At the same time, the adopted measures of reliability are abstract and immeasurable directly, as they obtain a physical meaning only when the behaviour of a large sample is considered.

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[23] Typically, it is calculated as a ratio between the total time of operation and the total number of observed failures, which is known as the arithmetic average, in mathematics. It is necessary to stress that no other measures could be obtained from this data.

In absence of anything else, the practicing reliability and safety engineers, in the 1960s created a model of reliability that required the acceptance of the concept of an "alternative universe" where all the components, and consequently systems, possess a constant failure rate, leading to the following expression of the reliability function: $R(t) = \exp(-\lambda t)$. This approach stems from neither science nor mathematics, but from a desperate necessity to make reliability and safety predictions based on the in-service information. Regrettably, these practises were "legitimised" by numerous industrial and military standards, created to demonstrate contractual compliance in legally binding acquisition processes, which is the case in many industries, continues even today.

In summary, reliability and safety engineers, knowingly or unknowingly, adopted this parallel universe where well-known and physically observed physical phenomena like: corrosion, fatigue, creep, wear and similar time-dependent mechanisms do not exist. They tried to rectify the situation by the invention of a bath-tub curve, the concept of which has never been incorporated into quantitative predictions of reliability and safety measures.

According to Knezevic [1] the collection of failure data and their statistical analysis by the reliability and safety community clearly demonstrated the following fact, "As the past can be quantified through statistical measures only, then the future can be predicted through probabilistic measures, only." Consequently, the rest of the text will expose the currently used reliability function based approach to the modelling of reliability and safety, the accuracy of which is tested by the author through the analyses of a large number of physically observed failure events that have shaped the reliability and safety performance of defence, aerospace and nuclear power industries during the last 50 years.

2. Mathematical reality of reliability

Mathematics is a body of knowledge created by humans, which is based on a set of axioms that are not related to the existing universe. At the same time, mathematics is used in every aspect of human life, from shopping to space travel, not because it represents an absolute truth, but because it is found to be useful through our experience.

The existing body of knowledge of mathematics enabled the developed probabilistic measures of reliability, like: failure function, reliability function, expected time to failure, hazard function, mission success and so forth. [2] All of these measures of reliability are uniquely defined by the probability distribution of a random variable, known as the Time To Failure (TTF). However, it is necessary to stress that the concepts of: probability, probability distribution and random variable exist only in mathematics, not in the real physical world.

2.1 The concept of failure function

Occurrences of the failure events are clearly manifested and physically observed phenomena during the operation of systems. Thus, the length of the "failure free" operational time, measured in: hours, miles, cycles or any other physical units, is used as a quantitative measure of reliability. In order to fully understand the nature of the TTF it is necessary to make the following point. Any given system, say a radio, exists only through its manifestation as an end entity. Hence, there will be many individual radios of a specific type, each with the same functionality, like: frequency, voltage, power and so forth. Thus, the fundamental question here is, "Is the TTF a single number identical for every single copy of the given radio produced or does it vary from copy to copy, of the same type radio?" Experience teaches us that every individual copy of the type of the radio under consideration will fail at a different instant of operating time. Thus, the variability of the individual behaviours is a result of the complex interactions of numerous physical mechanisms engaged during the operationally defined physical reality that govern their in-service behaviour. Hence, it is impossible to specify a single instant of operating time when a failure will occur to each individual copy within the whole population considered. The reliability of "the system considered", in this case a radio of a specific type, is determined by the collective behaviour of all individual copies of that type.

The only way forward to quantitatively describe reliability performance is to employ an existing probability theory that offers a mathematical scheme for the probabilistic description of the TTF. Thus, it is possible to assign a certain probability that a failure will take place during a given interval of operating time. That measure, in reliability theory, is known as the Failure function, *F(t).* [2] It represents the probability that the transition to the state of failure (or simply failure), will occur before or at the instant of time t, thus:

$$F_1(t) = P(\text{Time To Failure} \leq t) = P(TTF \leq t) = \int_0^t f(t)dt, \quad \text{t} \geq 0 \qquad 1$$

where: *f(t)* is a probability density function of the time to failure (TTF).

In probability theory this type of function is called the Cumulative Distribution Function (CDF) and adapted to reliability theory it has the following mathematical properties:

$$\begin{gathered} 0 \leq F(t) \leq 1 \\ if\ \ t_1 \leq t_2,\ \ F(t_1) \leq F(t_2) \\ F(0) = 0 \text{ and } F(\infty) = 1 \end{gathered}$$

It is necessary to stress that each observed/measured TTF has its own CDF. This practically means that the probability distribution of the time to the first failure (TTF_1), the time to the second failure (TTF_2) and the time to any other failure (TTF_i), from the point of view of mathematics, could be defined by identical or totally different functions.

2.2 Reliability model of a component

The most frequently used model of reliability is the reliability function, denoted as *R(t).* It is the probability that a component[24] will operate without failure during a stated interval of time *[0,t]*. It is the complementary expression to the expression of the failure function, thus:

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[24] Component is any entity that has the following two properties: finite number of discrete states and the mechanism of its transfer between states is known.

$$R(t) = P(TTF > t) = 1 - P(TTF \le t) = 1 - F(t) = \int_t^{\infty} f(t)dt, \qquad t \ge 0 \qquad 2$$

Once a probability distribution of the TTF is identified the reliability function and all other reliability measures become known. From the point of view of mathematics any well-defined probability distribution that satisfies mathematical rules for CDF (given above) can be used to model the reliability of components. However, to be practically used the selected probability distribution function should reflect the expected in-service behaviour of components considered. Hence, designers and producers of components are the most suitable source of information regarding the selection of the relevant probability distributions to model the mechanisms that generate their failures. [2]

2.3 Reliability model of a system

A system is a collection of components on which at least one measure of performance is defined. An expression that defines the state of a system as a function of the states of its components is called a system function, which is a mathematical model of the physical entity considered. Thus, the reliability function for a system, $R_S(t)$, which consists of several components, is determined by the impact of failure of each component on the reliability performance of a system, which is graphically described by the reliability block diagram (RBD) of a system considered. For a hypothetical system that will experience a failure event when either component A fails, or components B and C fail, the RBD is shown in Figure 1.

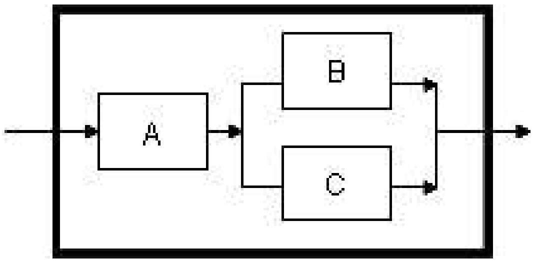

Figure 1: Reliability Block Diagram for a Hypothetical System

The failure function of a system, $F_S(t)$, based on the axioms of probability theory, is equal to:

$$\begin{aligned} F_S(t) &= P(TTF_S \le t) \\ &= P(TTF_A \le t) + P(TTF_B \le t)P(TTF_C \le t) - \left[P(TTF_A \le t)P(TTF_B \le t)P(TTF_C \le t)\right] \\ &= F_A(t) + F_B(t) \times F_C(t) - F_A(t)F_B(t)F_C(t), \qquad t \ge 0 \end{aligned}$$

Consequently, the probability of not experiencing a failure event at the system level, during a given interval of in-service time [0,t], is quantified by the reliability function of a system, $R_S(t)$, which is defined as:

$$\begin{aligned} R_S(t) &= P(TTF_S > t) = 1 - P(TTF_S \le t) \\ &= R_A(t)R_B(t) + R_A(t)R_C(t) - R_A(t)R_B(t)R_C(t), \quad t \ge 0 \end{aligned} \qquad 3$$

Given that reliability functions of consisting components A, B and C are known it is possible to plot the reliability function for a system and calculate the probability of not experiencing a failure event during any interval of future time, as shown in Figure 2, for a hypothetical system.

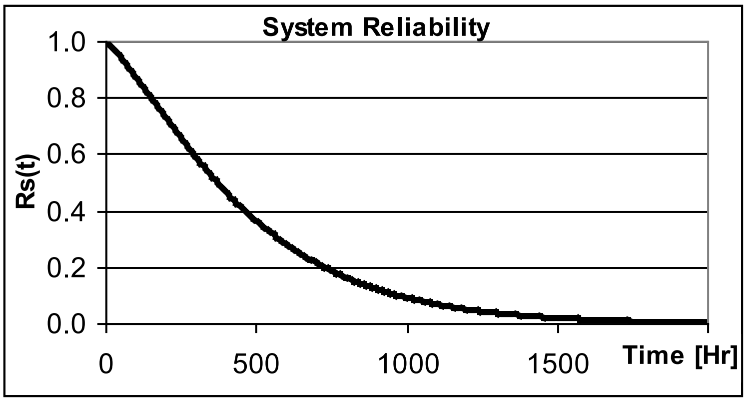

Figure 2: Reliability Function for a hypothetical system shown in Figure 1.

The above two figures summarise the essence of the mathematical approach to the reliability modelling process. As its main concern is a prediction of the probability of a given system not experiencing a failure event during a given interval of time it is the governing information for the safety, hazard and similar types of analyses performed at the design stage.

It is necessary to point out that when a value of reliability functions is calculated, say 0.83 for a given interval of time t, it does not mean that the system under consideration will or will not experience a failure event. It is not known, but what is known is that, "out of 100 systems of that type put into operation about 83 of them will not experience a failure event during that period of operation stated". Hence, this is the maximum possible information to be obtained with a mathematical model of reliability. [3]

In summary, mathematics is telling reliability and safety modellers that there is a probability function associated with the operation of each physical system. However, mathematics is saying nothing about the probability distribution of that function. From a mathematical point of view the number of possible probability functions is unlimited. Consequently, the final statement of mathematics to reliability and safety modellers is, "I know my limitations". [4]

3. Voyage To The Ice

> *"The machine does not isolate man from the great problems of nature but plunges him more deeply into them."* Antoine de Saint Exupery[25], Wind, Sand, and Stars, 1939.

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[25] Antoine Marie Jean-Baptiste Roger, comte de Saint-Exupéry (1900-1944) a French writer, poet, aristocrat, journalist, and pioneering aviator.

In order to scientifically understand the physical reality of the operational process of an aircraft, from the point of view of reliability, the MIRCE Akademy[26] sponsored British Aviatrix Polly Vacher's unsupported solo flight around the world in a single-engined aircraft via the North and South Pole. The project was named "Voyage To The Ice" (VTTI) [5] and had been planned to materialise between May 2003 and March 2004, with the objective to raise awareness of a Flying Scholarship for a Disabled (FSD)[27].

The longest and the most challenging leg of the whole journey was expected to be the flight between Christchurch in New Zealand and McMurdo in Antarctica, the 2068 nautical miles of inhospitable Southern Ocean. Hence, reliability wise, the major consideration was the direction of the flight between these two destinations. Both options, eastbound (New Zealand to Antarctica) and westbound (Antarctica to New Zealand) had their advantages and disadvantages. However, this decision would determine the starting date of the project and consequently all other dates and events.

At the beginning of January 2002, the MIRCE Akademy allocated four students from the Master Diploma Programme to study the proposed flight plan with the aim of determining the necessary reliability and supportability issues concerned with its successful completion. They created the RBD of Polly's aircraft, obtained the all-necessary information and made reliability predictions, in the manner described earlier in the text, for both options. After reading the Akademy's report and speaking with pilots who had flown in either, or both, directions, Polly decided to fly westbound, which meant that, in her judgment, flying from Antarctica to New Zealand was the safer option. Consequently, Polly planned to start the flight in the British springtime with a route starting from Birmingham, UK, heading north towards Scotland and Norway with the intention of over-flying the North Pole during the month of June. This timing was considered to be the best chance for clear skies in that region. As a result of the annual rotation of the Earth around the Sun, Polly had around five months to complete the flight south towards Argentina in order to fly over Antarctica during the summer months in the Southern Hemisphere. So, after over-flying the North Pole, the route south would take her through Canada, USA, Mexico, Guatemala, Belize, Antigua, Tobago, Trinidad, Brazil and Argentina. [5] Polly was aware that a great deal of patience is required in waiting for the right weather window for the flight to Antarctica. From there, the journey home was pretty much well defined. Namely, through New Zealand, Australia, Indonesia, Malaysia, Thailand, India, Bhutan, Oman, Bahrain, Jordan, Egypt, Greece, Yugoslavia, Italy, France and back to Birmingham, UK. [5]

In order to assist the science based research studies in reliability at the MIRCE Akademy Polly generously accepted to record relevant in-service data during the trip. The main purpose of the research was to study the impact of the environmental conditions on the reliability and supportability of VTTI system. The data to be collected as the basis for reliability research are shown Table 1.

Departure	In Flight	Arrival
Location Co-ordinates Time	Altitude Winds/directions Distance	Location Co-ordinates Time

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[26] www.mirceakademy.com

[27] Knezevic, J., B2B/A+A - Polly Vacher's Voyage To The Ice, Birmingham To Birmingham Over Arctic & Antarctic http://www.MIRCE Akademy.com/index.php?page=applied

Fuel Load	Fuel consumption	Refuel Qty
Oil Refill	Oil Temp & Pressure	Oil refill
Maintenance Actions	Fuel Mix	Maintenance Actions
Battery Charge	Cabin Temperature	Battery Charge
Ambient Température	Ambient Temperature	Total Distance
Cabin Temperature	Engine Temperature	Ambient Temperature
Max G-force	Engine RPM	Max G-force

Table 1: Physical Parameters Continuously recorded by Polly during the VTTI project.

Generally speaking, the problem for reliability engineers and managers is the variability of the internal and external drivers of reliability, in time and locations. This research was planned to collect the largest possible range of data in respect to any flights anywhere in the world made by any pilot, as commercial flights over North and South Pole are almost non-existent! Hence, the expectation was to use the data collected by Polly in the endeavour of the MIRCE Akademy to address the reliability modelling process, by understanding the physical reality of operational processes that drive a reliability performance of systems, in respect to time and locations.

On the 6 May 2003, at 16:22 Polly took off from Birmingham airport, in her Piper Dakota PA-28-236[28] (G-FRGN) with the thoughts "when will I see home again" [5] flying north in the direction of Scotland. She arrived at a cloudy and cold Wick at 19:20. After five days of waiting for the weather "window", Polly flew onward across the North Sea to Norway, through Bergen to Tromso. On the 26th May 2003 she finally left Europe, ready for the Arctic flight.

The flight to the first of the Ice Challenges, at the beginning, was slow due to the strong headwind. At some stages of the flight Polly was flying at only 98 kts (cruising speed 135 kts.). Then, as she described in her diary, "My ferry tank ran dry and I switched to the left wing tank. About five minutes after changing tanks THE ENGINE STOPPED - panic - why is it stopping now? I went into automatic mode and changed onto the right tank; put the fuel pump on and the carburettor heat[29]. Heaven be blessed it started again, but from then onwards, every little noise every little whistle became a huge problem." [5] Despite having to manage this operational challenge, in real time, she successfully landed at Resolute on the 27th May 2003.

During the following 5 months Polly had flown through: USA, Mexico, Guatemala, Belize, Cayman Islands, Dominican Republic, Antigua, Trinidad and Tobago, Suriname, Brazil and Argentina to arrive to Ushuaia, the most southern tip of Argentina, on the 25th October. Then, the waiting for the favourable weather started. On the 29th November 2003, after 8 hours of flying, she landed at the British Research Station in Rothera (67°33'S, 68°07'W) in Antarctica, to start her flight over the South Pole. [5]

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[28] Knezevic, J., From B to B, Polly Vacher's Global Challenge, pp 50, MIRCE Science, 2001, Exeter, UK

[29] The problem was two-fold. First: the fuel mixture being on the lean side. Second: carburettor icing. All the time Polly was using the warmer fuel from the ferry tank within the aircraft, no ice was forming in the carburettor. But once this was all used and she had to change to the fuel tanks in the wings where the outside temperature was –20°C, the injection of such cold fuel froze any moisture in the carburettor, and caused the engine to cough and splutter unless carburettor heat was continuously applied.

On the 5th December at 07:00 the weather forecast was good, overall winds +3 kts. The first hour into the flight was good: tail wind at 5000 ft and the cruising speed was 111 kts. Polly flew up the glacier and flying over the top the views were stunning. Four hours into the flight the wind changed from a tailwind to a headwind and soon the ground speed decreased to 80 kts. The GPS indicated that the planned 11-hour trip would now take 15 hours! Soon Polly reached the point of no return. An updated weather report was not encouraging, as the headwinds were expected to continue to increase in strength. As a captain, in charge of the VTTI system, whose function was to “safely fly solo a single-engined aircraft around the world” she made the decision to turn back! Naturally, Polly’s speed rapidly increased to 133 kts and she safely landed back at Rothera. [5]

As the fuel for Polly’s one-way flights over Antarctica were pre-positioned several months in advance, she had no fuel to make the second attempt to fly over the South Pole. The only help came from the Argentine Air Force that on the 17th December delivered 4 drums of fuel to their Antarctica base located in Marambio Island, from where it was impossible to fly to McMurdo without refuelling on the way. Hence, without any other option, Polly had to abandon her Antarctic flight! However, on New Year’s Day, 2004, Polly started on a re-routed flight, back up to the Americas to California, then across the Pacific to New Zealand. Thus, 14,000 miles later, on the 30th January 2004 Polly landed in Auckland, to be in the position to continue the planned trip and honour commitments made to this part of the world in aid of FSD charity. [5]

After 357 days of circumnavigating the globe via all seven continents, 60,000 nautical-miles, thirty countries and spending over 500 hours in the pilot’s seat, Polly arrived, on schedule, at 12:30 at her starting point, Birmingham International Airport, but this time from the south and “landed” in the aviation record history books as: The first woman to fly solo:

- In a single engine light aircraft over the North Pole
- In a single engine light aircraft over Antarctica
- The first person to fly solo around the world landing on all seven continents.

Aviatrix Polly Vacher generated £400,000 for the FSD and recorded over 20,000 in-flight technical data of the physical reality of the flight around the world via poles, to support the research at the MIRCE Akademy. Today, this data is a part of the Polly Vacher Collection[30] at the Akademy’s Resource Centre.

3.1 Impact of VTTI on reliability modelling at the MIRCE Akademy

> *“Success is a lousy teacher. It seduces smart people into thinking they can't lose.”*
>
> Bill Gates[31]

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[30] Mirceakademy.com/index.php?page=Resource-Centre

[31] https://www.brainyquote.com/quotes/quotes/b/billgates122131.html

Polly Vacher's flight of 11 hours and 53 min, covering 1092 miles, from Rothera to Rothera on the 5th December 2003, had a profound impact on the studies of reliability at the MIRCE Akademy. Although the syllabus offered by the Akademy, was comparable with postgraduate programmes in Reliability Engineering with all other universities in the world, it was unacceptable to the author that no a single part of the whole body of existing knowledge was able to address the observed physical reality. If, the "wind direction change", event was predicted and the decision was made to pre-position enough fuel for one attempt, the author would have been happy as a scientist, but unhappy as a project manager. However, to have a science-based body of knowledge that predicts the system operational behaviour that is unable to even address the wind direction was totally unacceptable to the author. The brutal truth is that all the components of Polly's aircraft, contained in the RBD, were performing their expected functions and yet the final result was a mission failure! Thus, the author asked himself, "How is it justifiable to construct a reliability block diagram for an aircraft without a single block being related to the air?" [1]

Requesting a scientific approach when entering into the MIRCE Akademy, from his students, the author, as its president, had no option than to suspend the studies of Reliability Engineering until the "scientific approach" was found. Hence, the MIRCE Akademy stopped admitting students to the Master and Doctoral Diploma Programmes in Reliability Engineering, from October 2004.

4. Physical meanings of mathematical reality of reliability

> *"For whosoever has fix'd on his Cause, before he has experimented; can hardly avoid fitting his Experiment, and his Observations, to his own Cause, which he had before imagin'd; rather than the cause of the truth of the Experiment it self."* The History of the Royal Society [6]

Being exposed to the well established educational process where scientifically proven deterministic models are used for all engineering predictions, the author has accepted and promoted existing probabilistic model is used for the predictions of the reliability and safety performance of future systems (Eq. 3), govern by reliability functions of consisting components (Eq. 2), which is promoted by existing reliability and safety literature.

After gaining the first hand experience from the VTTI and realisation that air, as a natural physical entity essential for the flying process, was not a part of the RBD of an aircraft, the author decided to try to "understand" mathematical understandings of the physical reality of the operational reliability and safety performance of defence, aerospace and nuclear power systems. The main outcomes of this research are presented below.

4.1 Mathematical reality: Quality of components production is one hundred percent

The integral that defines a reliability of components (Eq. 2) is defined by values of time greater or equal to zero, which means that no reliability and safety relevant events can take a place before the beginning of the operation. Consequently, all theoretical probability distributions used to define component reliability must have a range $[0,\infty)$. Knezevic [2], warned reliability modellers that a normal probability distribution, which is defined between minus and plus infinity, should be used in reliability predictions only when the expected value is a minimum three times greater than the standard deviation, which means that the left tail of the distribution could be ignored, for the modelling purposes.

4.2 Mathematical Reality: Errors during system transportation, storage and installation tasks are zero percent

As a system consists of components, then the system reliability function must have the same mathematical properties as described in 4.1 for a component reliability function. Consequently, all reliability considerations of a system, as far as mathematics is concerned, start at the “birth” of systems, totally “ignoring” any physical event that could take place during the transportation, storage and installation process and impact the reliability of a system.

4.3 Mathematical reality: All components are one hundred percent independent

The fact that the contribution the reliability of components connected in series to the system reliability is equal to the product of their individual reliability is valid only if there is no interaction, whatsoever, between them. According to mathematics, individual components exist in their own rights, like they are the only one. This practically means that no failure of any component can impact the reliability performance of any other within a system.

4.4 Mathematical reality: Zero maintenance actions (inspections, repair, cleaning, etc.)

As the integrals defining failure/reliability functions (Eq. 1 and 2) of components within a system are continuous integrals within a given interval of time [0,t] exclusively related to the TTF, interruptions for inspections, testing, condition monitoring and similar maintenance actions related to any of consisting components are “non existent”, as far as mathematics is concerned. Thus, no maintenance actions are incorporated into failure or reliability functions, as both are covering the length of operational time to failure.

4.5 Mathematical reality: Continuous operation of the system and components

As expressions for reliability of any component and system are defined by the continuous random variable, namely Time To Failure, TTF, no interruptions in continuity of time are “allowed”. In other words, shifts, weekends, “Queen jubilees”, national days, religiously significant days, are totally non-existent, from the point of view of Reliability Theory.

4.6 Mathematical reality: Time counts from the “birth” of the system

As the expression for the reliability of any system has only one random variable which is the time to failure of a system, TTF_s, with a origin from $t=0$, then all of its constituting parts must refer to the same instant of time with a range [0,t] (Eq. 3).

The time to failure of all components connected in parallel is measured by the time to failure of the last component, measured from the origin of the system, irrespective of when all the other components had failed. Even further there is no option for introducing into the reliability function of a system, the beginning of the operation of the replaced components!

4.7 Mathematical reality: Fixed operational scenario (load, stress, temperature, pressure, etc.)

There are systems whose operational scenario are determined by the seasonal, daily, or even hourly changing patterns, each of which generates different stresses and loads on the systems, and consequently impact the reliability and safety. However, probability distribution functions available in mathematics to be used for modelling TTF are unable to deal with the operational variability of physical reality.

4.8 Mathematical reality: Reliability is independent of the location in space (GPS or stellar coordinates)

In all probability distributions where the TTF is used as a relevant random variable for the reliability predictions, the mathematically defined probability density function is totally divorced from the physical location of a system. Hence, a system defined by identical reliability function, will have identical reliability performance irrespective of the location of a system in the geographical or astronomical space. The reason for these is very simple; no mathematical axiom is related to physical reality, in any shape or form.

4.9 Mathematical reality: Reliability is independent of human actions

Although trains, cars, bicycles, buses, lorries and other means of transport are driven by humans no a single block in the reliability block diagram is related to them. Hence, human actions have no impact on the reliability function.

4.10 Mathematical reality: Reliability is independent of maintenance actions

Well-trained maintainers are a daily feature of the operation of any system and yet they are totally excluded from the mathematics based modelling of reliability, as there is not a single block that represents them in the reliability block diagram.

4.11 Mathematical reality: Reliability is independent of calendar time (seasons do not exist)

Mathematical models based on the reliability function are totally immune to calendar time, which reflects seasonal variabilities, as the calendar time, represented by mathematical models clearly exhibits the continuation of time, which does not differentiate where on the time axis the interval is located.

4.12 Mathematical reality: Reliability is independent of the natural environment

To the best of the author’s knowledge, not a single RBD of any reliability of an aircraft contains a block that represents air, which for a start is a fundamental element of the flying process. Also, air is the fundamental physical medium through which an aircraft comes into contact with birds, ice, rain, lightening, wind and many other well know atmospheric phenomena that have a significant impact on its reliability and safety.

4.13 Concluding remarks regarding mathematical reality of reliability function

> "*Mathematics does not teach us how to think correctly.*" Josephine Pasternak[32]

All of the above factual "discoveries", by the author, are not weaknesses of the probability theory, at all. They are just clarified mathematical views of the physical reality of the reliability of functionable systems. According to the axioms of probability[33] any probability distribution, defined by the probability density function whose area under curve is equal to 1, is perfectly suitable to be used in the expression for failure and reliability functions, defined by Eq. 1 and 2, as far as mathematics is concerned. Mathematics has neither intention nor ability to decide what is a physical reality of human created and managed systems. The above-deduced "reality" of the reliability measures of systems is just a clear statement of the mathematical truth that says, "In my reality my predictions are correct."

From the point of view of the probability theory any repeated experiment that provides different outcomes under identical conditions is a probabilistic experiment, irrespective of which mechanisms generate that behaviour. Hence, the probability theory is a mathematical concept that is totally unconcerned with the physical causes and mechanisms that generate failure events in the life of human created and operated systems. At the same time it is the only body of knowledge that enables predictions of the occurrences of failure events throughout the life of systems used daily by humans to be made.

5. Physical reality of reliability

Scientific truth is fundamentally different from mathematical truth. Although there are axioms in the scientific theory, but unlike mathematical axioms, they are related to the universe in which we exist and its laws. The definition of scientific truth is based on the physical experiment, which is defined by Dubi [4] as, "A statement is true if and only if it can be verified in an objective scientific experiment." For example, one of the fundamental axioms is the axiom of causality, which states that, "In our universe the cause always precedes the result". This axiom exists and is believed to be true only because no one has ever demonstrated in an experiment that it does not hold. Although, according to Dubi [4], many scientists are still designing experiments at the atomic and sub atomic scale to challenge causality. Should any of these experiments succeed, a major change will take place in what is known today to be "truth". Hence, unlike mathematical truth, scientific truth can change through time as new experiments and observations are made.

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[32] Pasternak, J., Indefinability, An Essay on the Philosophy of Cognition, Page 118, edited by Arne F. Petersen, pp. 144, Published by Museum Tusculanum Press, University of Copenhagen, Denmark, 1993. ISBN 10: 877289531

[33] Kolmogorov, A.N., Foundations of the Theory of Probability, Chelsea Publishing Company, USA, 1950.

To understand the physical reality of the in-service reliability of defence, aerospace and nuclear power industries the author has systematically studied the reliability performance of their in-service "experiments". Hence, in the remaining part of the text: types, causes and mechanisms of failures analysed are presented against the titles used earlier in the text to examine the mathematical reality of a reliability function.

5.1 Physical reality: Quality of produced components and assemblies is less than 100 percent

5.1.1 A400M crashed by incorrectly installed engine software[34]

On 29 May 2015 the Airbus Group revealed that incorrectly installed engine control software had caused the fatal crash of an A400M airlifter in Spain. The incorrect installation took place during the final assembly of the aircraft, which led to engine failure and the resulting crash. The conclusion was based on the data extracted from the flight data recorder, which confirmed the Airbus engineer's internal hypothesis that there had been no problem with the aircraft. France has continued flying its fleet of six aircraft, while Germany, Malaysia, Turkey and the U.K. paused flight operations.

5.1.2 Quality control issue halted F-35 deliveries to us government[35]

On 11 December 2019 the Pentagon (US Government) temporarily suspended deliveries of the F-35 Joint Strike Fighter for 15 days because the Defence Contract Management Agency (DCMA) discovered "instances" of co-mingling of titanium and Inconel fasteners. Lockheed Martin and the U.S. government conducted engineering analyses and determined those aircraft were safe to fly and the Pentagon began accepting aircraft. The Pentagon does not have any indication this was a systemic problem, as DCMA representatives are on the production floor working alongside Lockheed Martin personnel. This is not the first time a quality control issue stopped F-35 deliveries. Corrosion was identified in several fastener holes under the fuselage panels of a F-35A conventional-takeoff-and-landing aircraft that was in maintenance at Hill Air Force Base in Utah, USA. Other previous problems included faulty insulation that disintegrated into the fifth-generation fighter's fuel tank and an engine-rubbing problem that increased the likelihood of fire.

5.1.3 Japanese rocket start-up blow up after 2 seconds[36]

On 30 June 2018 Japanese start-up Interstellar Technologies' Momo-2 lost thrust 8 sec after lift off, reaching a maximum altitude of about 20 m before falling back to Earth about 5 m from the launch pad. The rocket burned for about 2 hours after the impact, until the fire eventually extinguished itself. The flame was seen squirting from the top of the engine, immediately after lift off. The crash set the booster and ground equipment on fire, and some parts were scattered beyond the concrete launch pad, but no one was injured. Video of the launch shows a small flame emerging from the top of the engine barely 2 sec after the vehicle leaves its support stand. The Momo-2 was out of sight when the rocket is heard losing thrust. Then the vehicle falls vertically back to Earth, motor still burning, and explodes in a fireball on impact. This is Japan's first

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[34] MIRCE Akademy Archive- MIRCE Functionability Event 20150529

[35] MIRCE Akademy Archive- MIRCE Functionability Event 20191211

[36] MIRCE Akademy Archive- MIRCE Functionability Event 20180730

privately developed launch vehicle, with a length of 9.6 m and takeoff weight of 1,000 kg. Momo is fuelled with pressure-fed ethanol and liquid oxygen. The single-stage rocket is designed to carry a 20-kg payload to 120 km and provide 260 sec of micro gravity flight.

5.1.4 After in-flight diversion Boeing 777 production-line wiring inspections[37]

Chafing and arcing of incorrectly installed wire bundles caused an in-flight diversion of a Boeing 777, in October 2017, during a flight from Abu Dhabi to Sydney. As the aircraft neared Adelaide, the flight crew "noticed a burning smell coming from an air vent." The issue soon triggered on-board warnings of a forward cargo fire. The crew performed its "non-normal" checklist, discharged forward-cargo fire bottles, and declared an emergency. The aircraft, carrying 349 passengers and 16 crewmembers, arrived "uneventfully" at Adelaide Airport about 50 min after the incident began. The aircraft involved was delivered in November 2013 and had 21,493 hours and 2,284 cycles at the time of the incident. A post-incident inspection found soot damage on the forward cargo compartment ceiling. A more detailed investigation traced the soot's source to heat damage and a chafed electrical wire in a bundle running between the cargo compartment ceiling and the cabin floor above. Boeing determined the entire wiring loom that contained the chafed wire, which powered a re-circulation fan, was "incorrectly routed, likely during aircraft manufacture, and had not been installed as per the design drawings." Four years in service caused the miss-routed wire bundle to chafe on a nearby screw. This sent a current "through the passenger floor carbon-fibre beam" at body station 508. The current generated enough heat to damage 14 ceiling brackets, and cause "several areas" of the beam to chafe and delaminate. Late last year, Boeing added a production-line inspection and issued recommendations to operators following an Etihad Airways Boeing 777-300 in-flight diversion caused by chafing and arcing of incorrectly installed wire bundles, which was the fifth incident linked to the faulty production process.

5.1.5 Design errors

Most designed induced errors end up with partial or gradual corrections and changes through modifications and upgrades. However, in certain cases even the whole production run has to be made. The “top-ten” recalls in auto industry are briefly described below:

- 1971 General Motors: After sudden acceleration problems caused by engine motor mounts, GM had to recall 7 million cars. The resolution involved putting in a restraining bolt to keep the engine in place.
- 1980 Ford: 21 million vehicles had to be recalled and it wasn’t just one model that was at fault. Unfortunately for the company, there was an issue with cars shifting out of parking mode and running away down the road. Ford responded to the problem by trying to issue each owner with a special warning sticker before they were eventually convinced to recall and repair.
- 1981 General Motors: 5.8 million cars were recalled in the early 80s because of a rear suspension bolt issue. The vehicles included all intermediate models that

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[37] MIRCE Akademy Archive- MIRCE Functionability Event 20171000

had been produced since 1978. The problem was highlighted after reports of accidents began to come through.
- Ford: 7.9 million cars were recalled in the mid 1990s and were down to the ignition switch that again caused fires in a number of vehicles.
- Ford: 15 million vehicles were recalled because of a potentially faulty cruise control switch that had caught fire in some cars.
- Toyota: 9 million cars were recalled in 2009/10 because of a sudden acceleration issue resulting from a faulty accelerator pedals. The case was complicated because the company initially misdiagnosed the problem so a second recall had to be rolled out after a small number of cars crashed.
- 2012 Toyota: 7.4 million cars taken back in because of faulty electric windows. Not a major, life threatening issue but it cost the company a substantial amount, although the final figure was never revealed.
- 2014 General Motors: 5.8 million cars were recalled in 2014 and it was down to an ignition switch issue, which had a tendency to cut off the engine while driving, and prevented the airbag from inflating in some cars. It’s estimated that the total recall cost the company just over $4 billion.
- 2014, Honda: had to recall 5.4 million cars because of an airbag issue relating to about 20 different models. The fact that the bags were not inflating properly made them potentially dangerous in the event of an accident.
- 2016: Volkswagen: 8.5 million vehicles needed to be recalled. This was down to software installed that gave false results on emissions, something that is against European Union rules. It’s expected to cost the company more than £12 billion to put right.

5.2 Physical reality: Transportation, storage and installation tasks are not 100 percent error free

5.2.1 SpaceX explosion at launch pad[38]

On 1 September 2016 an explosion destroyed a Falcon 9 and its payload, at launch pad. This vehicle was scheduled to launch the Amos-6 communications satellite on 3rd September. SpaceX indicated that the anomaly occurred around the upper stage oxygen tank during propellant loading for the static fire test. The explosion triggered a blast wave that was reported up to 30 mi away, and was followed about 2 min later by further explosions that appear to have originated around the base of the strong back launch support structure.

5.2.2 Leonardo calls for AW169 and AW189 tail rotor inspections[39]

On 7 November 2018 operators of the Leonardo AW169 twin-engine medium helicopter received safety directives requiring them to check correct installation of the tail rotor (TR) servo-actuator, following a crash that killed five people on the 27 October 2018. According to the UK Civil Aviation Authority the aircraft that crashed, G-VSKP, was registered new in July 2016, and it had flown less than 300 hr up to the end of last June. The helicopter was transporting 5 people including the pilot and crashed just moments after takeoff from the Leicester club’s King Power Stadium

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[38] MIRCE Akademy Archive- MIRCE Functionability Event 20160901

[39] MIRCE Akademy Archive- MIRCE Functionability Event 20181107

following a football match. TV footage shows the aircraft turning around after takeoff, climbing out of the stadium and drifting backward as per common procedure in case of engine failure to return to land. Once well above the stadium, the aircraft appeared to suddenly go out of control, spinning rapidly toward the ground before crashing into a nearby parking lot.

The inspections also applied to the company's AW189 super-medium helicopter, as they feature a similar design to that of the AW169. The directive, published by the European Aviation Safety Agency (EASA) says, "The incorrect installation of the TR servo-actuator, if not detected and corrected, depending on the flight condition, could possibly result in loss of control of the helicopter. Checks should be carried out within five flight hours or 24 hr of the directive being issued and requested that all inspection results should be reported back to the manufacturer."

5.3 Physical reality: There are interactions between "independent" components

5.3.1 Power plant's inlet cowl detached in midair of Boeing 737-700[40]

On 27 August 2016, during the flight of a Southwest Airlines B737-700, on the left CFM56-7B engine inlet cowl detached in midair, causing the engine to be shut down as well as significantly damaging the airframe. The flight was enroute from New Orleans to Orlando, Florida and landed to Pensacola, Florida, showing that the fan and centrally located spinner intact after the cowl separated. There was no apparent indication that the cowl loss was associated with either a fan-blade failure or the release of a blade. Passengers reported a loud noise accompanied the event, which occurred around 13 min after takeoff at around 31,000 ft over the Gulf of Mexico. The cowl is normally attached to the fan case by bolts and two alignment points located at the 3 and 9 o'clock positions around the inlet. Damage visible to the airframe included significant buckling of the leading-edge wing root fairing, indicative of a heavy impact from part of the inlet assembly, as well as a puncture of the fuselage skin below the window belt above the leading edge. This latter damage was likely the main cause of the cabin depressurisation that occurred on separation of the inlet.

5.3.2 Oil system flaw caused PW1524g engine uncontained failure[41]

In May 2014, the uncontained failure of the Pratt & Whitney PW1524G engine, on Bombardier's C Series CS100 prototype, was triggered by the failure of a Teflon seal in the oil system, according to a Transport Safety Board of Canada report. The failure of the low pressure (LP) turbine, which occurred during engine ground runs, followed heat soaking of the oil feed tube to the No. 4 bearing at the back of the engine. The heat specifically impacted the integrity of the feed tube's Teflon C-seal after a series of engine "hot shutdowns". The damaged seal allowed engine oil to merge with the turbine rotor's cooling air stream, leading to ignition of the resulting air-oil mixture in the cavity around the base of the first stage of the three-stage LP turbine. "The ensuing combustion heated the low-pressure turbine rotor to the point of failure," says the report, which adds the resulting disintegration of the rotor "was uncontained, and resulted in major damage to the engine, nacelle and wing." Consequently, engine debris

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[40] MIRCE Akademy Archive- MIRCE Functionability Event 20160827

[41] MIRCE Akademy Archive- MIRCE Functionability Event 20140500

damaged the wing's lower surface, wing-to-fuselage fairing, leading-edge slats and flap fairings, as well as the landing-gear door panels and strut. The system "functioned as designed" to prevent a far more serious fuel fire, despite a 38-inch, hot section of the LP turbine rotor disk penetrating the centre fuel tank and wedging in the upper wing skin. At the time of the event, the centre tank was almost half-full with 12,200 lb. of fuel. Following the incident, interim measures were introduced to enable flight tests to resume, including a revised cool-down procedure with an increased pre-shutdown cooling period of 20 min. It also added a metallic face seal, in addition to the Teflon C-seal, on the No. 4 bearing oil-feed tube mounting flange, and changed the material of the mounting bolts of the flange to enable higher torque on the bolts. Thermocouples were also added to permit real-time monitoring of the LP turbine cavity temperature, while limiting the oil-seal temperature to 500°F. Also, daily post flight oil-consumption monitoring and increased daily borescope inspections were instituted. For the production-standard PW1500G, Pratt changed the design of the oil-supply tube and cooling-airflow areas to physically separate the turbine-rotor-cooling airflow from the bearing compartment, to prevent any chance of a repeat occurrence.

5.3.3 Faulty equipment partly due to crash of AirAsia flight QZ850[42]

The Airbus A320-200, flown by Indonesia AirAsia, on flight QZ8501 crashed on 28 December 2014 killing all 162 people on board. According to the report, issued by Indonesian National Transportation Safety Committee (NTSC), a fault in the connecting circuitry of the aircraft's rudder travel limiter (RTL) sent repeated operational warnings to the cockpit, which led the flight crew to attempt a reset of the system. This, in turn, led the aircrew to accidentally disengage the flight augmentation computer (FAC or autopilot) system, followed by what the NTSC report described as "an inability of the flight crew to control the aircraft". Also, report detailed that four repeated RTL warnings during the first hour of the flight had likely led the aircrew to disengage system circuit breakers in an attempt to reset the RTL, but this also disengaged the FAC, leading to an uncontrolled stall into the sea as the aircraft "departed from the normal flight envelope". The actual cause of the crash was found to be a "prolonged stall condition that was beyond the capability of the crew to recover", which resulted in the aircraft impacting the Java Sea. The report also revealed that RTL had suffered 23 reported malfunctions over the previous year, according to this aircraft maintenance records.

5.3.4 Ethiopian B787 fire due to runaway in the lithium-metal batteries[43]

On 12 July 2013 a parked Ethiopian Airlines Boeing 787-8 at London Heathrow Airport caught fire. Aircraft Accident Investigation Board (AAIB) classed it as a "serious incident," in which the fire badly damaged the crown of the fuselage just forward of the tail fin. Report states, "The fire was initiated by the uncontrolled release of stored energy from the lithium-metal battery in the aircraft's Emergency Location Transmitter (ELT). The fire was most likely triggered by an external short-circuit, created by the battery wires having being crossed and trapped under the Honeywell ELT battery compartment cover plate when the ELT battery was last accessed. This "probably created a potential short-circuit current path, which could allow a rapid discharge of the battery. Root Cause testing performed by the aircraft and ELT

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[42] MIRCE Akademy Archive- MIRCE Functionability Event 20141228
[43] MIRCE Akademy Archive- MIRCE Functionability Event 20130712

manufacturers supported this latent fault as the most likely cause of the ELT battery fire, most probably in combination with the early depletion of a single cell." According to AAIB, “Neither the cell-level nor battery-level safety features were able to prevent this single-cell failure, which then propagated to adjacent cells, resulting in a cascading thermal runaway, rupture of the cells and consequent release of smoke, fire and flammable electrolyte. The trapped battery wires in turn compromised the environmental seal between the battery cover-plate and the ELT, providing a path for flames and battery decomposition products to escape”. The flames “directly impinged on the composite aircraft structure, which led to resin in the composite material of the fuselage crown decomposing, providing further fuel for the fire. As a result of this, a slow-burning fire became established in the fuselage crown, which continued to propagate from the ELT location … even after the energy from the battery thermal runaway was exhausted.” It noted that the location of the ELT in the fuselage crown made it difficult for fire fighters to locate the fire. In the event of an in-flight fire from this source, AAIB noted, it would be “challenging” for cabin crew to locate and fight the flames.

5.3.5 Smoke and fumes event involving Boeing 787[44]

On 17 April 2016, a B787-9, (N36962) operated by United Airlines as flight UAL870, departed Sydney for San Francisco, USA. As a part of scheduled meal service cabin crew switched on the aft galley ovens. After the second oven was switched on, there was a short burst of smoke, which set off a fire alarm in a nearby toilet for about one minute. One of the ovens displayed a “FAILURE” message. Several cabin crews detected a strong chemical odour and an electrical smell, as well as a blue haze. The crew immediately pulled all relevant circuit breakers, and switched off all electrical sources to the aft galley. By the time that the in-flight service manager (ISM), together with a relief pilot from the cockpit arrived at the aft galley with fire extinguishers, the smoke had dissipated, but the odour persisted. As it could not be confidently ascertained that the ovens were the sole source of the problem, the captain contacted the ground-based technical operations maintenance controller (TOMC) by satellite phone. It was agreed that the safest option was to return the aircraft to Sydney. As the aircraft was well in excess of its allowed landing weight, fuel was dumped during the descent. The aircraft landed without incident in Sydney with emergency services in attendance. A post-engineering inspection quarantined the suspect oven, and after an inspection, a fuse was replaced. After appropriate testing, the aircraft was released back to service. The manufacturer individually tested all oven components and reported that all individual components worked correctly. However, an additional measurement of the oven motor current detected that the motor did not run smoothly, and its temperature was also above normal, most likely from insufficient airflow. The exact cause of the odour could not be determined.

5.3.6 Pilots unaware of B737 MAX’s automatic stall prevention system[45]

On 10 November 2018 Boeing issued a multi-operator message (MOM) explaining the MAX’s manoeuvring characteristics augmentation system (MCAS) “commands nose-down stabilizer” in certain flight profiles using “input data and other airplane systems.”

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[44] MIRCE Akademy Archive- MIRCE Functionability Event 20160417

[45] MIRCE Akademy Archive- MIRCE Functionability Event 20181010

MCAS is operated by the flight control computer and "activated without pilot input and only operates in manual, flaps-up flight." MCAS was not part of previous designs of 737, Boeing's MOM confirms. The system also was not covered in MAX flight crew operations manual (FCOM) or difference training for 737NG pilots. Most likely this is linked to the ongoing investigation into the fatal crash on 29 October 2018 of a Lion Air Boeing 737 MAX 8, killing all 189 onboard. Aviation Week has reviewed the 737 MAX-family flight crew operations manual for another large MAX-family operator. It does not reference MCAS. A multi-page document issued by the airline's flight operations department that highlights the differences between the MAX and 737 NG does not mention MCAS or any other changes to the auto-trim system.

5.4 Physical reality: Maintenance activities like: inspections, repair, cleaning, etc., have significant impact on the reliability of a system

5.4.1 In-service cracks trigger Airbus A380 wing-spar inspections[46]

After reports of cracks on in-service Airbus A380 wing outer rear spars (ORS) Airbus and EASA are developing an inspection program for it. The program, revealed in a proposed EASA airworthiness directive (AD) published on 5 July 2017, targets "the 25 oldest wing sets" in the A380 in-service fleet. Affected operators are to conduct initial "special detailed inspections" on a schedule based on the aircraft's age. Follow-up checks should be done every 36 months. The initial inspection results would be evaluated by Airbus and EASA and, "based on inspection findings," may expand the program to other A380s, the proposed AD explained. Out of the 25 aircraft listed for initial inspections Emirates Airline has 9, followed by Qantas 6, including the aircraft that suffered substantial damage during a November 2010 engine failure and was out of service for nearly 18 months. Singapore Airlines has 4, while 2 aircraft once operated by Singapore are in storage with Afa Press UK Ltd. as the listed owner. The remaining airframes are with Air France (2), Lufthansa, and Portuguese charter carrier Hi Fly. The initial program is in response to "occurrences" of ORS cracks on in-service aircraft, EASA explained, but the AD does not say how many aircraft have turned up with cracks.

5.4.2 ANA grounded Boeing 787 for Rolls Royce engines inspections[47]

On the 28th August 2016 All Nippon Airways (ANA) had six of its Boeing 787s out of action as it continues inspections due to concerns about turbine blade erosion in the fleet's Rolls-Royce Trent 1000 engines. The airline intends to progressively inspect its B787 engines and replace turbine blades. The six aircraft currently grounded are part of this process, which has caused the carrier to cancel several domestic flights. So far ANA has replaced turbine blades on 17 engines, out of the total of 100 engines on its 50 787-8s and -9s. The carrier says it has "identified that multiple engines need to be serviced".

5.4.3 Chemical residue causes in-flight shutdown to A380[48]

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[46] MIRCE Akademy Archive- MIRCE Functionability Event 20170705
[47] MIRCE Akademy Archive- MIRCE Functionability Event 20160828
[48] MIRCE Akademy Archive- MIRCE Functionability Event 20170500

In May 2017, an Airbus A380 operated by Qantas Airways departed Los Angeles destined for Melbourne. The crew turned back 2 hr into the flight after hearing a loud bang followed by an unusual vibration and what turned out to be a false fire warning. After an uneventful landing, the initial inspection found no breach of the No. 4 engine casing and minor damage to the right flap due to exiting debris. A subsequent analysis found fatigue cracking due to internally corroded low-pressure turbine blades, which had resulted in blade debris and downstream damage through the engine. The corrosion was attributed to a chemical residue in the hollow blades left after a July 2015 cleaning operation. In response to the occurrence, the manufacturer modified its blade-cleaning instructions to include best practices for the removal of process solutions and chemical residues. The revised procedures, which include flushing of aerofoil cavities and modifying the orientation and support of the blades while cleaning, were adopted at all applicable Trent 900 Stage 2 low-pressure turbine blade maintenance facilities. An internal manufacture safety alert also was distributed to raise awareness of the issue and its potential impact on other engine types.

5.5 Physical reality: Neither all systems nor all components operate continuously

5.5.1 Airbus A320 was flying with a failed actuator on minimum equipment list[49]

On 22 March 2014 at 18:28:32, Airbus A320-232 aircraft (G-EUUE), took off from London Heathrow International Airport to perform the Flight BA870 for the British Airways airline. The take off as well as the flight was in order until 19:24:32 (the aircraft was cruising at an altitude of FL370 and speed of 250 knots at that time), when the crew received “Right Aileron Fault & Elevator Aileron Computer (ELAC1) fault” messages. This caused the right aileron to be locked into a position 8.8 deg. up from neutral, later moving as high as 15.9 deg. of the maximum 25 deg. of motion. Despite this, the aircraft remained in normal control mode with the autopilot engaged, and the captain was able to perform a normal landing at Liszt Ferenc International Airport in Budapest, Hungary, at 20:35. A day before the incident, mechanics had deactivated the aircraft’s blue hydraulics system connected to one of the two servo controls for the right aileron. This occurred after a string of three failure notifications during flights on March 19 and March 21, which pertained to ELAC2 and its related servo controls. Based on the approved minimum equipment list, British Airways had 10 days to fix the problem. Meanwhile, the right aileron could only be commanded by ELAC1 and one hydraulic system. Mechanics later replaced the captain’s sidestick, which was considered to be the root cause of the problem, as well as ELAC1. However, the Transportation Safety Bureau of Hungary (TSB) said, “As no faults could be found with either component during post incident testing, one or both could have been responsible.”

5.6 Physical reality: Components and a system have different “times”

5.6.1 ANA to replace turbine blades on RR Trent 1000 engines on B787 fleet[50]

After identifying problems related to corrosion and cracking, on 1 September 2016, the Japanese airline group All Nippon Airways (ANA) confirmed that turbine blades on the

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[49] MIRCE Akademy Archive- MIRCE Functionability Event 20140322

[50] MIRCE Akademy Archive- MIRCE Functionability Event 20160901

Rolls-Royce Trent 1000 engines powering its fleet of B787 aircraft will be replaced. It is expected that the process of fitting all of their 50 aircraft of this type with engines equipped with new blades could take up to three years to complete. Although only five of the engines are in need of repairs at present, the company decided to repair the entire fleet of 100 Trent 1000s as a safety measure. All of this was started by three engine failures in 2016 related to the blades, resulting in 18 domestic flights being cancelled by ANA last week due to engine issues. As result of this decisions made by ANA, the Air New Zealand, which is another carrier operating Trent 1000-powered 787s, said it has put "proactive systems" in place across its fleet of seven of the aircraft to any potential monitor turbine problems.

5.6.2 International space station electrical issue delays SpaceX launch[51]

The planned 1 May 2019 launch of a SpaceX cargo ship to the International Space Station (ISS) has been delayed due to a problem with the station's electrical system. The problem, that posed no immediate concerns to the station or its six-member crew, involved a Main Bus Switching Unit (MBSU), which distributes electrical power to two of the station's eight channels. Electrical power generated by the station's solar arrays is fed to all station systems through these power channels. One of these units has failed in a manner that cannot be recovered, so it effectively lost one-quarter of the power to the space station. It is possible to move loads around and keep payloads operating, but to lose of redundancy. Among the systems lacking backup power were the station's robot arm and mobile base, which is needed to capture SpaceX's Dragon cargo ship and berth it to the docking port. Launch has been tentatively rescheduled for 3 May, pending a successful robotic change-out of the failed MBSU, on the May 2. In the past the ISS had two failures of this particular box, one of which was repaired on orbit. This one looks like it's probably not repairable on orbit as it is lifetime issue.

5.7 Physical reality: Variable operation scenarios (load, stress, temperature, pressure, etc.)

5.7.1 Aeroflot Superjet 100 (RA-89098) crashed in Moscow[52]

On 5 May 2019 a Superjet 100 airplane, operated by Aeroflot on the flight SU1492, took off from Moscow Sheremetyevo airport (SVO/UUEE) runway 24C at 18:04L (15:04Z). The crew stopped the climb at about FL100 and declared initially loss of radio communication. Later the crew declared an emergency via transponder codes and returned to Sheremetyevo for an emergency landing. According to radar tracks, the first approach was discontinued, the airplane made a 360° turn and approached Sheremetyevo runway for landing on Runway 24C. Weather at the time of landing was not a factor for the landing, although not confirmed information said that a lightning strike might be involved in the accident. According to CCTV cameras, the airplane bounced on the runway during landing and when it hit the runway again, caught fire. During the deceleration, the Superjet 100 burst into flames, veered to the left off the runway and came to a stop on the grass adjacent to the runway, after making a 180° turn. While the aircraft burned down, an evacuation started from the L1 and R1 doors via emergency slides, but 41 people are confirmed dead, including 2 children.

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[51] MIRCE Akademy Archive- MIRCE Functionability Event 20190501

[52] MIRCE Akademy Archive- MIRCE Functionability Event 20190505

5.7.2 Hard landing of Wings Air ATR 72-600 in Indonesia[53]

On the night of 25 December 2016 at the Achmad Yani International Airport in Semarang, Indonesia, a hard landing accident of a Wings Air ATR 72-600 took place. Flight 1896 from Bandung, Indonesia, with 68 passengers and four crew members on board, was attempting to land after an instrument approach to Runway 13 in light rain and relatively light winds. The aircraft touched down hard and bounced, with a second touchdown also resulting in a bounce. Despite an attempted go-around by the captain after the second bounce, the aircraft touched down hard again, collapsing the right-side main landing gear, and breaking about 10 in. off of each blade of the six-bladed propeller, as the aircraft swerved off the right side of the runway. Air traffic controllers, noticed that the aircraft was “tilted to the right” during the landing roll, and called out rescue and fire fighting services. However, those crews could not approach the aircraft, because the pilots had not shut down the engines. “While waiting for the assistance, the pilot kept the engines running to provide the lighting system on in the cabin,” the airline said, adding that the tower then radioed the pilots to shut down. Passengers evacuated approximately 10 min after the aircraft stopped. Wings Air’s standard operating procedures for an emergency evacuation on the ground called for the pilots to shut down the engines after notifying air traffic control, and to turn on cabin lighting (which would be powered by the battery).

5.7.3 Gear retracted landing of Emirates B777 at Dubai[54]

On 3rd August 2016 an Emirates Airlines Boeing 777-300, on flight EK-521 from India, with 282 passengers and 18 crew, was on the final approach to Dubai's runway 12L when an attempt to go around was made after the first ground contact. However, the aircraft did not climb, but after retracting the gear touched down on the runway and the right wing caught fire and the right hand engine separated from the aircraft that burst into flames. All occupants evacuated via slides, 13 passengers received minor injuries (10 were taken to hospitals and 3 treated at the airport). The aircraft burned down completely. A fire fighter attending to the aircraft lost his life. The airline reported that both captain and first officer had accumulated more than 7000 flying hours. The aircraft involved was equipped with Trent 800 engines and had been delivered to the airline in March 2003.

5.7.4 Weather scrubs SpaceShipTwo glide flight test[55]

On 2nd November 2016, Virgin Galactic called off the first planned glide flight test of its second SpaceShipTwo sub orbital spacecraft because of high winds in the skies above its California test site. The plan was to release the spaceplane from its WhiteKnightTwo carrier aircraft during a flight from the Mojave Air and Space Port in California. The flight should have been the first in a series to test the flying characteristics of the vehicle before beginning powered test flights with SpaceShipTwo’s hybrid rocket motor. The tests would examine how it glided in varying conditions, such as whether or not it is carrying a full load of payload and propellant. This testing was designed to demonstrate how aircraft would perform as it

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[53] MIRCE Akademy Archive- MIRCE Functionability Event 20161225

[54] MIRCE Akademy Archive- MIRCE Functionability Event 20160803

[55] MIRCE Akademy Archive- MIRCE Functionability Event 20161002

returns from space, after the feather system is retracted and the vehicle becomes a glider and lands on the runway like an airplane.

5.7.5 Airbus A319 safely landed after windscreen burst[56]

On the 5 May 2018 a Sichuan Airlines A319-100, en route from Chongqing to Lhasa, in China, experienced a windscreen burst in the cockpit and diverted to Chengdu, where it landed safely. The crew noticed that a crack had appeared in the inner right windscreen. At that time, the electronic centralised aircraft monitor (ECAM) issued an ice warning for the right windscreen. The crew immediately requested permission to descend and return. The windscreen blow out began with a crack appearing while the aircraft was flying at 32,000 ft at Mach 0.74. When the window burst, the pilot near the broken window was slightly injured. A cabin attendant was slightly hurt during the descent, according to the Civil Aviation Administration of China (CAAC), which has strong qualifications for flight crews operating services to high-altitude locations such as Tibet. The crew, handling the situation according to procedures, immediately descended reduced speed and donned oxygen masks. Radio contact was impossible, because of noise, so the crew adjusted the transponder to 7700 (the emergency code). At the same time, oxygen masks deployed in the cabin and cabin attendants made announcements and handled the situation. After a check for an overweight landing, the aircraft landed safely. The aircraft entered service on 26 July 2011 and had flown 19,912.25 hr and 12,920 cycles. The most recent maintenance A check was done on 4 April 2018 and most recent C check on 9 March 2017.

5.8 Physical reality: Reliability is dependent on the location in space defined by GPS co-ordinates

5.8.1 Cold weather operations[57]

On the first trip through Anchorage, a pilot learned the value of proper equipment when operating in extreme temperature conditions. He arrived at midnight on 12 May 2018, in the middle of a snowstorm, and basically just drained the water, closed the plane up and went to the hotel. At 10 a.m., two days later, it was time to leave and the plane looked like a white popsicle under about 3 in. of snow. Usually the temperatures in Anchorage are relatively mild compared to other locations in Alaska. That day the temperature was -9°F. After de-icing the aircraft and going through all the pre-flight checks he made the cabin ready for departure. All was set and when the passengers showed, he loaded, closed, started and taxied in a crystal clear, but frigid, day. After takeoff and at an altitude of about 100 ft, when he went to trim, the switch failed to move the trim at all. Reaching for the manual wheel revealed that it was completely frozen. He circled the field to get the landing weight down and kept the speed at that which was comfortable for the takeoff trim that was set. Landing was uneventful. Back at the ramp, he offloaded the passengers and a huge "Herman Nelson" heat generator was brought over, started, and the exhaust hose placed upward in the rear compartment. It actually took about half an hour for the trim to break free. It was a relatively easy fix, as the correct equipment was available. In other locations when warmth is needed in

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[56] MIRCE Akademy Archive- MIRCE Functionability Event 20180505

[57] MIRCE Akademy Archive- MIRCE Functionability Event 20180512

frigid conditions, the only solution is, “ to put the plane in a hangar and wait . . . for a long time, really long time!”

5.8.2 GPS sensors data for forecasting dangerous solar storms[58]

Fully aware that today’s worldwide web of power and data links are vulnerable to extreme space-weather events, the U.S. milspace-sensor network was designed to help the Air Force to examine the effects that space weather may have on spacecraft operations. The U.S. government released their environmental information, collected with national-security spacecraft, on 22 February 2017. The released GPS historical dataset is likely to be of value to scientists studying how Earth’s magnetic field interacts with the solar wind and to engineers developing radiation-hardened avionics to extend the total ionising dose spacecraft can withstand over a service life of 15 years or more. The radiation sensors on the nation’s GPS satellites, which operate in mid Earth orbit where radiation trapped by the planet’s magnetic field, the Van Allen belts, is most intense. The charged particles there can cause havoc with the micro-circuitry that makes spacecraft computers and other avionics operate. The sensors measure and record the energy and intensity of electrons, protons and other charged particles in six orbital planes about 12,600 mi above the surface. The network records 92 measurements per day. As more and more satellites are using solar-electric propulsion to place their platforms in geostationary orbit, the avionics will be spending more time in the high-radiation regions of mid Earth orbit as they progress upward. It is quite possible that the technology for refuelling and maintaining operational spacecraft will increase the demand for longer avionics service life in space. This data also may help space-weather forecasters predict much more serious Solar storms, like the Carrington Event[59] that took place in 1859 and disabled the U.S. telegraph system. Unquestionably a similar event today could be detrimental to the world’s tightly interconnected global communication and data networks.

5.8.3 SpaceX delays launch due to weather[60]

On 9 January 2017 the bad weather in California prompted SpaceX to delay its planned return to flight until 14 January, at the earliest. The company had planned to resume lift-offs after finishing its investigation into the spectacular explosion of a Falcon 9 rocket in September 2016 (the rocket and its $195 million payload were destroyed, causing heavy damage to the Launch Complex 41 at Cape Canaveral). Like much of the country, California was getting pounded that weekend by extreme weather with rain and gusty winds, according to the National Weather Service. Some areas were expected to receive 10 or more inches of rain over the weekend. The delay came two days after the Federal Aviation Administration re-authorised SpaceX's Commercial Space Transportation License, allowing it to resume launches. SpaceX launches have been suspended since the last explosion.

5.8.4 Passengers stranded after Delta flights grounded worldwide[61]

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[58] MIRCE Akademy Archive- MIRCE Functionability Event 20170222

[59] Named after the British astronomer Richard. C. Carrington who observed the coronal mass ejection that triggered it during solar cycle 10 (1855-1867)

[60] MIRCE Akademy Archive- MIRCE Functionability Event 20170109

[61] MIRCE Akademy Archive- MIRCE Functionability Event 20160808

On 8 August 2016 tens of thousands of passengers were stranded after Delta Air Lines flights were grounded around the globe due to a system outage. As for the cause of the problem, Delta pointed to an overnight power outage in its hometown of Atlanta, which "impacted the Delta computer systems and operations worldwide, resulting in flight delays". Delta said that systems were back online by 8:40 a.m. ET, but warned disruptions would continue amid a "limited" resumption of departures. By 1:30 p.m. ET, the airline had cancelled 451 out of its 6,000 daily flights. It remained to be seen how large a portion of the carrier's daily schedule would ultimately be cancelled by the end of the day.

5.9 Physical reality: Reliability is dependent on humans

5.9.1 Damage to Embraer business jet due to deviations from standard operation procedure[62]

On 22 February 2019, a chartered Belgium-registered, Embraer EMB-500 departed from Kortrijk-Wevelgem Airport (EBKT), Belgium, at 07.38 hr on an IFR flight plan to Berlin-Schonefeld Airport (EDDB) with three people on board. The aircraft was severely damaged on the final approach to Runway 07L at EDDB, when the left wing had suddenly dropped and touched the runway during the flare as the aircraft crossed the threshold. Subsequently, the airplane rolled right, the right main landing gear hit hard and collapsed, and the aircraft slid along the runway toward the right runway edge where it came to a stop 447 meters from the threshold beyond the right runway edge marking but still on the asphalt area. There was no fire. Both pilots and the passenger were uninjured, but the accident brought attention the EMB-500’s deice system and training of pilots. The causes of the accident, according to German air safety investigators, were, “The crew conducted the approach under known icing conditions and did not activate the wing and horizontal stabiliser deice system, which was contrary to the Standard Operating Procedures. The aircraft entered an abnormal flight attitude during the flare phase and crashed due to ice accretion on wings and horizontal stabilizer and infringement of the required approach speed.” A major contributing factor was the crew’s “insufficient knowledge of the connection between the ice protection system and the stall warning protection system (SWPS).”

5.9.2 Catering track damage ramifications on Qantas A380 turn back[63]

On 29 August 2018, passenger-door seal damage caused by a catering truck created an unnerving onboard noise that led a Qantas Airbus A380 to return to Sydney 2 hr into a scheduled flight to the U.S., according to the Australian Transport Safety Board (ATSB) report. The A380 conducted a routine departure from Sydney Airport on a scheduled flight to Dallas/Fort Worth International Airport. As it passed FL250, a loud noise was detected coming from a door on the upper deck. The crew determined the door was closed and locked correctly and not at risk of opening. However, “passenger discomfort” combined with “the unknown nature of the issue” convinced the flight crew to return to Sydney. The aircraft dumped fuel and landed safely. Post-flight inspection found damage to a seal retainer and seal along the underside of an upper-deck passenger door, which was caused by a catering truck that serviced the aircraft prior to the flight. The flight was rescheduled for later the same day, but flight crew

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[62] MIRCE Akademy Archive- MIRCE Functionability Event 20190222

[63] MIRCE Akademy Archive- MIRCE Functionability Event 20180829

duty-time limitations forced the airline to cancel that flight. Ramp accidents and incidents continue to be a costly problem for airlines, causing around $10-12 billion annually in aircraft damage, injuries and related costs.

5.9.3 Human error behind Air Asia diversion[64]

On 4 October 2016 while programming an AirAsia Airbus A330-300's initial co-ordinates, a captain's data-entry error, led to a myriad of navigation errors and an eventual diversion. The incident began when the captain entered incorrect co-ordinates into the Air Data and Inertial Reference System (ADIRS). The longitude was incorrectly entered as 01519.8 east (15 deg. 19.8 min E. Long.) instead of 15109.8 east (151 deg. 9.8 min E. Long.). As a result, the aircraft's systems placed it near Cape Town, South Africa, instead of at Sydney Airport's International Terminal Gate 54. The magnitude of this error adversely affected the aircraft's navigation functions, global positioning system (GPS) receivers and some electronic centralised aircraft monitoring alerts, The flight crew did not realise it had a problem until a series of warnings upon takeoff en route to Kuala Lumpur. The crew then attempted to follow the course assigned by air traffic control, including a right turn. But the aircraft, operating on autopilot and guided by the erroneous starting co-ordinates, turned left instead, crossing the departure path of a parallel runway. After nearly an hour of fruitless troubleshooting, the crew diverted to Melbourne Airport, as the weather at Sydney had deteriorated. The incident's cause was clear: The mistyped longitude triggered a series of events that led the flight crew to believe the aircraft had malfunctioning avionics. The extensive post incident troubleshooting concluded that the only problems were human erroneous data entry and missed clues that would have highlighted the problem.

5.9.4 Difficulties with fume investigations of Ryanair's Boeing 737[65]

On the 1 September. 2014, Ryanair flight crew on B737-800 reported an "electrical smell" after landing with a new auxiliary power unit (APU) activated, which was a replacement of the one that was replaced due to "hot-section distress". Maintenance crews could not find any problems with the APU, but asked flight crews to monitor the system. Between 3 - 18 September 2014 there were several separate reports of odours on the flight deck, with descriptions ranging from "slight smell" to "cheesy smell" to "seriously obnoxious smell", particularly during descents with the engines idling. Maintainers investigated the various components of the bleed-air delivery system after every incident, and ultimately replaced numerous components, including both engines and the APU. Reports from the engine overhaul facility found that: "Oil leakage may have been present, but not to an extent that it would cause significant oil smell in cabin complaints," according to the AAIU. The most likely source of the odours was oil in the air conditioning system ductwork from the faulty APU that was installed on 1 Sept. 2014. On 18 September the aircraft's captain "became aware of an unusual smell" as the aircraft descended through 20,000 ft for an approach to London Stanstead Airport. The captain and first officer, who did not notice a smell, donned oxygen masks, declared an emergency and landed at London Stanstead. After the aircraft was taken out of service following the incident, maintenance actions included performing the oil-contamination removal task. The aircraft was put back into service seven days later and

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[64] MIRCE Akademy Archive- MIRCE Functionability Event 20161004

[65] MIRCE Akademy Archive- MIRCE Functionability Event 20140918

did not experience any further odour events. Air Accident Investigation Unit (AAIU), investigators found that the most likely cause of the numerous reports was an internal oil leak in the APU. The leak, which the AAIU found was caused by a faulty bearing repair during APU maintenance, likely contaminated the ductwork in the bleed-air system primarily feeding the flight deck.

5.9.5 Ground crew "sucked" into an Air India's aircraft engine[66]

On 14 December 2015 a member of the Air India ground crew was "sucked into" an aircraft engine and killed. The technician, who worked for Air India, died when he was working on the plane that was due to fly from Mumbai to Hyderabad. The plane was "pushing back" from the gate to begin its taxiing to the runway when the accident happened.

5.9.6 Tug caused Southwest nose gear snap on B737-300[67]

On 4 August 2016 excessive speed by a tug driver caused the nose gear of a Southwest Airlines Boeing 737-300 to collapse when pushed back from the gate at the Baltimore-Washington International Airport. None of the 135 people on board were injured, but the aircraft was “substantially” damaged when the nose gear collapsed in the forward direction, damaging the gear structure, the nose gear well and the forward bulkhead. With help from an airport surveillance video it was calculated that the tug was pushing the aircraft back at approximately 7 mph, while the airline general operating manual specifies that pushback at a walking speed. According to the pilots, the aircraft bounced several times during the pushback before the gear collapsed and the nose fell. The tug driver said he had tried to slow down the pushback, having started too fast, but applying the tug brakes did not slow down the aircraft. Instead, the braking caused it to “start to rock and bounce,” he said. “As I finally got the (tug) to slow up, the plane then had too much momentum and pulled away from me and the tow bar pulled the nose gear off the plane.”

5.9.7 Smoke event involving Airbus A380[68]

On 15 May 2016 a Qantas Airways Airbus A380 (VH-OQD) was on route from Sydney, New South Wales to Dallas-Fort Worth, USA, when approximately two hours prior to the arrival, a passenger alerted the cabin crew to the presence of smoke in the cabin. The cabin crew then initiated the basic fire drill procedure. Two of the cabin crew proceeded to the source of the smoke with fire extinguishers. At the same time, the customer services manager (CSM) made an all stations emergency call on the aircraft interphone to alert the flight crew and other cabin crew to the presence of smoke. The cabin crew located the source of the smoke at seat 19F, on the upper deck. The crew removed the seat cushions and covers from the seat while the CSM turned off the power to the centre column of the seats. When the seat was further dismantled, the crew found a crushed personal electronic device (PED), containing a lithium battery, wedged tightly in the seat mechanism. By that time, the PED was no longer emitting smoke, but a strong acrid smell remained in the cabin. The crew then manoeuvred the

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[66] MIRCE Akademy Archive- MIRCE Functionability Event 20151214
[67] MIRCE Akademy Archive- MIRCE Functionability Event 20160804
[68] MIRCE Akademy Archive- MIRCE Functionability Event 20160515

seat and freed the PED and placed it in a jug of water, which was then put in a metal box and monitored for the remainder of the flight.

5.9.8 Near loss of A330 due to positioning of captain's personal camera[69]

On 4 September 2015 the report published by the Military Aviation Authority describes how the Airbus A330-200 Voyager multi-role tanker transport came close to being lost with all 198 passengers and crew on-board. The event took place during a trooping flight to Afghanistan on 9 February 2014 at 33,000 ft over the Black Sea. The captain was alone on the flight deck as the co-pilot took a break. During this time, the captain took 28 photos of the flight deck using his personal digital camera before placing it between the captain's seat armrest and the left-hand side-stick controller. One minute before the incident, the captain moved his seat forward, creating a slight physical jam between the armrest and the side-stick, which had the camera wedged between them forcing the side-stick fully forward and initiating the pitch-down command. The stick command disconnected the autopilot and sent the aircraft into a steep dive, losing 4,400 ft in 27 sec. With no co-pilot in the right-hand seat, the command could not be countermanded. The aircraft's on-board self-protection systems overrode the stick input, with pitch-down protection activated 3 sec after the pitch-down command was given, while high-speed protection was triggered 13 sec after the event started as the aircraft passed through 330 kt. With the flight control system idling the engines, it recovered the dive to level flight. Report states that the camera became free from the side-stick and armrest after 33 sec. During the action in the cockpit, passengers and crew in the cabin were thrown to the ceiling, with 24 passengers sustaining injuries during the dive, along with all seven of the cabin crew. Most of the injuries occurred as the individuals hit the ceiling and overhead fittings or were struck by loose objects. The flight was diverted to Incirlik air base in Turkey, where it landed safely. Although the event caused damage to a number of fixtures and fittings inside the cabin, there was no damage to the cockpit and no structural damage to the aircraft.

5.9.9 Confusion over power setting key factor in Emirates crash[70]

On the 3 August 2016, the Emirates Boeing 777-300 operated as Flight 521, slid down the runway, burst in flames and was completely destroyed. Twenty one passengers, one cabin crew member and one pilot suffered minor injuries, while one flight attendant was seriously injured. A fire fighter died when the centre fuel tank exploded 8 min, after the failed landing. The report, released by the General Civil Aviation Authority (GCAA) of the United Arab Emirates, says the pilots tried a go-around following a long landing, but moved the thrust levers from the idle position to full forward only 3 sec before impact on the runway. The 34-year-old captain was a pilot flying with 7,457 total flight hours and 5,128 hrs on the aircraft type. The 777-300 was configured for landing with flaps set at 30 and an approach speed of 152 kt selected, as it neared runway 12L. There was a wind shear warning in place for all runways and Dubai air traffic control cleared the flight to land with wind reported from 340 deg. at 11 kt. As the aircraft descended through 1,100 ft at 152 kt, the wind direction started to change from a headwind component of 8 kt to a tailwind. The autopilot was disconnected at 920 ft, but the autothrottle remained engaged. The tailwind component increased to 16

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[69] MIRCE Akademy Archive- MIRCE Functionability Event 20150904

[70] MIRCE Akademy Archive- MIRCE Functionability Event 20160803

kt. The pilot flying flared the aircraft at 35 ft and 159 kt, and the autothrottle transitioned to idle. During the flare and 5 sec before eventual touchdown, the wind changed back to a headwind. Wheel sensors indicated the right main landing gear touched the ground at 12:37 a.m. local time, already 1,100 meters from the threshold and at a speed of 162 kt. The left gear made contact with the runway 3 sec later, but the nose gear remained airborne. The aircraft's runway awareness advisory system warned the crew about the long landing, following which the decision to go around was made. After lift off, the flap lever was moved to the 20 position and the landing gear was selected to the up position. The aircraft was cleared by air traffic control for a straight runway heading and a climb to 4,000 ft. The 777 then climbed to a maximum of 85 ft and an indicated airspeed (IAS) of 134 kt. According to the report, the aircraft began sinking back toward the runway and the first officer called out, "Check speed." Three seconds before impact the thrust levers were moved to full forward. One second before the aircraft hit the ground, with the gear in the process of retracting, the engines started to respond. Report concluded, "The aircraft was in a rapidly changing and dynamic flight environment. The initial touchdown and transition of the aircraft from air to ground mode, followed by the lift off and the changes in the aircraft configuration in the attempted go-around, involved operational modes, logics and inhibits of a number of systems, including the autothrottle, the air/ground system the weather radar and the GPWS."

5.9.10 USAF spreads blame for fatal WC130h crash[71]

On 12 November 2018, according to the report by an Aircraft Accident Investigation Board (AAIB) less than 2 min after taking off from Savannah/Hilton Head International Airport in Georgia, the Puerto Rico Air National Guard pilot caused the WC130H aircraft to stall and crash by commanding a leftward yaw while already banking left at low speed despite the failure of the outboard engine on the left wing, killing all eight crewmembers. U.S. Air Force investigation report cited, "A pilot's mistakes, a maintenance crew's failures and an overall "culture and climate of complacency" are causal factors. The board singled out the rudder input as the primary cause of the accident since it led the WC-130 into a "skid," slowing its speed until the left wing stalled at an elevation of 900 ft above sea level. The WC-130's flight manual advises crews to avoid banking into a direction on the same side of an aircraft with an inoperative engine, as it requires an increase in velocity to stay above the minimum control speed. Although the rudder input was the primary cause, the 52-page AAIB report documented a long list of errors and deficiencies that led to the fatal crash on what should have been an uneventful flight to retire the 53-year-old aircraft in the Arizona desert. The AAIB report highlights the conditions at Muñiz Air National Guard Base in Carolina, Puerto Rico, which at the time of the crash was still recovering from the devastation of Hurricane Maria in September 2017. The report criticized the 156th Airlift Wing for a "lack of initiative or urgency to repair, replace, or fix the structural damage to several buildings from Hurricane Marina." The inadequate facilities required the wing to fly the WC-130H to another Air National Guard base in Savannah in early April to fix a faulty fuel cell. As another crew ferried the WC-130H to Savannah, the outboard engine, a Rolls-Royce T56-A-15 turboprop, on the left wing malfunctioned, with rotations per minute dropping to 96%. The report finds several mistakes made by the maintenance crew dispatched to Savannah to fix the engine problem on 24 April.

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[71] MIRCE Akademy Archive- MIRCE Functionability Event 20181112

The crew skipped the first step of the maintenance test procedure, the AAIB report says. The manual requires the crew to plug a precision tachometer into the engine to measure RPM during an engine ground test. All but one of the precision tachometers were broken. However, the only functioning device was being used by another crew elsewhere. Thus, the maintenance crew borrowed a precision tachometer from the host unit in Savannah, but it was a different model that did not fit the WC-130H’s engine without an adapter. Rather than search for an available adapter, the maintenance crew decided to skip that step of the procedure, relying on the aircraft’s less precise, built-in engine tachometer to measure the RPM, the accident report says. The T56 is designed to operate at 100%, but the crew concluded the problem was fixed after observing a tachometer reading of 99% during a second engine test on the ground, the AAIB found. In fact, an inspection of the aircraft’s data recorder showed that the engine achieved an RPM of only 96.8% during the test, indicating the problem may never have been fixed.

5.10 Physical reality: Maintenance induced failures

The National Transportation Safety Board of the USA, and Civil Aviation Authorities of the UK, published on 12 August 2002 the following maintenance induced failures and their consequences in commercial aviation, among many others, were reported:

- 25 May 2002: China Airlines B747-200 experienced a structural failure at top of climb to cruise altitude resulting in a crash into Taiwan Strait; due to use of a steel doubler which are prohibited by the structural repair manuals, while repairing previous tail strike. Toll: 225 killed.
- 24 August 2001: Air Transat A330. Improper engine repair caused by leak from cracked fuel line resulted in duel engine flameout at cruise over Atlantic. Aircraft glided 135 miles to emergency landing in Azores. No serious injuries.
- 26 April 2001: Emery Worldwide Airlines DC-8-71F. Left main landing gear would not extend for landing. Cause was failure of maintenance to install the correct hydraulic landing gear extension component and the failure of inspection to comply with post-maintenance test procedures. No injuries.
- 20 March 2001: Lufthansa A320. Cross-connected pins reversed the polarity of captain’s side stick. Post-maintenance functional checks failed to detect the crossed connection. Aircraft ended up in 21° left bank, almost hitting the ground. Co-pilot switched his side-stick to priority and recovered the aircraft. No injuries.
- 16 February 2000: Emery Worldwide Airlines DC-8-71F. Crashed attempting to return to Rancho Cordova, California. Cause was improperly installed right elevator control. Toll: 3 crew killed.
- 31 January 2000: Alaska Airlines MD-83. Crashed in Pacific Ocean near Port Hueneme due to loss of horizontal stabilizer caused by the maintainer failure to lubricate jackscrew assembly that controls pitch trim. Toll: all 88 aboard killed.
- 21 January 1998: Continental Express ATR-42. Fire in right engine during landing, due to improper overhaul of lugholes in the fuel/oil heat exchanger. No serious injuries.
- 27 September 1997: Continental Airlines B737. Separation of aileron bus cable forced the crew to return to the airport shortly after takeoff. Separation was caused by wear in the cable and inadequate inspection of it. No serious injuries.
- 18 March 1997: Continental Airlines DC-9-32. Failure of maintenance personnel to perform a proper inspection of the combustion chamber outer case,

allowing a detectable crack to grow to a length at which the case ruptured, causing uncontained failure of right engine. No injuries.

- 17 July 1996: TWA Flight 800, B747. Fuel/air explosion due to inadequate maintenance on an aging fleet and noncompliant parts. Toll: all 230 passengers and crew killed.
- 6 July 1996: Delta Air Lines MD-88. Uncontained engine failure on takeoff due to inadequate parts cleaning, drying, processing and handling. Toll: 2 passengers killed, 2 passengers seriously injured.
- 8 June 1995: ValuJet Airlines DC-9-32. Maintenance technicians failed to perform a proper inspection of the 7th stage high compression disk, allowing a detectable crack to grow to a length at which it ruptured. Toll: 1 crew seriously injured.
- 12 February 1995: British Midland B737-400. Oil pressure lost on both engines. Covers had not been replaced from borescope inspection the previous night, resulting in loss of almost all oil from both engines during flight. Diverted and landed safely. No injuries.
- 1 March 1994: Northwest Airlines B747. Narita, lower forward engine cowling dragged along runway. During maintenance, the No. 1 pylon diagonal brace primary retainer had been removed but not reinstalled. No injuries
- In August 1993: Excalibur Airways A320. Un-commanded roll in first flight after flap change. Returned to land safely at Gatwick. Lack of adequate briefing on status of spoilers (in maintenance mode) during shift change. Locked spoiler not detected during standard pilot functional checks. No injuries.
- 11 September 1991: Horizontal stabilizer on Continental Express Airlines, EMB-120 separated from fuselage during flight because maintenance personnel failed to install 47 screw fasteners. Toll: all 14 passengers and crew killed.
- 21 August 1990: Flashlight left by maintenance, on United Airlines B737, sandwiched between cargo floor and landing gear retract/extend linkage, causing the crew to make a gear up landing. Toll: No injuries.
- 22 July 1990: USAir B737. A fuel pump control failure due to improper machining. No injuries
- In June 1990: British Airways BAC1-11. Captain sucked halfway out of windscreen, which blew out under effects of cabin pressure, as 84 of 90 securing bolts were smaller than the specified diameter. Toll: 1 serious injury.
- 12 August 1985: Japan Air Lines B-747SR. Improper repair of aft pressure bulkhead led to sudden decompression in flight that damaged hydraulic systems and vertical fin. Aircraft struck Mt. Ogura. Toll: 520 passengers and crew killed; 4 surviving passengers injured.

5.11 Physical reality: Reliability is dependent on natural environment

5.11. 1 Hailstorm damaged Boeing 787 returns back to China[72]

On 29 July 2015 American Airlines' Boeing 787 was climbing out of Beijing, China, when it encountered a hailstorm that left the 3-month-old airplane somewhat beat up. Flight 88 from Beijing to Dallas/Fort Worth Airport, DFW, was about 20 min out of Beijing and climbing above 26,000 ft when it began descending. It landed back at Beijing less than 45 min after takeoff. The composite fuselage, one of the things that

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[72] MIRCE Akademy Archive- MIRCE Functionability Event 20150729

separate the Boeing 787 from most other airplanes, itself took no apparent damage from the hailstorm in Beijing. The radome, the nose cone that protects the radar and other avionics on the airplane's front tip, was hammered. It was replaced in Beijing with a spare radome that American flew over to the Beijing airport. They also covered some small punctures on the wing's underside with speed tape, a strong, thin aluminium tape. The airplane was flown to Tokyo's Narita International Airport, where maintenance personnel replaced the side windscreens on the left and right sides. Those windscreen's outer panels had cracked on their front edges and bottoms, but the inner panels were not damaged, and the integrity of the window was maintained throughout. Then, when the airplane returned to Dallas/Fort Worth, American repair facilities, the major inspections started. Thus, 44 panels were removed and shipped to American's composite shop at its Tulsa composite repair centre maintenance base for repairs and repainting. Their large autoclave enables many of them to be repaired at one time. Some curved aluminium pieces that form the wing's leading edge are also being replaced.

5.11.2 Unfavourable winds delay test flight of NASA's low-density supersonic demonstrator[73]

On 12 June 2014 NASA suspended efforts to test launch a disk shaped craft for the demonstration of technologies intended to greatly increase the payload mass that can be landed on the Martian surface, at the U. S. Navy's Pacific Missile Range Facility, due to "two weeks of uncooperative wind conditions". The announcement followed half a dozen attempts since June 3 to launch the rocket powered Supersonic Inflatable aerodynamic Decelerator from a high altitude balloon. NASA team studied wind data in the region from 2012-13 that suggested early June was favorable for the test flight. However, the weather pattern in the Northern Hemisphere changed in 2014, leading to a longer winter and unfavorable winds in the region. The test flight represents a major milestone for the $200 million, five-year initiative managed by NASA's Space Technology Mission Directorate.

5.11.3 Rat on plane forces Air India flight to return to Mumbai[74]

On 31 December 2015 an Air India aircraft flying to London was forced to return to Mumbai after passengers reported spotting a rat on board. Though the rat was not found, the pilot returned to Mumbai keeping passenger safety in mind, Air India said in a statement. A separate aircraft later flew passengers to London. The aircraft will be fumigated and checked before it is returned to service. Maintenance workers checked that the rat did not damage equipment or chew any wires and the plane was certified to be rodent-free.

5.11.4 Elevator malfunctions in MD-83's rejected takeoff[75]

On 8 March 2017 Ameristar Jet Charter pilots attempting to takeoff from Runway 23L at the Willow Run Airport in Ypsilanti, Michigan were not able to lift the nose of the aircraft at the 152-kt takeoff speed due to a jammed right elevator. Based on a preliminary report by the NTSB, flight data recorder (FDR) information showed that the pilots continued accelerating for 5 sec with no pitch change, until reaching a speed

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[73] MIRCE Akademy Archive- MIRCE Functionability Event 20140612
[74] MIRCE Akademy Archive- MIRCE Functionability Event 20151231
[75] MIRCE Akademy Archive- MIRCE Functionability Event 20170308

of 166 kt, before initiating a rejected takeoff procedure. The aircraft travelled 1,000 ft past the end of the runway, coming to rest in a field where the 109 passengers and seven crewmembers evacuated, using escape slides. One passenger received a minor injury. The NTSB said the forward right slide did not deploy correctly. A strong headwind with right crosswind component was blowing at the time of takeoff, from 260 deg. at 35 kt, gusting to 50 kt. According to investigators, a post-accident examination revealed that the cockpit controls moved normally; however, upon inspecting the elevator assembly on the tail, investigators found the right side to be jammed. The cause was a bent linkage to a control tab on the trailing edge of the right elevator, which prevented the elevator from moving to the nose-up position. The left side of the split elevator functioned normally. Data from previous flights showed both elevators operating normally. One possible cause the NTSB will investigate is whether strong winds may have damaged the elevator while the aircraft was parked after arriving March 6 in Ypsilanti. According to Weather Underground, winds were gusting to 25 kt on 6 March, to 35 kt on 7 March and to 50 kt on 8 March.

5.11.5 Lightning strikes caused power cut on National Grid in UK[76]

The National Grid in the UK suffered a power failure on 9 August 2019. The outage left 1.1 million customers without power for between 15 and 50 minutes. Problems on the railways were mainly blamed on one particular type of train, of which there were around 60 in use, reacting unexpectedly to the outage, and half of them failing to restart, requiring an engineer to attend to do so. Other "critical facilities" hit by the power cut included Ipswich hospital and Newcastle airport. National Grid is facing an investigation by Ofgem over this event. The regulator has the power to fine firms up to 10% of UK turnover. The failures knocked out Hornsea off-shore wind farm, off the Yorkshire coast, owned by the Danish company Oersted, as well as the Little Barford gas power station in Bedfordshire, owned by Germany’s electric utility company RWE, resulting in the loss of 1,378MW. That was more than the 1,000MW being kept by National Grid at that time, a level designed to cover the loss of the single biggest power generator to the grid. The preliminary report blamed an "extremely rare and unexpected" outage at two power stations caused by one lightning strike at 4.52pm that day. That resulted in a combined power loss to the network that was greater than the backup capacity held in case of emergency. The report said the system automatically turned off 5% of Britain's electricity demand to protect the other 95%, a situation that it said had not happened in over a decade. The National Grid also admitted that the government, the regulator and the media were not made aware of what had happened as quickly as they should have been "impacted by the availability of key personnel given it was 5pm on a Friday evening". The business department was not updated until 5.40pm and Ofgem at 5.50pm, nearly an hour after the initial event.

5.11.6 Plastic sandwich bag caused retirement of Williams F1 car in Melbourne[77]

Brake failures in F1 are rare, especially early in a race, but Sergey Sirotkin’s F1 debut in Australia, on 25 March 2018, was just five laps old when he ran out of brakes and rolled to a stop up the escape road at Turn 13. Understandably the Williams Team was keen to find out what had happened. The result was, “a plastic sandwich bag that went

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[76] MIRCE Akademy Archive- MIRCE Functionability Event 20190809

[77] MIRCE Akademy Archive- MIRCE Functionability Event 20180325

into the rear-right brake duct caused massive overheating, which caused massive temperature spikes destroying the brakes and total loss of the brake pedal". After the "forensics analysis" the residue of what looks like a melted plastic bag was found that completely blocked the brake duct on the right rear with all the temperatures going through the roof, eventually catching fire, and then the actual catastrophic failure. All the sensors were lost, progressively as they got burned and eventually the seal has probably gone on the calliper because there's a fluid leak and the pedal went to the floor. Closing Apostrophe missing but not sure where

5.11.7 A Burst of asteroid activities in Europe[78]

According to the European Space Agency (ESA) expected a rare convergence of asteroid-related activities in Europe. They estimated that around 10 September 2019, there would have been 878 asteroids in the 'risk list'. This ESA catalogue brought together all asteroids known of having a 'non-zero' chance of impacting Earth in the next 100 years, meaning that an impact, however unlikely, cannot be ruled out. An impact by even a small asteroid could cause serious destruction to inhabited areas. This is why the ESA, together with international partners, are taking action to search for asteroids, develop technology that could deflect them in future and collaborate at the international level to support mitigation measures. Thus, planetary defence and other experts are meeting in three locations to coordinate humanity's efforts to defend us from hazardous space rocks. Such intense levels of international scientific collaboration are driven in part by the fact that an asteroid impact could cause devastating effects on Earth. But this is also a testament to the fact that we are at a point in human history where we can do something about risky asteroids. The flurry of upcoming meetings will cover vital topics in planetary defence, including the planned, first-ever test of asteroid deflection, coordination and communication of asteroid warnings and how to ensure the most effective emergency response on the ground. With all the work being done, the planet has never been so prepared for the unlikely but very real threat of an asteroid impact.

5.11.8 Northeast Airlines cancelled 1,900 U.S. flights due to storm

On 26 January 2015 air travel to New York is being slashed as carriers scrap thousands of U.S. flights to keep planes, crew and passengers out of the path of a blizzard threatening the Northeast with as much as 2 ft of snow. New York's three airports: LaGuardia, Kennedy and New Jersey's Newark Liberty, were feeling the brunt of the schedule changes. Airlines eliminated about half of Monday's arrivals at the trio of hubs, which make up the busiest U.S. travel market, while departures were cut by more than a third. Preliminary cancellations in the face of foul weather help carriers in part by relocating aircraft to unaffected airports. That positions airlines to resume service faster once flight conditions improve.

5.11.9 Impact of bird strikes on aircraft reliability[79]

The U.S. Department of Agriculture, through an interagency agreement with the Federal Aviation Administration, compiles a database of all reported bird/wildlife

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[78] MIRCE Akademy Archive- MIRCE Functionability Event 20190900

[79] Knezevic, J., Bird Strike as a Mechanism of the Motion in MIRCE Mechanics, pp 167-173, Journal of Applied Engineering Science, No 3, Vol 12, 2014, Belgrade, Serbia,

strikes to U.S. civil aircraft and to foreign carriers experiencing strikes in the USA. Over 87,000 strike reports from over 1,650 airports have been compiled, 1990-2008.

The federal Aviation Authorities (FAA) estimates that this represents only about 20% of the strikes that have occurred. The following historical examples of strikes from 1905-1989 and examples from the database from 1990-2008 are presented to show the serious impact that strikes by birds or other wildlife can have on aircraft, and surely somehow reflected in its Reliability Function. Selected examples of the bird strikes are presented below[80]:

- 4 October 1960, a Lockheed Electra turbo-prop ingested European starlings into all four engines during takeoff from Boston Logan Airport (Massachusetts). The plane crashed into Boston Harbor, killing 62 people. Following this accident, the FAA initiated action to develop minimum bird ingestion standards for turbine-powered engines.
- 26 February 1973, at the departure from Atlanta's Peachtree-Dekalb Airport (Georgia), a Lear 24 jet struck a flock of brown-headed cowbirds attracted to a nearby trash disposal area. Engine failure resulted. The aircraft crashed, killing seven people and seriously injuring one person on the ground. This incident prompted the FAA to develop guidelines for the location of solid waste disposal facilities on or near airports.
- 12 November 1975, on departure roll from John F. Kennedy International Airport (New York), the pilot of a DC-10 aborted takeoff after ingesting gulls into one engine 12 November 1975. The plane ran off runway and caught fire as a result of engine fire and overheated brakes. The resultant fire destroyed the aircraft. All 138 people on board were evacuated safely.
- 25 July 1978, a Convair 580 departing Kalamazoo Airport (Michigan, USA) ingested one American kestrel into an engine on take-off. The aircraft crashed in a nearby field, injuring 3 of the 43 passengers.
- 1980; Royal Air Force Nimrod aircraft lost control and crashed after ingesting a number of birds into multiple engines at Kinross, Scotland.
- 18 June 1983, during the landing process at Clifford, Texas, the pilot of a Bellanca 1730, saw two "buzzards" on final approach. Hence, he added power and maneuvered to avoid them, then continued approach, which resulted in a landing beyond the intended point. As the middle of the runway was higher than either end, the pilot was unable to see a large canine moving toward the landing area until the aircraft was halfway down the runway. A go-around was initiated, but the lowered landing gear hit some treetops causing the pilot to loose control. The aircraft came to rest about 250 yards from initial tree impact after flying through additional trees. The aircraft suffered substantial damage, and two people in the aircraft were seriously injured.
- September 1987, U.S. Air Force B1-B lost control and crashed after an American white pelican struck the wing root area and damaged the hydraulic system. The aircraft was on a low level, high-speed training mission in Colorado, USA. Only three of the six occupants have survived this negative functionability event.

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[80] Dolbeer, R. A., Birds and aircraft: fighting for airspace in crowded skies, pp 37-43, Proceedings of 19th Vertebrate Pest Conference, University of California, Davis, California, USA, 2000.

- 5 November 1990, during takeoff at Michiana Regional Airport (Indiana), a BA-31 flew through a flock of mourning doves. Several birds were ingested in both engines, and take-off was aborted. Both engines were destroyed. Cost of repairs was $1 million.
- 30 December 1991, a Citation 550, taking off from Angelina County Airport (Texas), struck a turkey vulture. The strike caused major damage to the engine number 1 and resulting shrapnel caused minor damage to the wing and fuselage. Cost of repairs was $550,000.
- 3 December 1993, a Cessna 550 struck a flock of geese during the initial climb out of Du Page County Airport (Illinois). The pilot heard a loud bang, and the aircraft yawed to the left and right. Instruments showed loss of power to engine number 2 and a substantial fuel leak on the left side. An emergency was declared, and the aircraft landed at Midway Airport. The cost to repair two engines was $800,000, and the aircraft spent 3 months in repair shop.
- 3 June 1995, an Air France Concorde, while landing at John F. Kennedy International Airport (New York), ingested one or two Canada geese into engine number 3. The engine suffered an uncontained failure and its shrapnel destroyed the engine number 4 and cut several hydraulic lines and control cables. The pilot landed safely, but the runway was closed for several hours. The repair cost was around $7 million.
- 22 September 1995, Airborne Warning and Control System aircraft (known as AWACS) crashed killing all 24 on board. The cause of the accident was ingestion of four Canada geese into engines 1 and 2 during take-off from Elmendorf Air Force Base (Alaska).
- 14 July 1996, NATO E-3 AWACS aircraft struck a flock of birds during takeoff at Aktion Airport in Greece. The crew aborted the takeoff and the aircraft overran the runway. The aircraft was not repaired; none of the crew was seriously injured.
- 15 July 1996; Belgian Air Force Lockheed C-130 struck a large flock of starlings during approach to Eindhoven, Netherlands and crashed short of the runway. All four members on the crew and 30 of the 37 passengers were killed.
- 5 October 1996, a Boeing-727 departing Washington DC Reagan National Airport struck a flock of gulls just after takeoff, ingesting at least one bird. One engine began to vibrate and was shut down. As the burning smell entered the cockpit, the pilot declared an emergency, and the aircraft, carrying 52 passengers, landed at Washington Reagan National. Several engine blades were damaged
- 7 January 1997, an MD-80 aircraft struck over 400 blackbirds just after take-off from Dallas-Fort Worth International Airport (Texas). Almost every part of the plane was hit. The pilot declared an emergency and safely landed. Substantial damage was found on various parts of the aircraft, and engine number 1 had to be replaced. The runway was closed for 1 hour. The birds had been attracted to an un-harvested wheat field close to the airport.
- 9 January 1998, while climbing through 3,000 feet, following takeoff from Houston Intercontinental Airport (Texas), a Boeing-727 struck a flock of snow geese with three to five birds ingested into one engine. The affected engine lost all power and was destroyed. The radome was torn from aircraft and leading edges of both wings were damaged. The Pitot tube for the first officer was torn

off. After declaring emergency the flight returned safely to Houston with major damage to aircraft.

- 22 February 1999, a Boeing-757 departing Cincinnati/Northern Kentucky International Airport was forced to return and make an emergency landing after hitting a large flock of starlings. Both engines and one wing received extensive damage. Around 400 dead starlings were found on the runway area.
- 7 February 2000, DC-10-30, belonging to an American-owned cargo company, ingested a fruit bat into one engine at 250 feet Above Ground Level (AGL), while departing from Subic Bay, Philippines. The aircraft returned to the airport safely. Five damaged fan blades had to be replaced keeping aircraft out-of-service for 3 days. Total repair and related costs exceeded $3 million.
- 21 January 200, an MD-11 departing Portland International Airport (Oregon) ingested a herring gull into engine number 3 during the takeoff run. The engine stall blew off the nose cowl that was sucked back into the engine and shredded. The engine had an un-contained failure. The pilot aborted take-off and safely landed 217 passengers, with two blown tires.
- 9 March 2002, a Canadair RJ 200 at Dulles International Airport, Washington DC, struck two wild turkeys during the takeoff roll. One of them shattered the windshield spraying the cockpit with glass fragments and remains.
- 19 October 2002, a B767 departing Logan International Airport in Boston, encountered a flock of over 20 double-crested cormorants. At least 1 cormorant was ingested into engine number 2. There were immediate indications of engine surging followed by compression stall and smoke from the engine. The engine was shutdown. An overweight landing with one engine was made without incident. The nose cowl was dented and punctured. There was significant fan blade damage with abnormal engine vibration. One fan blade was found on the runway. The aircraft was towed to the ramp. Hydraulic lines were leaking, and several bolts were sheared off inside engine. Many pieces fell out when the cowling was opened. The aircraft spent 3 days in the repair shop and the total repair bill was $1.7 million.
- 8 January 2003, a Bombardier de Havilland Dash 8 collided with a flock of lesser scaup ducks at 1,300 feet AGL on approach to Rogue Valley International Airport (Oregon), At least one bird penetrated the cabin and hit the pilot who turned control over to the first officer for landing. Emergency power switched on when the birds penetrated the radome and damaged the DC power system and instruments systems.
- 4 September 2003, a Fokker 100 struck a flock of at least five Canada geese over the runway shortly after take-off at LaGuardia Airport (New York), ingesting one or two geese into engine number 2. The pilot was unable to shut the engine down with the fuel cutoff lever, so the fire handle was pulled and the engine finally shut down. The flight was diverted to nearby JFK International Airport where a landing was made. A depression on the right side of the nose behind the radome was found with a maximum depth of 10 cm. Impact marks were found on the right wing. A fan blade separated from the disk and penetrated the fuselage. Several fan blades were deformed. Holes were found in the engine cowling. Bird remains were recovered and identified by the Wildlife Services.
- 17 February 2004, a Boeing 757 during a takeoff run from Portland International Airport (Oregon) hit five mallards and returned with one engine out. At least one bird was ingested, and parts of five birds were collected from

the runway. As the damaged engine was beyond repair, the new one was fitted at the cost of $2.5 million, keeping the aircraft 3 days out of service.
- 15 April 2004, an Airbus 319 climbing out of Portland International Airport (Oregon) ingested a great blue heron into engine number 2, causing extensive damage. The pilot shut the engine down as a precaution and made an emergency landing. The runway was closed 38 minutes for cleaning. The engine and nose cowl were replaced at the cost of $388,000, keeping aircraft in repair shop for 72 hours.
- 14 June 2004, a great horned owl struck a Boeing 737, during a nighttime landing roll at Greater Pittsburgh International Airport. The bird severed a cable in the front main gear and disabled the steering system causing the aircraft to run off the runway and became stuck in mud. Passengers were bused to the terminal. Repair team replaced 2 nose wheels, 2 main wheels and brakes keeping the aircraft out of service for 24 hours at the total cost of $20,000.
- 16 September 2004, departing Chicago O'Hare (Illinois), a MD 80 hit several double-crested cormorants at 3,000 feet AGL and 4 mi from airport. Engine number 1 caught fire and failed, sending metal debris to the ground in a Chicago neighborhood. The aircraft made an emergency landing back at O'Hare with no injuries to any of the 107 passengers.
- 24 October 2004, a Boeing 767 departing Chicago O'Hare (Illinois) hit a flock of birds during the take-off run. A compressor stall caused the engine to flame out. A fire department got calls from local residents who reported seeing flames coming from the plane. The pilot dumped approximately 11,000 gallons of fuel over Lake Michigan before returning to land.

The nature of aircraft damage from bird strikes, which is significant enough to create a high risk to continued safe flight, differs according to the size of aircraft.

5.12 Closing remarks regarding physical reality of reliability

The above presented set of physically observed and documented facts seriously raised the question of the accuracy of the reliability predictions currently provided through the reliability function (Eq. 3) to even the time to the first failure of a system.

Even further, it is impossible to say anything about all subsequent physically observable phenomena during the in-service operation of systems that are totally "nonexistent", as far as the reliability function of a system is concerned, (Eq. 3), which covers only the time to the first failure.

6. Mathematical versus physical reality of reliability

Base on the information provided thus far it is possible to summarise that there are clear differences between a mathematical reality of reliability and the observed physical reality of reliability described through observed reliability related events described in the text. The major points of the differences between them are presented in the Table 2.

Mathematical Reality	Physical Reality
Quality of produced components and assemblies is hundred percent	Quality of produced components and assemblies is less than hundred percent
Errors during system transportation, storage	Errors during system transportation,

and installation tasks are zero percent	storage and installation tasks are greater zero percent
There is no interactions between "independent" components	There are a huge interactions between "independent" components
Maintenance activities like: inspections, repair, cleaning, etc., do not exist	Maintenance activities like: inspections, repair, cleaning, etc., exists
System and all components operate continuously (24/7)	Neither system not all components operate continuously (24/7)
First observable failure is a failure of a system	First observable failure is not necessarily the failure of a system
Components and a system have the same "times"	Components and a system have different "times"
Fixed operation scenario (load, stress, temperature, pressure, etc.)	Variable operation scenario (load, stress, temperature, pressure, etc.)
Reliability is independent of the location in space defined by GPS coordinates	Reliability is dependent on the location in space defined by GPS coordinates
Reliability is independent of humans	Reliability is dependent on humans
Reliability is independent of maintainers	Reliability is dependent on maintainers
Reliability is independent of calendar time	Reliability is dependent on calendar time
Reliability is independent of environment	Reliability is dependent on environment

Table 2: Comparison between mathematical and physical reality of reliability

7. Closing Question

The main objective of this text was to expose the reliability and safety community to the mathematical and physical realities of the reliability function with the objective to focus their attention to the following question, "*What is the body of knowledge on which reliability and safety modelling should be based, in order for the predictions made to be confirmed by reliability measures obtained in operationally defined physical reality?*"

8. Acknowledgement

The author wishes to acknowledge that the majority of the information regarding the reliability and safety events presented in this text originated from the Aviation Weekly[81].

Also, the author wishes to acknowledge the contribution of the numerous students, at Exeter University (1986-1999) and the MIRCE Akademy (1999-current), towards his endeavour to understand the physical mechanisms that cause occurrences of failure events through the collection and analysis of information related to the in-service behaviour of functionable systems, as the only way towards the creation of the modelling method that would provide predictions of reliability and safety which are confirmed by measurements obtained in the operationally defined physical reality, as it is achievable in mechanical, electrical, chemical, nuclear and other branches of engineering.

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