

## Publication of the MIRCE Academy



# 2020 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 Academy**

**Publication Date: 31 December 2020**

**Publisher:**

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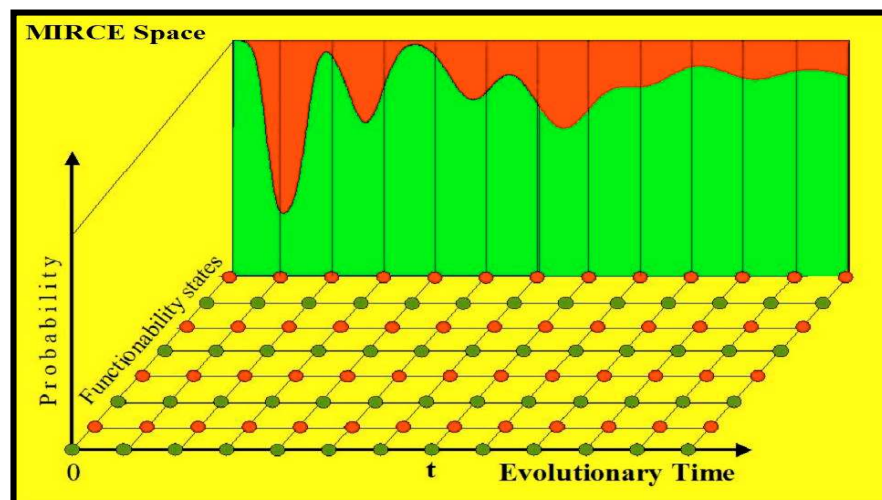
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### MIRCE Science

*The philosophy of MIRCE Science is based on the premise that the purpose of existence of any functionable system<sup>1</sup> 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<sup>2</sup>, which certainly 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<sup>3</sup>. 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

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

<sup>2</sup> 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).

<sup>3</sup> MIRCE Space: a conceptual 3-dimensional 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]

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## **Emergency Oxygen Provision as a Mechanism of the Motion of an Aircraft through MIRCE Space**

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*The paper addresses the provisioning of emergency oxygen as a physical mechanism of the motion of an aircraft through MIRCE Space. [1] Although the malfunctioning of this process is not frequently observed event, their occurrences could cause significant consequences to airline and flying public, impacting the functionability performance of commercial aircraft in the air and on the ground [2]. A full understanding of the mechanisms of these actions is essential for the accurate predictions of the functionability performance of functionable system using MIRCE Functionability Equation. Thus, this paper focuses on the observed physical phenomena or human activities related to the aviation industry and some of them are briefly described and analysed in the paper. Based on the evidence available recommendations for the reduction of the probability of occurrence of negative functionability events of the emergency oxygen provision are presented.*

### **0. Preface**

“Oh, we humans, never content to remain on the earth that holds us down with its gravity and sustains us with oxygen-laden atmosphere to breathe. No, as soon as we figured out how to ascend into that atmosphere, cheating gravity with hydrogen-filled balloons or artificial wings, we were compelled to claw our way ever higher into the thin, cold air of the stratosphere. But alas, fragile mammals that we are, we could not survive for long – let alone maintain consciousness to control our fabricated aerial conveyances. So we learned to take containers of our precious gravity-thickened atmosphere aloft with us to inhale through rubber hoses or to encase our bodies in suits and helmets pumped full of that life-fortifying gas.” David Esler [3]

### **1. Introduction**

For thousands of years humans believed that air is an element<sup>4</sup>. Today we know that air is a composition of gases that include nitrogen, oxygen, argon, carbon dioxide and water vapour, together with solid particles such as dust, sand and carbon, with a traces of other gases such as helium, hydrogen and neon. Oxygen makes up approximately 21% of the dry atmosphere, by volume, and is essential for life. As any other tangible material substance the universal force known as gravity influences air. Gravitational force of Earth shapes and influences all atmospheric processes and causes the density and pressure of air to decrease exponentially with a distance from its surface. As the

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<sup>4</sup> “We live submerged at the bottom of an ocean of the element air, which by unquestioned experiments is known to have weight, and so much, indeed, that near the surface of the Earth where it is most dense, it weighs (volume for volume) about the four-hundredth part of the weight of water, whereas on the tops of high mountains it begins to be distinctly rare and of much less weight.” E. Torricelli (1608-47)

altitude increases, the consequent decrease in pressure reduces the amount of oxygen the human body can absorb when breathing. At higher altitudes, flight crews and passengers would quickly be overcome by hypoxia, oxygen starvation, followed rapidly by unconsciousness and soon ending with a death.

To enable flight at high altitudes, which significantly reduces fuel consumption, either the aircraft cabin has to be pressurised, to replicate the pressure at a lower altitude, or the occupants of the aircraft have to be given supplemental oxygen. A healthy person at sea level has a bodily oxygen saturation of 97 %. Medical officials consider that an oxygen saturation of 93% is to be the lower limit of normal functioning. At an altitude of 10,000 ft, saturation drops to almost 90%, at 15,000 ft it is at 80% and at 25,000 ft it is a mere 55% leading to incapacitation. The higher the altitude, the lower the time of useful consciousness, as shown by Figure 1.

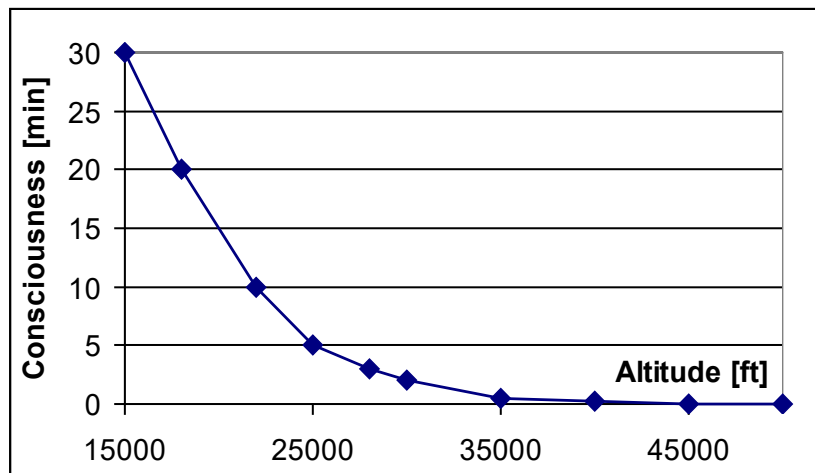


Figure1: The relationship between the altitude and the time of useful consciousness

Consequently, commercial aircraft are pressurised to the cabin equivalent of 8,000 ft, meaning that passengers sitting in an aircraft cruising at 35,000 ft are experiencing the same concentration of oxygen that they would experience at an altitude of 8,000 ft. The basics of pressurised aircraft date back to the mid-1930s. Nowadays, on most pressurised aircraft, in cases that the cabin pressurisation is lost at the altitude above 14,000 feet, emergency oxygen is automatically provided. The supply of emergency oxygen typically provides enough air to last 12 to 20 minutes, which gives the flight crew sufficient time to descend at the safe altitude where masks are not needed anymore.

The main objective of this paper is to examine the emergency oxygen provisioning process as a mechanism of the motion of an aircraft through MIRCE Space, which impacts the functionality work done by an aircraft and resources consumed during a given interval of calendar time. Although the malfunctioning of this process is not frequently observed phenomena, their occurrences could cause significant consequences to airline and flying public, impacting the functionality performance of commercial aircraft in the air and on the ground.

## 2. MIRCE Science Fundamentals

According to MIRCE Science<sup>5</sup>, at any instant of calendar time, a given functionable system<sup>6</sup> 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 measurable function(s),
- Negative Functionability State (NFS), a generic name for a state in which a functionable system is unable to deliver the expected measurable function(s), resulting from any reason whatsoever.

In MIRCE Science a life of a functionable system is defined by the trajectory of its motion thorough MIRCE Space. Mathematically, it is a three dimensional space containing functionability points, each representing functionability state that a functionable system could be found in, probability of being in each of these states, at any instant of the calendar time.

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

- Positive Functionability Action (PFA), a generic name for any human activity or physical phenomena that compels a system to move to a PFS.
- Negative Functionability Action (NFA), a generic name for any physical phenomena or human activity that compels a system to move to a NFS.

Chemical reaction between oxygen and a fuel is a negative functionability action that generates a combustible process causing a flame and smoke. Consequently, oxygen-generating equipment on aircraft presents a significant fire hazard and has contributed to several aircraft fires, both on the ground and in flight. For example:

- On 11 May 1996, ValuJet Flight 592 carried expired chemical oxygen generators that were improperly prepared and labelled as company material. Without being designated as HAZMAT<sup>7</sup> they were placed in the cargo hold of a passenger aircraft, where they caught fire in flight resulting in a crash in Everglades, Florida, United States, which killed all 110 persons onboard.
- On 28 June 2008, ABX Air Flight 1611 a cockpit fire took place in a B767-200 on the ground before engine start-up. The National Transportation Safety Board determined that, “the probable cause of this accident was the design of the supplemental oxygen system hoses and the lack of positive separation between electrical wiring and electrically conductive oxygen system components. The lack of positive separation allowed a short circuit to breach a combustible oxygen hose, release oxygen, and initiate a fire in the supernumerary compartment that rapidly spread to other areas. Contributing to this accident

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<sup>5</sup> MIRCE Science comprises of mathematical axioms, equations and methods that enable predictions of expected functionability performance of each feasible option of the future functionability system to be done, based on the time-dependent interactions between: physical properties of consisting components and applied functionability rules regarding operation, maintenance and support processes.

<sup>6</sup>According to Knezevic [1], functionable system is “a set of mutually related entities put together to do a functionability work in accordance to physical laws and given functionability rules.”

<sup>7</sup>HAZMAT is an abbreviation for “hazardous materials”, which are substances in quantities or forms that may pose a reasonable risk to health, property, or the environment, like: toxic chemicals, fuels, nuclear waste products, and biological, chemical, and radiological agents

was the Federal Aviation Administration's failure to require the installation of non-conductive oxygen hoses after the safety issue concerning conductive hoses was initially identified by Boeing.<sup>8</sup> Both pilots safely evacuated through cockpit windows, but the aircraft was declared a total loss.

- On 30 July 2008, Qantas flight between Hong Kong and Melbourne, carrying 369 passengers and crew, rapidly depressurised following the forceful rupture of one of the aircraft's emergency oxygen cylinders in the forward cargo hold<sup>9</sup>. At the time a Boeing 747-438 was cruising at 29,000 ft. Following an emergency procedure the flight crew descended to 10,000 ft and diverted the aircraft to Ninoy Aquino International Airport, Manila, Philippines, where it landed safely. None of the passengers or crew sustained any physical injury. The aircraft was repaired and returned to service in 2009.
- On 29 July 2011 during the preparation for the EgyptAir Flight 667 an electrical spark in the presence of the supplemental oxygen system turned the flight deck of a Boeing 777-200 into a conflagration, at Cairo International Airport (CAI)<sup>10</sup>. The captain unsuccessfully attempted to extinguish the fire with the cockpit fire extinguisher. As the aircraft was on the ground at the time, the captain ordered an emergency evacuation and all of 307 passengers and crewmembers escaped without serious injury. Due to the growing fire in the cockpit the first officer was unable to use a radio to contact emergency services. Thus, after exiting the Boeing he stopped a car on a service road to call the fire department. Although there were no fatalities, the aircraft was damaged beyond repair.

MIRCE Mechanics is a part of MIRCE Science that focuses on the scientific understanding of the mechanisms that generate functionability actions that govern the motion of functionable systems through MIRCE Space [1]. A full understanding of these mechanisms is essential for predicting the expected functionability performance and the cost of resources consumed by a given functionable system using MIRCE Science Equations.

### 3. Description and Certification of Aircraft Emergency Oxygen System

Brief description of the certification regulations related to the aircraft emergency oxygen system is presented here together with the description of their main parts.

#### 3.1 Regulations

National regulations for the provision and use of supplemental or emergency oxygen systems are based on the guidance provided in Annex 6 of the International Civil Aviation Organisation (ICAO) Standards and Recommended Practices (SARPS)<sup>11</sup>. The most significant items found in the guidance on oxygen are following:

- All Aircraft: An operator shall ensure that passengers are made familiar with the location and use of: oxygen dispensing equipment, if the provision of oxygen for the use of passengers is prescribed.
- Non-pressurised Aircraft

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<sup>8</sup> <https://aviation-safety.net/database/record.php?id=20080628-0> (accessed 11 June 2018)

<sup>9</sup> <http://news.bbc.co.uk/1/hi/world/asia-pacific/7532357.stm> (accessed 7 May 2020)

<sup>10</sup> <https://aviation-safety.net/database/record.php?id=20110729-0> (accessed 10 May 2020)

<sup>11</sup> [https://www.skybrary.aero/index.php/Aircraft\\_Oxygen\\_Systems](https://www.skybrary.aero/index.php/Aircraft_Oxygen_Systems) (accessed on 07.02.2019)

- An aeroplane intended to be operated at flight altitudes at which the atmospheric pressure is less than 700 hPa in personnel compartments shall be equipped with oxygen storage and dispensing apparatus
- A flight to be operated at flight altitudes at which the atmospheric pressure in personnel compartments will be less than 700 hPa shall not be commenced unless sufficient stored breathing oxygen is carried to supply:
  - all crew members and 10 per cent of the passengers for any period in excess of 30 minutes that the pressure in areas occupied by them will be between 700 hPa and 620 hPa
  - the crew and passengers for any period that the atmospheric pressure in areas occupied by them will be less than 620 hPa
- Pressurised Aircraft
  - An aeroplane intended to be operated at flight altitudes at which the atmospheric pressure is less than 376 hPa or which, if operated at flight altitudes at which the atmospheric pressure is more than 376 hPa, cannot descend safely within four minutes to a flight altitude at which the atmospheric pressure is equal to 620 hPa shall be provided with automatically deployable oxygen equipment. The total number of oxygen dispensing units shall exceed the number of passenger and cabin crew seats by at least 10 per cent.
  - All flight crew members of pressurised aeroplanes operating above an altitude where the atmospheric pressure is less than 376 hPa shall have available at the flight duty station a quick-donning type of oxygen mask which will readily supply oxygen upon demand.

## 3.2 Equipment

Due to the different requirements of the equipment used on the flight deck and that used in the passenger cabin their design and functionality methods differ.

### 3.2.1 Flight Deck

Oxygen for the use of the flight deck occupants is normally stored as pressurised gas in one or more tanks or cylinders. In certain aircraft types, oxygen is stored as a liquid.

The total oxygen capacity must be sufficient to supply all flight deck occupants with adequate oxygen for a defined period of time at an altitude profile specified in the applicable National Aviation Authority regulations. Commonly, the altitude profile will incorporate an emergency descent segment and followed by a period in level flight at a defined altitude.

A quantity gauge or other means of determining the amount of available oxygen will be incorporated.

A regulator is installed to reduce storage cylinder pressure to a usable level. Depending upon the aircraft type, regulators can be:

- Constant flow type, that provides the same output pressure or flow regardless of altitude. The regulator is therefore optimized for a specific altitude. At altitudes lower than the designed optimum altitude, it will provide more oxygen than is actually required. This type of regulator is most often found in non-pressurised aircraft and on portable oxygen systems. A single constant flow regulator is able to control the oxygen flow to all users.
- Diluter-demand type that provides oxygen at each crew position. Depending upon user selection, the diluter-demand regulator can provide 100% oxygen, 100% oxygen under positive pressure or a mixture of oxygen "diluted" with cabin air on a specific, altitude-based schedule.

### **3.2.2 Passenger Compartment**

In non-pressurised aircraft that routinely fly above 10,000 ft, passenger oxygen is typically provided by:

- Fixed systems that draw their oxygen supply from a pressurised cylinder of gaseous oxygen. This can be a dedicated cylinder or it might be the same cylinder that is used to supply the flight deck occupants. An oxygen manifold runs from the cylinder into the passenger compartment via a single regulator. Attachment ports allow passenger oxygen masks to be connected to the manifold. A shutoff valve capable of isolating the passenger compartment is normally incorporated.
- Portable systems that consist of a storage tank, a regulator and one or more passenger masks. These will be distributed to the passengers when required.

Pressurised aircraft which have a certified maximum altitude of 25,000 ft or less do not require passenger oxygen systems subject to the aircraft being able to descend to 13,000 ft or below within 4 minutes of loss of pressurisation. If the aircraft is not capable of achieving the descent profile or the route structure does not allow the descent due to terrain, an oxygen system must be fitted in the aircraft as per the provisions which apply to aircraft which are certified to fly at higher altitudes (above 25,000 ft).

For pressurised aircraft that are certified to operate above 25,000 ft, emergency oxygen equipment must be available. Some aircraft utilise cylinders of pressurised oxygen to meet this requirement but most types are fitted with chemical oxygen generators. The emergency oxygen supply must last a minimum of 10 minutes.

Provisions must be provided in the system to automatically deploy the emergency oxygen masks when the cabin altitude exceeds a pre-determined level (typically 14,000 ft). Sufficient masks must be provided for at least 10% more passengers than there are seats in the passenger compartment.

## **3.3 Oxygen Mask**

Oxygen masks used in the flight deck are different from those that are available in passenger cabin.

### **3.3.1 Flight Deck**

An oxygen mask is provided at each flight deck station. The mask could be of the "full face" variety incorporating smoke goggles or a "mouth and nose" type mask with smoke goggles available separately. The masks at the pilot stations will incorporate microphones to allow internal and external communications.

Masks are fitted to the face utilising various suspension harnesses. For aircraft which routinely fly above 25,000 ft, masks are generally of the "quick-donning" variety, which allow them to be put on in 5 seconds or less using only one hand.

For diluter-demand systems, selectors for normal, 100% and positive pressure may be incorporated into the mask itself. If not, they will be found on the associated regulator. Diluter-demand oxygen masks are stowed with the selector in the 100% oxygen position and should be reselected to the normal (or diluting) position when mask utilisation is required for other than a smoke or fume event.

### **3.3.2. Passenger Compartment**

The most typical passenger oxygen masks consist of a soft, yellow, silicone cup fitted with elastic bands for securing the mask to the face. The bands are adjustable to accommodate passengers of different sizes. The mask may also have a clear concentrator or re-breather bag. Depending upon the cabin altitude, the concentrator bag may or may not inflate. Airlines make a point during their safety presentation of pointing out that the bag may not inflate as, in the past, lack of bag inflation has led some passengers to believe that their mask was not working and to remove it resulting in hypoxia. [2]

The bag is attached to a tube, connected to the oxygen source in the compartment, allowing for it to drop down and hang in front of the passengers. To operate on all aircraft except the L-1011 and B787, they must be pulled sharply toward the passenger who needs it to un-clip the flow pin and start the process of transporting the oxygen to the passenger. Passenger oxygen masks cannot deliver enough oxygen for sustained periods at high altitudes. This is why the flight crew needs to place the aircraft in a controlled emergency descent to a lower altitude where it is possible to breathe without emergency oxygen.

While the masks are being used, passengers are not allowed to leave their seat for any reason until it is safe to breathe without the emergency oxygen. If there is a fire on board the aircraft, masks are not deployed, as the production of oxygen may further fuel the fire.

### **3.4 Types of Oxygen Generating Systems**

There are two systems that are typically found on commercial aircraft, namely:

- A chemical oxygen generator system that is connected to all masks in the compartment. Pulling down on one oxygen mask removes the firing pin of the generator igniting a mixture of sodium chlorate and iron powder, opening the oxygen supply for all the masks in the compartment. During the short period of oxygen production, the generator becomes extremely hot and should not be touched. A burning smell may be noted and cause alarm among passengers, but this smell is a normal part of the chemical reaction. For any aircraft which carries more than a very few passengers, the weight, complexity and maintenance issues associated with a compressed gas system would be

prohibitive. Hence, the commercial aviation industry relies on chemical oxygen generators.

- A gaseous manifold system that connects all oxygen masks to a central oxygen supply usually is in the cargo hold area. Pulling down on one oxygen mask starts the oxygen supply for that mask only. The entire system can usually be reset in the cockpit or in some other location in the aircraft.

#### 4. Malfunctions of Emergency Oxygen Provisioning Systems

Veillette [5] conducted a search of 100 recent NASA Aviation Safety Reporting System (ASRS)<sup>12</sup> records regarding involving incidents, in which oxygen masks were employed, submitted in 2016 and 2017. Out of the records analysed 71 are related to a loss of pressurisation or suspected smoke or fumes. In all of these cases emergency oxygen systems operated as designed, enabling the flight crews to breathe and they safely got the aircraft and their passengers on the ground. However, the remaining 29 reports draw attention to the serious risk posed for a flight crew being without supplemental oxygen as well as other serious problems with masks used when needed. The following few examples are extracted from Veillette [5].

**Case 1:** NASA ASRS Report 1498858, published in November 2017, contains the following statement by flight crew whose oxygen masks and hoses physically failed: “In cruise flight, I went to put on quick-donning mask as first officer was going to leave the flight deck for physiological needs. I pulled the mask out of the box and it came apart in my hands. It was useless had there been an emergency. Where the hose attaches with the microphone to the main rubber face area was broken and dangling. The full mask section was intact but the hose/microphone area was detached and hanging by a wire, no ability to breathe oxygen from the mask.”

**Case 2:** NASA ASRS Report 1462284, published in July 2017, contains the following statement “While out on the lavatory break a co-pilot heard a loud whoosh noise from up in the flight deck. So he immediately returned to the flight deck to request entry back in. When arrived to his seat he saw the captain holding the oxygen hose and mask together in his hands, accomplished with a hissing sound. The captain explained that the oxygen hose for his crew mask would not stay attached to the mask. The captain made several attempts to re-secure the oxygen hose to the mask but did not succeed. Due to the positive pressure of oxygen coming from the hose, neither of them was successful at securing the oxygen hose. After several minutes they became unable to even hold the oxygen hose to the mask. At this point there was nothing to even slow the flow of the crew oxygen and they began to lose crew oxygen at an extremely fast rate.”

**Case 3:** On 3 September 2010, a UPS Boeing 747 departed Dubai International Airport (DXB) on a cargo flight to Cologne, Germany (CGN). Twenty minutes into the flight, at approximately 32,000 ft., the crew advised ATC that there was an indication of an onboard fire and declared an emergency. Both pilots had donned their oxygen masks approximately 90 sec. after the fire bell sounded. Less than 90 sec. later, the fire caused severe damage to the flight control system and filled the cockpit with continuous

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<sup>12</sup>

<https://asrs.arc.nasa.gov/#:~:text=ASRS%20%2D%20Aviation%20Safety%20Reporting%20System,information%20to%20the%20aviation%20community>. (accessed 3 July 2019)

smoke. During the emergency descent the cabin reached a pressure altitude of 21,000 ft., followed almost immediately by the rapid failure of the captain's oxygen supply without any indication of trouble. Unknown to the flight crew, the fire had severely damaged many significant systems on the aircraft, including the crew supplementary oxygen system supply. The damage caused a cessation of oxygen flow to the captain's mask and reduced capacity for the remainder of the flight to the F/O's mask. To obtain the portable oxygen bottle, the captain left his seat, but did not return due to incapacitation from toxic gases. As the F/O could not view outside the cockpit, or see the primary flight displays, the aircraft subsequently entered an uncontrolled descent into terrain, killing both pilots in the crash.

During the investigation, several UPS line pilots commented on the use of the oxygen mask and goggle sets during their training. They reported receiving little hands-on instruction for the actual use of the set and smoke vent, and what they did receive occurred during initial training for the aircraft in the form of computer-based text and images. They also stated that they were never taught about the relationship between the emergency selector on the regulator and the need to simultaneously open the smoke vent to clear contaminants from inside the goggles or how to locate the switches on the oxygen regulator after the oxygen mask was donned. Further more, they were never required to practice these actions in the presence of an instructor or check airman.

**Case 4:** On 20 July 2009 United Airlines Flight 949 was on route from London Heathrow Airport (LHR) to Chicago O'Hare International Airport (KORD). At 37,000 ft. the flight crew encountered smoke in the cockpit and diverted to Keflavik International Airport (KEF) in Iceland. During the event, the flight crew donned their oxygen sets and attempted, with difficulty, to establish and maintain their communications. The following statement the pilot provided to the Icelandic Aircraft Accident Investigation Board, "We struggled with the audio panels to communicate with the masks on." Thus, he removed the oxygen mask to communicate with the Flight officer (F/O) and relief pilot in the cockpit. The F/O said, "The entire process of donning goggles, the use of the oxygen mask, pushing all the different buttons and toggles to communicate with all the people involved was very frustrating at times. Between the goggles scratching my glasses and the smoke film in front of them too, it was hard to see at times. Too many items have to come together for this setup to work." Also, the pilot added that "Crew communications with oxygen masks on was non-effective and increased crew workload significantly. It was made worse with three crewmembers plus ATC all trying to communicate."<sup>13</sup>

**Case 5:** Retired FedEx pilot Bob Bostick Jr. commented on the Veillette's article [5] with a following words<sup>14</sup>, "Years ago I was the right seater in the 727. My habit pattern for checking the oxygen mask was to pull the mask off the spring loaded strap it was hanging from, test for flow without putting it on, and reinstall the mask on the strap. Yup, I was not doing a full check and that was my habit pattern until I got an education. Just by chance, during one pre-flight I decided to take the mask off the strap, put it on, and give it a full test, along with taking out the smoke goggles and seeing how well it all worked with my glasses on. Had a simulator ride the next day and knew using the

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<sup>13</sup> In response to these events the NTSB issued Safety Recommendation A-11-089, to require airline, charter and fractional operators "to include, during initial and recurrent training, aircraft-specific training on establishing and maintaining internal cockpit communications when the oxygen masks are donned."

<sup>14</sup> [a300bob](#) (accessed 28 January 2019)

mask would be part of the drill. Donned the mask, flipped the switch on, took a breath...and something came out of the mask and lodged in my throat. That something was moving. After ripping off the mask and doing some very dramatic coughing and heaving, while the Captain and Flight Engineer were watching and wondering what the heck was wrong, I finally spit out a fairly good sized live moth! Wow. How did that happen? Didn't take long to figure it out, the mask hangs from the top left corner of the Flight Engineer panel, and just above the attach point is one of the flood lights for the panel. Hmm. Light attracts bug, bug gets tired, bug falls into mask. A good lesson, from that point on in my flying career I made it my habit to pull the mask out of wherever it was, clean it with a mask wipe, put some pressure to it, check it, then put it on and check for function and communication. And yes, on several occasions there was another moth in the mask. Can imagine how bad things could go with smoke/fumes/loss of pressurisation and inhaling a moth with that first deep breath."

**Case 6:** On 25 October 1999, a chartered Learjet 35 was scheduled to fly from Orlando, Florida, to Dallas, Texas. Early in the flight, the aircraft, which was climbing to its assigned altitude on autopilot, quickly lost cabin pressure and all six on board were incapacitated due to hypoxia (a lack of oxygen). The aircraft continued climbing past its assigned altitude, then failed to make the westward turn toward Dallas over north Florida and continued on its north-western course, flying for almost four hours (1,500 miles). The plane ran out of fuel over South Dakota and crashed into a field near Aberdeen after an uncontrolled descent. The NTSB has several levels of investigation, but the final conclusion was; "The probable cause of this accident was incapacitation of the flight crew members as a result of their failure to receive supplemental oxygen following a loss of cabin pressurisation, for undetermined reasons.<sup>15</sup>"

However, the crash investigation has highlighted that in Learjet model 35/36, the oxygen bottle regulator/shutoff valve is located in the nose cone of the airplane and therefore inaccessible to flight crewmembers during flight. It was further discovered that pilots may have difficulty visually verifying the position of this valve during a pre-flight inspection because of the way it is installed in the airplane. The Safety Board noted that it is critical that the valve position indicators are clearly visible and easily understandable during pre-flight check. Oxygen bottle supply pressure is indicated on a gauge in the cockpit of the Learjet 35/36. Since a visual check of the oxygen bottle supply may not provide information about the position of the oxygen bottle regulator/shutoff valve, the pilots' only sure indication in the cockpit that the oxygen bottle regulator/shutoff valve is in the OFF position would be the failure of the oxygen mask to deliver oxygen.

## **5. Oxygen Masks Related Negative Functionability Actions**

Although emergency oxygen masks and connecting lines are used very infrequently they are not protected from negative functionability actions, like "wear out" process. The most common components that fail are around valves, fittings, and connections involving rubber seals, tubing and hoses. Other possible negative functionability action that affects oxygen system components is a "dry rot", which occurs when rubber or plastic surfaces are exposed for long periods to alternative heating and cooling temperature swings in dry air (which is an apt description of an aircraft cockpit.)

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<sup>15</sup> [https://en.wikipedia.org/wiki/1999\\_South\\_Dakota\\_Learjet\\_crash](https://en.wikipedia.org/wiki/1999_South_Dakota_Learjet_crash) (accessed 11 February 2019)

Moisture within the rubber or plastic is wicked away, degrading its flexibility and elasticity over time. Cracking, tearing, and breakage are common indications of dry rot.

The Australian Civil Aviation Safety Authority (CASA) issued Airworthiness Bulletin 35-004 (Nov. 29, 2012) noting service difficulty trends with oxygen systems service during maintenance identified by their Service Difficult Report database. The observed negative functionability actions that caused the transition of emergency oxygen provisioning system from PFS to NFS include [4]:

- Lines and fittings disconnected or blanked during inspections.
- Missing information on part number identification labels.
- Contaminated oxygen masks.
- Contaminated oxygen fittings.
- Passenger service unit doors glued at hinges.
- Unserviceable oxygen masks.
- Incorrectly packed oxygen masks.
- Discharged oxygen generators.
- Worn or damaged components and fittings.
- Kinked oxygen lines and hoses.
- Passenger service unit doors not closed properly.
- Overstrained oxygen hoses.
- Oxygen fill line nuts cracked.
- Cracked in-line oxygen flow indicators.
- Incorrect oxygen cylinder configuration.
- Bent oxygen generator firing pins.
- Leaking pilot oxygen regulators

## **6. Functionability Improving Actions for Emergency Oxygen Provisioning**

The analysis of ASRS reports performed by Veillette [5] lead to the deduction of the following recommendations for the reduction of the probability of malfunctioning of emergency oxygen provisioning process, thus:

- The pressure-demand masks must be properly stowed in their containers to qualify as quick-donning equipment. Each mask has two red harness inflation levers that, when squeezed, allowing the mask to be removed from the storage box. Releasing the levers after placing the mask over the head fits it securely to the head and face. Although, it can be "challenging" stowing the oxygen mask after completing pre-flight checks, it is imperative to do so correctly as it could help safely resolve a dangerous in-service situation!
- The frequent pre-flight inspections could cause undetected wear and tear on the mask and hose connections. The pilots expressed concern that some mask designs are not sturdy enough for repeated extraction and re-stowing. These reports were submitted by regional airline crews whose aircraft can be operated by a dozen different pilots within a handful of days, each necessitating a full inspection of the oxygen system during an aircraft acceptance check. In addition, the ASRS submitters were concerned that many of the facemasks are

getting scratched to the point that they would be difficult to see through in a real event.

- Aircraft cabin that has become cold-soaked, it may require the cabin to be warm sufficiently to ensure the proper deployment and operation of passenger oxygen masks. For example, the Cessna Encore manual, stipulates that cabin temperature must be held at or above 32° F for a minimum of 15 minutes prior to takeoff after a prolonged ground cold soak.
- It is vital that all flight crewmembers to personally make sure that during the pre-flight checks that their oxygen equipment is: functioning, fitted properly and connected to appropriate supply terminals, the oxygen supply and pressure are adequate, and the oxygen buttons are selected for optimum performance in case of emergency.
- All pilots of high-performance aircraft should receive appropriate, hands-on instruction regarding the use of oxygen mask/goggle sets, including the regulator's emergency selector and smoke goggle venting, and practice communications using the mask microphones during initial and recurrent training.

## 7. Impact of the Descent on Human Body

After addressing the emergency oxygen provision systems to complete the study it is necessary to address the impact of the emergency descent on human body. In the case of an uncontrolled depressurisation, the crew would try to descend immediately to an altitude at which they and the passengers can breathe without supplementary oxygen. When a cabin depressurises, the percentage of oxygen in the air stays about the same, but the molecules get further and further apart. It is usually given as 10,000 feet amsl<sup>16</sup> subject to adequate terrain clearance. If it happens quickly, there is little time to react, although pilots are trained to keep an eye on cabin pressure and adjust the plane's oxygen levels accordingly. Once pressure dips below acceptable levels, oxygen masks drop down and people put them on to breathe in pure oxygen for as long as it lasts. Protocol dictates that the pilot fly to a lower cruising altitude, usually below 10,000 feet, so that breathing would no longer be a problem for a healthy person. [5]

The oxygen, or lack of it, is the underlying issues concerning rapid emergency descents. While a reasonably healthy person may be able to endure a cabin depressurisation and the subsequent rapid descent, the experience may not be the same for someone who is 'pneumatically challenged' with a condition like COPD<sup>17</sup>, asthma or the effects of heavy smoking. Other factors can include obesity, advanced age and

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<sup>16</sup> AMSL is an abbreviation for the Above Mean Sea Level, and it refers to the elevation or altitude used in aviation (for recording and reporting most heights) and in the atmospheric sciences.

<sup>17</sup>Chronic Obstructive Pulmonary Diseases (COPD) defines a group of lung conditions that make it difficult to empty air out of the lungs because the airways have become narrowed.

lack of fitness. Bad depressurisation can cause additional medical problems like gastronomic, dental, anxiety, the bends<sup>18</sup>.

It is necessary to stress that if depressurisation happened slowly, passengers might not notice right away.

## 8. Conclusions

The main objective of this paper was to address the emergency oxygen provisioning as a physical mechanism of the motion of an aircraft through MIRCE Space. [1] Although the malfunctioning of this process is not frequently observed negative functionability event, their occurrences could cause significant consequences to airline and flying public, impacting the functionability performance of commercial aircraft in the air and on the ground [5].

Emergency oxygen provisioning systems have been briefly described in the paper considering their main characteristics and potential negative impact on crew and flying passengers. Timely response by a flight crew to a loss of cabin pressurisation or to smoke or fumes is critical for the safe operation of an aircraft and certainly not the time to discover that emergency oxygen provisioning system is in a negative functionability state (NFS).

It has been pointed out in the paper that in many instances the accident report concluded that the deterioration of the condition of emergency oxygen provisioning systems were intensified by inadequately maintained oxygen masks, their attachments to the rest of the system and frequent inspections by flight deck crew.

This paper clearly confirms that malfunctions of emergency oxygen provisioning system have caused considerable contributions to the transition of an aircraft from positive to negative functionability state, resulting in the reduction of the functionability work done and occasional destruction of the aircraft or human fatalities.

Recommendations provided in the paper, based on the observed in-service functionability events, should be used for the design of the future emergency oxygen provisioning systems as well as the planning of their maintenance programmes and a corresponding cabin crew training.

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<sup>18</sup> A condition experienced by divers when the dissolved nitrogen in the blood begins bubbling out of the circulatory system. At the higher altitudes that some aeroplanes fly today, without cabin pressurisation, the pilots 's blood can actually boil.

[it?utm\\_rid=CPEN1000001174516&utm\\_campaign=24318&utm\\_medium=email&elq2=7f1865b582244d209f3a999aa4981d73](http://it?utm_rid=CPEN1000001174516&utm_campaign=24318&utm_medium=email&elq2=7f1865b582244d209f3a999aa4981d73) (accessed 10 June 2020)

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## Reliability + Maintenance = Work Done

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### Abstract

*The main objective of any business is to stay in business. The best way to achieve that is to increase the revenue generating work done by an asset, while reducing the resources consumed for it. One way towards that target is to improve the reliability of the asset by using appropriate engineering and production methods. Another way is to reduce the time asset spends in maintenance by applying appropriate condition monitoring and management technologies. Hence, the work done by an asset is driven by the combined impact of inherent reliability and maintenance policies chosen. Although, reliability and maintenance are well-recognised disciplines in their own rights, there is no a body of knowledge for predicting their combined impact on the work done and resources consumed, in a quantitative and comparative manner.*

*The main objective of this presentation is to introduce reliability and maintenance professionals to MIRCE Science [1], a body of knowledge that enables quantitative prediction of the complex interactions between reliability and maintenance issues on the work done by an asset and resources required. Hence, by making use of MIRCE Functionability Equation it is possible to perform quantitative trade-off between feasible reliability and maintenance options to select the compromising solution that would yield greatest benefit measured through the work done.*

*A numerical example, where the trade off between reliability improvements by increasing the expected time to failure by 50% or decreasing maintenance time by 50%, is provided to illustrate the applicability of MIRCE Science to assets management process.*

**Key words:** Reliability, Maintenance, Work Done, Profit, MIRCE Science

### 1. Introduction

The philosophy of MIRCE Science<sup>19</sup> is based on the premise that the purpose for the existence of any asset is to do a work. The work is done when the expected measurable function is performed through time. The best way to achieve that is to increase the revenue generating work done by an asset, while reducing the resources consumed for

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<sup>19</sup> MIRCE Science comprises of mathematical axioms, equations and methods that enable predictions of expected functionability performance of the future asset to be done, based on the complex, time-dependent, interactions between: physical properties of consisting components and applied functionability rules regarding operation, maintenance and support processes. [1]

it. One way towards that target is to improve the reliability of consisting parts by using appropriate engineering and production methods. Another way is to reduce maintenance time by applying appropriate condition monitoring and management technologies. Although there is an infinite number of combinations between the amount of improvements in reliability and reduction in maintenance time, it is safe to conclude that the work done is driven by the combined impact of them of them. Their impact on the amount of work done by an asset during its operational life could quantify through the following two approaches:

- Measuring it during the operation process
- Predicting it during the planning process.

Measuring the work done is rather straightforward process where the operational hours are counted together with resources consumed<sup>20</sup>. However, possessing the data regarding the past performance of assets does not have any impact on the asset's performance. On the other hand, the ability to predict the future performance at the planning state gives opportunity for any changes necessary to create assets with desirable performance to be made, within the given budget, in order to generate the expected return on their investment (e.g. profit, reputation, loyalty, public benefit and similar). However, to achieve that, it is necessary to have mathematical model<sup>21</sup> that would facilitate that, as mathematics is the only body of knowledge that enables quantitative predictions to be made in all natural sciences, from quantum mechanics (the motions of subatomic particles) to astrophysics (the motion of spacecraft).

Although, reliability and maintenance are well-recognised disciplines in their own rights, best to the author's knowledge there is no body of knowledge for predicting their combined impact on the work done and resources consumed, in a quantitative and comparative manner.

The main objective of this text is to introduce reliability and maintenance professionals to MIRCE Science [1], a body of knowledge that enables quantitative prediction of the complex interactions between reliability and maintenance on the work done and resources required. Hence, by making use of MIRCE Functionability Equation it is possible to perform quantitative trade-off between feasible reliability and maintenance options to select the compromising solution that would yield greater productivity measured through the work done.

## 2. Brief overview of MIRCE Science

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

- Positive Functionability State (PFS), a generic name for a state in which an asset is able to deliver the expected measurable function(s),

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<sup>20</sup> Boeing 747, registration number N747PA, which belonged to Pan Am airways, have delivered the work of 80,000 flying hours and received 806,000 maintenance man-hours, during the 22 years of in-service life

<sup>21</sup> Newton, Maxwell, Lagrange, Boltzmann and other well know and applied equations for predicting the physical behaviour of natural world.

- Negative Functionability State (NFS), a generic name for a state in which an asset is unable to deliver the expected measurable function(s), resulting from any reason whatsoever.

In MIRCE Science work done by an asset is uniquely defined by the trajectory generated by its motion through the MIRCE Space<sup>22</sup>. That motion is driven by functionability actions, which are classified as:

- Positive Functionability Action (PFA), a generic name for any human activity or physical phenomena that compels an asset to move to a PFS.
- Negative Functionability Action (NFA), a generic name for any physical phenomena or human activity that compels an asset to move to a NFS.

The motion of an asset through the MIRCE Space is physically manifested through the occurrences of functionability events, which are classified as:

- Positive Functionability Event (PFE), a generic name for any physically observable occurrence in the calendar time that signifies the transition of an asset from a NFS to a PFS.
- Negative Functionability Event (NFE), a generic name for any physically observable occurrence in the calendar time that signifies the transition of an asset from a PFS to a NFS.

### 3. Mathematical Principles of MIRCE Science

The ability to “normalise” all competing options of an asset enables comparisons to be made between them and finally select the best one, in accordance to a given criteria. Hence, MIRCE Science is a body of knowledge that enables quantitative assessment of the impact of the multidimensional interactions between: components, architecture, naturally environment and human imposed rules regarding operation, maintenance and support processes of an asset to be done by predicting expected the work done and resources required.

#### 3.1 Positive Work in MIRCE Science

According to MIRCE Science “philosophia” positive work is done when an asset is delivering functionality performance, which means that it must be in positive functionability state. Thus, the area under the trajectory of the motion of an asset through MIRCE Space, defined by the MIRCE Functionability Equation, must be equivalent to the positive work done by the asset in the interval of calendar time  $T$ .

According to Knezevic [1] the expected positive work to be done by an asset during a given interval of calendar time  $T$ ,  $PFWS(T)$ , measured in calendar hours, Hr, can be calculated by making use of the following equation:

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<sup>22</sup> MIRCE Space is a conceptual 3-dimensional space containing infinite set of possible discrete functionability states that an asset could be found in, at any instant of the calendar time, and corresponding probabilities. [1]

$$PFW_s(T) = \int_0^T y_s(t) dt \quad [Hr] \quad 1$$

where:  $y_s(t)$  is MIRCE Functionability Equation<sup>23</sup> [2] that quantifies the probability of the event  $\{Asset \text{ is being in a PFS at instant of calendar time } t\}$ , thus:

$$y_s(t) = P\{PFS_s(t)\} = \sum_{i=1}^{\infty} y_s^i(t) = \sum_{i=1}^{\infty} [O_s^{i-1}(t) - F_s^i(t)], \quad t \geq 0 \quad 2$$

where:  $O_s^{i-1}(t) = P(TPE_s^{i-1} \leq t)$  and  $F_s^i(t) = P(TNE_s^i \leq t)$ . In accordance to the 1<sup>st</sup> axiom of MIRCE Science  $O_s^0(0) = 1$  [1].

The infinite sum of positive and negative functions represents a mathematical scheme that theoretically defines the sequential occurrences of the functionability events in the direction of the calendar time, for each feasible variation of the asset considered. In the language of mathematics these are systems of the convolution integrals. Thus, the sequential positive functionability function,  $O_s^i(t)$ , which defines the probability that the  $PFE_s^i$  in the life of an asset, will take place before or at the instant of calendar time  $t$ , is defined by the following convolution integrals [1]:

$$\begin{aligned} O_s^i(t) &= P(TPE_s^i \leq t) \\ &= P(TNE_s^i \leq x \cap TPE_{s,i} \leq t-x) = P(TNE_s^i \leq x) \times (TPE_{s,i} \leq t-x) \quad 3 \\ &= \int_0^t F_s^i(x) o_{s,i}(t-x) dx = \int_0^t F_s^i(x) dO_{s,i}(t-x), \quad i = 1, 2, \dots, \infty, \quad t \geq 0 \end{aligned}$$

In order for the  $i^{th}$  sequential positive functionability event,  $PFE^i$ , to take place before, or at the instant of calendar time  $t$ , it is necessary that the previous functionability event, which in this case is  $NFE^i$ , take place sometime before time  $t$ , denoted by  $x$  in the above expression. Then, the sequential  $PFE_i$  has to take place during the remaining interval of calendar time, which in this case is denoted with  $t-x$ .

The process of defining the negative sequential distribution Function,  $F_s^i(t)$ , which defines the probability that the  $i^{th}$  sequential  $NFE$  of an asset will take place before or at an instant of calendar time  $t$ , follows the same mathematical principle. Thus, the sequential negative functionability function is fully defined by the following equation:

$$\begin{aligned} F_s^i(t) &= P(TNE_s^i \leq t) \\ &= P(TPE_s^{i-1} \leq x \cap TNE_{s,i} \leq t-x) = P(TPE_s^{i-1} \leq x) \times (TNE_{s,i} \leq t-x) \quad 4 \\ &= \int_0^t O_s^{i-1}(x) f_{s,i}(t-x) dx = \int_0^t O_s^{i-1}(x) dF_{s,i}(t-x), \quad i = 1, 2, \dots, \infty, \quad t \geq 0 \end{aligned}$$

This multidimensional scheme of convolution integrals defines the motion of an asset through MIRCE Space, depicting a passing through each sequential functionability

<sup>23</sup> <https://www.academia.edu/8357448/Mirce> Functionability Equation

state in the direction of calendar time, generating a trajectory unique to each asset. Thus, the same set of generic equations, when applied to different operational and maintenance policies generate different trajectories of the motion through MIRCE Space, which means different functionability performance, namely different works done and different. Hence, a generic platform had been created on which each feasible plan for the operation and maintenance policies and strategies would generate its own future “trajectory”.

#### 4. Application of MIRCE Science

To illustrate the applicability of the MIRCE Science to the quantitative assessment of the combined impact of reliability and maintenance on the performance of an asset the following hypothetical example will be used.

The simplest possible asset consists of one component and exists in two functionable states, namely positive and negative. Event further, a single positive or negative action causes the occurrences of positive and negative events at which the asset changes its functionable states. This example is chosen, not because the real assets consist of a single component, but because it is extremely useful for the understanding of the mathematical scheme that defines the motion of an asset through MIRCE Space, which is turn, quantifies its functionability performance, namely the expected work done and resources to be consumed during that process.

To illustrate the applicability of the MIRCE Science to the quantitative assessment of the combined impact of reliability and maintenance of the performance of an asset the three questions will be addressed:

**Question 1:** Assuming that the asset under considerations is expected to experience an occurrence of a failure event with the expected value of  $E[TNE_S]=1080$  Hr (45 days) determine the amount of positive work that is expected to be delivered during a calendar year of continuous operation, without performing any maintenance action.

**Question 2:** What would be the additional work done if maintenance actions were performed after occurrences of failures? Assuming that maintenance action that returns an asset to operation has the expected value of  $E[TPE_S]=168$  Hr (7 days).

**Question 3.** Assuming that expected positive work, in the question 2, is not satisfactory, some changes must be made to improve it. Fundamentally, there are two main directions for improvement, namely:

3.1 Increase the current value of  $E[TNE_S]$ , say by 50 %,

3.2 Reduce the current value of  $E[TPE_S]$ , say by 50 %.

Which option should be adopt and why?

Undoubtedly, the ability to accurately predict the answer to the above questions, at early stages of the planning of utilisation of an asset would be invaluable for decision makers which have engineering solutions or management methods on

disposal for the creation and operation of a future productivity, within the given budget, which would to generate the expected return on their investment (e.g. profit, reputation, loyalty, public benefit and similar).

**Answer to Question 1:**

Based on the information available the only possible conclusion regarding the probability distribution of the TTF is that it is the exponential distribution uniquely defined by the scale parameter  $A_N = E[TNE_{S,1}] = 1080$  Hr. The answer to the above question is the solution to the expression for the Positive Functionability Work , defined by the equation 1.

A generic expression for an exponentially distributed cumulative distribution function of a random variable  $TNE_1$  is  $F_{S,1}(t) = P(NFE_{S,1} \leq t) = 1 - \exp[-(t/1080)]$ . Based on the data available, the probability of NFE taking part before of at a given instant of time  $t$ ,  $0 \leq t \leq \infty$ , is:

$$F_S^1(t) = P(TPE_{S,0} + NFE_{S,1} \leq t) = \int_0^t O_S^0(x) dF_{S,1}(t-x) = F_{S,1}(t) = 1 - \exp[-(t/1080)].$$

this specific case, where no positive action is taken after the occurrence of the first negative functionability event, MIRCE Functionability Equation is defined as:

$$y(t) = \sum_{i=1}^1 [O_S^{i-1}(t) - F_S^i(t)] = 1 - F_S^1(t) = \exp[-(t/1080)].$$

Finally, it is possibility to derive the expression for the expected work done, as shown below:

$$PFW(T) = \int_0^T [\exp(-t / A_N)] dt = A_N [1 - \exp(-T / A_N)]$$

For the planned continuous operation of the asset during a calendar year,  $T=24 \times 365 = 8760$  Hr. Hence, the amount of expected positive functionability work is:

$$PFW(8760) = 1080 \times [(1 - \exp(-(8760/1080)))] = 1079.68 \text{ Hrs}$$

In summary an asset defined with a data above is expected to deliver 1079.68 hours of operation during a calendar year with no maintenance actions performed, out of 8760 Hr available.

**Answer to Question 2:**

The answer to the second question will numerically defined the impact of setting up a maintenance department to repair failed asset, which otherwise would deliver only 3.12% of possible operational hours in one calendar year.

Following the logic used in question 1, in this particular example the probability distribution of TNE is defined by the exponential probability distribution with expected value of  $A_P = 168$  Hr. Based on the data available, the cumulative distribution function for the time of occurrence of  $i^{\text{th}}$  PFE is defined as:  $O_{S,i}(t) = 1 - \exp(-t / A_P)$ ,  $i = 1, \infty$ . In this specific case MIRCE Functionability Equation is defined as:

$$y(t) = P(PFS_S(t)) = \sum_{i=1}^{\infty} [O_S^{i-1}(t) - F_S^i(t)], \text{ where}$$

$$O_S^i(t) = P(TNE_{S,i} + TPE_{S,1} \leq t) = \int_0^t F_S^i(x) dO_{S,i}(t-x).$$

Dubi [4] has proven that a generic expression for MIRCE Functionability Equation, for identically distributed exponentially distributed time to positive and negative

functionability events  $y(t) = \left[ \frac{A_N}{A_p + A_N} + \frac{A_p}{A_p + A_N} e^{-\left(\frac{A_p + A_N}{A_p A_N}\right)t} \right]$ . Hence, the amount of

positive work expected to get from the asset considered with execution of maintenance tasks after failures could be calculated by solving the following integral:

$$PFW(T) = \int_0^T y(t) dt = \int_0^T \left[ \frac{A_N}{A_p + A_N} + \frac{A_p}{A_p + A_N} e^{-\left(\frac{A_p + A_N}{A_p A_N}\right)t} \right] dt.$$

The analytical solution to the above integral could be obtained by making use of the

substitution method, thus:  $PFW(T) = -\frac{A_N A_p}{A_p + A_N} \left[ -\frac{T}{A_p} - \frac{A_p}{A_p + A_N} \left( 1 - e^{-\left(\frac{A_p + A_N}{A_p A_N}\right)T} \right) \right]$

After substituting the values for the parameters in the above expression the expected positive functionability work will be  $PFW(8760) = 7600.34 \text{ Hrs}$ .

In summary it could be said that by doing maintenance, i.e. repairing failed asset, the total work done would be increased by 6520.66 Hr, or 74 %.

The cost of introducing maintenance programme and the additional revenue generated could be calculated by making use of the equations provided in the Appendix A.

### Answer to Question 3:

Based on the data available the proposed changes to the current operational plan, for the asset considered, introduce the following changes:

- Increase the current value of  $A_N$  from 1080 Hr to 1620 Hr, while maintaining the same probability distribution for  $TPE_{S,i}$  of 168.
- Decrease the current value of  $A_p$  from a current 168 hours to a 84 Hr, while maintaining the same probability distribution for  $TNE_{S,i}$  of 1080 Hr.

Thus, the impact of possible changes in the original plan would have the following impacts on the operational performance of the asset considered:

- Increase the current value of  $A$  from 1080 Hr to 1620 Hr, while maintaining the same probability distribution for  $TPE_{S,i}$ , thus:

$$\begin{aligned}
 PFW(8760) &= -\frac{A_N A_P}{A_P + A_N} \left[ -\frac{T}{A_P} - \frac{A_P}{A_P + A_N} \left( 1 - e^{-\left(\frac{A_N A_P}{A_P + A_N}\right) T} \right) \right] \\
 &= -\frac{1620 \times 168}{1620 + 168} \left[ -\frac{8760}{168} - \frac{168}{1620 + 168} \left( 1 - e^{-\left(\frac{1620 \times 168}{1620 + 168}\right) 8760} \right) \right] = 7951.21 \text{ Hr}
 \end{aligned}$$

- Reduce the time in NFS from a current 168 hours to a 84 Hr, while maintaining the same probability distribution for  $TNE_{S,i}$ , hence:

$$\begin{aligned}
 PFW(8760) &= -\frac{A_N A_P}{A_P + A_N} \left[ -\frac{T}{A_P} - \frac{A_P}{A_P + A_N} \left( 1 - e^{-\left(\frac{A_N A_P}{A_P + A_N}\right) T} \right) \right] \\
 &= -\frac{1080 \times 84}{1080 + 84} \left[ -\frac{8760}{84} - \frac{84}{1080 + 84} \left( 1 - e^{-\left(\frac{1080 \times 84}{1080 + 84}\right) 8760} \right) \right] = 8133.46 \text{ Hr}
 \end{aligned}$$

The final solution is to adopt the configuration of the future asset where the expected duration of maintenance actions is reduced from 168 to 84 hours, as it provides an additional work of 351 Hr in respect to the competing configuration (improved reliability) and 533 Hr in respect to the original solution.

The impact of all feasible solutions presented above on: revenue, cost and profit could be easily predicted by making use of the equations provided in the Appendix A.

## 5. Conclusion

Thus, the main objective of this paper was to introduce reliability and maintenance professionals to MIRCE Science, a body of knowledge that enables quantitative prediction of the complex interactions between reliability and maintenance issues on in-service performance of assets to be done.

By making use of MIRCE Functionability Equation it is possible to perform analytical trade-off between feasible reliability methods and maintenance policies to select the compromising solution that will maximise “up time” for a given budget. A numerical example provided clearly illustrates the applicability of MIRCE Science to asset’s planning and management processes that are the essential part for any business’s main objective to stay in businesses.

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## Appendix A: Costs of Work Done

### Cost of Positive work

Cost of Positive Work (CPW): a generic name for the physically measurable performance of an asset determined by the monetary value of all the resources related to the delivery of positive work, like operational personnel, consumable material, equipment, facilities, energy and similar. Generally speaking it encompassed all the costs related to delivery of the positive work by the asset during a given interval of calendar time  $T$ , denoted as  $CPW(T)$ . It is equal to the sum of the following cost elements:

- The Set Up Cost ( $CPW_{set}(T)$ ): a generic name for the cost related to the provision of a new or modification of existing operational resources like equipment and tools needed for the asset operation, additional training of operational personnel, modification of existing or construction of new operational facilities, and similar types of resources that have to be obtained prior to the introduction of the asset into service.
- The Fixed Cost of delivering positive work ( $CPW_{fix}(T)$ ): a generic name for the cost related all expenditure that is not related to the amount of positive work done. Typical examples are cost related to: insurance, health and safety issues, training, licensing and so forth.
- The Variable Cost of delivering positive work ( $CPW_{var}(T)$ ): a generic name for the cost related to the resources consumed by the asset while delivering positive work.

The variable cost is the most difficult to predict. Hence, in the context of MIRCE Science, it is equal to the product of the Hourly Cost of doing the positive work,  $HC_{PFW}$  [MU/Hr] and the amount of the positive work done by the asset during the given interval of calendar time  $T$ , defined by the equation 1, thus:

$$CPW_S(T) = CPW_{set}(T) + CPW_{fix}(T) + HC_{PFW} \times PFW_S(T), \quad [MU] \quad A1$$

### Cost of Negative work

Cost of Negative Work (CNW) is a generic name for the physically measurable performance of an asset determined by the monetary value of all the resources used by an asset to perform the negative work, like spare parts, qualified personnel, material, equipment, facilities, energy and similar. Thus, it encompassed all the costs related to performing the negative work, performed on the asset during a given interval of calendar time  $T$ , denoted as  $CNW(T)$ , is equal to the sum of:

- The Set Up Cost ( $CNW_{set}(T)$ ): a generic name for the cost related to the provisioning of new or modification of existing maintenance resources. Typically, new equipment and tools for the maintenance of the asset, additional training of maintenance personnel, modification of existing or construction of new maintenance facilities, and similar types of resources that have to be obtained prior to the introduction of the asset into service.
- The Fixed Cost of delivering negative work ( $CNW_{fix}(T)$ ); a generic name for the cost related to all expenditure that is not related to the amount of the negative work done. Typical examples are insurance cost, health and safety related issues, personnel training cost, facilities rent, licensing costs, updating of technical information and so forth.
- The Variable Cost of negative work ( $CNW_{var}(T)$ ): a generic name for the cost related to the resources used while delivering negative work. Hence, the cost of doing negative work is a measurable quantity for each asset considered.

Based on the above cost categories a generic expression for the total cost of delivering the negative work during the stated period of calendar time  $T$ , in MIRCE Science is defined by the following expression:

$$CNW_S(T) = CNW_{set}(T) + CNW_{fix}(T) + HC_{NFW} \times PFW_S(T) \quad [MU] \quad A2$$

The delivery of positive and negative work through time uniquely determines the positive and negative functionability costs that correspond to the motion of an asset through the functionability states. As this motion is in the direction of calendar time, it means that the magnitudes of the positive and negative functionability costs are non-decreasing measurable characteristics of the assets, and as such they are “legitimate” measures of their overall functionability performance.

### MIRCE Profitability Equation

Generally speaking, the revenue generated by each asset during a given interval of calendar time, denoted as  $REV(T)$ , is equal to the product of the hourly income, denoted as  $HI$ , expressed in [MU/Hr] and the amount of the positive work done by the asset during the stated interval of calendar time,  $PFW_S(T)$  expressed in [Hr], thus:

$$REV(T) = HI \times PFW_S(T) \quad [MU]$$

In MIRCE Science a profit,  $PRF(T)$ , is equal to the difference between the revenue,  $REV(T)$  and the Total Functionability Cost, during the stated period of calendar time,  $TFC(T)$ , thus [3]:

$$\begin{aligned} PRF(t) &= REV_S(T) - TFC_S(T) \\ &= [HI_S \times PFW_S(T)] - [CPW_S(T) + CNW_S(T) + CLR(T)] \quad [MU] \end{aligned} \quad A3$$

The MIRCE Profitability Equation unifies all aspects of the functionality performance of an asset including the cost of lost revenue,  $CLR(T)$ , which in reality, is an in-separable element on the expected profit. This equation enables more accurate predictions of the expected profit to be made for each operational scenario, maintenance policy and support strategy of the asset considered. Also, the above equation “integrates” the whole organisation into a single “normalised” analytical entity, rather than a large collection of self-standing numbers generated by specific models to address specific a few characteristics at a time, in the hope that the performance of the asset will be satisfactory, when it enters into service,

## **Managing an Aircraft Microbial Contamination of Fuel Tanks as a Mechanism of the motion through the MIRCE Space**

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### **Abstract**

*The paper addresses the management process of microbial contamination of fuel tanks as a physical mechanism of the motion of an aircraft through MIRCE Space. [1] Contaminated fuel could cause undesirable consequences for a fuel system, like: clogging of fuel filters, corroding tanks and performance degrading build up of deposits caused by the acids the microbes excrete which cause the fuel to break apart and lose combustion quality, as well as damaging the rubber system components specific to the fuel tank, impacting the functionability performance of an aircraft. Thus, this paper focuses on the observed physical phenomena or human activities related to the microbial contamination in the aviation industry and some of them are briefly described and analysed. Based on the evidence available recommendations for the reductions of the probability of occurrence of microbial contamination of fuel tanks are presented. A full understanding of this mechanism is essential for the determination of the most effective maintenance policy for a functionable system consider by making use of the MIRCE Functionability Equation.*

### **1. Introduction**

On 13 April 2010 a Cathay Pacific Flight 780 was on route from Surabaya Juanda International Airport in Indonesia to Hong Kong International Airport with 309 passengers and a crew of 13 on board. As the Airbus A330 (B-HLL) approached Hong Kong the crew were unable to change the thrust output of the engines. As the control of thrust became impossible, the crew declared a PAN and then a MAYDAY. The aircraft landed at almost twice the normal speed causing the deflation of five main tyres after the aircraft came to a complete stop, generating a fire and smoke on the wheels. An emergency evacuation of passengers was performed. The 57 passengers sustained injuries during the slide evacuation. The cause of the accident was the contamination of the fuel uploaded at Surabaya, which gradually damaged both engines of the aircraft.<sup>24</sup> The contaminated fuel contained particles of a super absorbent polymer (SAP), which caused the main metering valves of the fuel-metering unit to seize. The valves were found to be stuck in positions corresponding to the recorded thrust output of each engine as the aircraft approached Hong Kong. [2]

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

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<sup>24</sup> "Pilots reveal death-defying ordeal as engines failed on approach to Chek Lap Kok". South China Morning Post. 20 April 2014. (Accessed 21 July 2020)

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 as a potential mechanism of the motion of an aircraft through MIRCE Space, which governs its physically measurable functionability performance, namely work done and resources consumed. Recommendations for the reduction of the probability of occurrence of microbial contamination of fuel tanks are presented, based on the industry best practices.

## 2. MIRCE Science Fundamentals

According to MIRCE Science<sup>25</sup>, at any instant of calendar time, a given functionable system<sup>26</sup> 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.
- 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

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<sup>25</sup> MIRCE Science is a body of knowledge that predicts the time evolution of operationally defined functionable systems by subjecting natural and human actions to the laws of mathematics. (accessed 23.11.2020)

<sup>26</sup> 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.” [1]

not give sufficient granularity of observations, which could lead to the prediction errors.

Microbial contamination impacts the functionality 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.”

### **3. Types of aviation fuel contamination**

#### **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 pass 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).

Yeasts and moulds belong to a group of microorganisms collectively known as Fungi. All of these organisms are present in the 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<sup>27</sup> 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 grows in the aircraft fuel environment is the fungus *Hormoconis resinae*<sup>28</sup>, due to its size. Compared to single-cell yeasts and moulds, 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.

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<sup>27</sup> Alkanes are functional saturated hydrocarbons that form a chain with single bonds between atoms.

<sup>28</sup> 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]

Aviation fuel is mainly composed of hydrocarbons<sup>29</sup> 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 that are 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 1/5 and 1/2 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 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

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<sup>29</sup> Compounds containing only carbon and hydrogen

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<sup>30</sup>, 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 to help prevent corrosion and some anti-microbial activities. Due to the current environmental consideration, chromates<sup>31</sup> 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

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<sup>30</sup> 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.

<sup>31</sup> Chromates are harmful when powdered because the dust is carcinogenic.

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<sup>32</sup> to withdraw EI 1583 Report<sup>33</sup>. 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.

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. Microbial Contamination Treatment and Prevention**

The best and most effective way of tackling 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<sup>34</sup>:

- Fuel monitoring program for the microbes: it involves periodic testing and sampling of the fuel, with the objective to minimise the problems through early 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 tanks is to reduce the exposure of the fuel to water. There are various ways this could be achieved<sup>9</sup>.
- 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

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<sup>32</sup> The Energy Institute is an independent professional organisation for engineers and other professionals in energy related fields established in 2003 in London, UK.

<sup>33</sup> EI 1583: Laboratory tests and minimum performance levels for aviation fuel monitors to be withdrawn at the end of 2020.

<sup>34</sup> <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%20spoilng> (accessed 5.8.2020)

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,
- speed desired to kill the microbes, in accordance to regulatory approvals.

## **6.1 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 contaminants. 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.

## **6.2 Topping up fuel tanks**

A good practice 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 rate of absorption will be significantly lower.

## **6.3 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.

#### **6.4 Cap fuel lines during maintenance**

During maintenance activities on the fuel system it is essential to remember to cap fuel lines to prevent particulates entering the system. Otherwise, the maintenance process designed to improve their condition can actually cause future problems as the following example<sup>35</sup> clearly illustrates. During an annual inspection that took place on Friday a dried-out, cracking fuel line was found. The qualified mechanic immediately started the fuel line replacement that was finished on Monday and the aircraft was approved for return to service. The pilot of the aircraft, his daughter, and two guests were killed when the engine quit after takeoff. The National Transportation Safety Board (USA) investigation found that a bee was present in the recently replaced fuel line, which the mechanic had left uncapped over the weekend.

#### **6.5 Fuel Tank Design**

The most important aspect of maintaining high quality in aircraft fuel is the design of the fuel system<sup>36</sup>. The current practice is to coat the internal areas of the piping, storage tanks and major equipment using high solids epoxy paint effective for hydrocarbon immersion service. It is expected that the slick surface will minimise corrosion and sediment build-up on the majority of the exposed surfaces.

### **7. COVID-19 disruption creates perfect conditions for microbial contamination**

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 is 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.

Aircraft should be tested by their airlines for signs of microbial contamination in the fuel, although it poses its own challenges. Microbe levels are highest at the interface between water and fuel and decline farther away from the water. Microbe populations can fluctuate over time. Even further, sampling and testing equipment must be kept sterile to avoid accidental contamination.

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<sup>35</sup> <https://www.aviationpros.com/aircraft/article/10387588/fuel-contamination-increasing-awareness-on-factors-that-lead-to-jet-fuel-contamination> (accessed 13.08.2020)

<sup>36</sup> <https://www.aviationpros.com/aircraft/article/10387588/fuel-contamination-increasing-awareness-on-factors-that-lead-to-jet-fuel-contamination> (accessed 29.07.2020)

As the duration of the 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 help will be required because disposal of contaminated fuel is not something that is routinely done at airports. [10] The logistics of this process is very challenging due to the access of injection carts, availability of the additive and also simple things like being able to access aircraft that are parked nose to tail on taxiways.

## 8. Conclusions

Aviation fuel, whose primary function is to power the aircraft, is a complex mixture of thousands of organic compounds known as hydrocarbons. Although at the end of the refining process the fuel is not contaminated. However, the journey from refinery to the aircraft fuel tank provides many opportunities for it to become contaminated. One of the major contaminants of aviation fuel is a microbe, as bacteria and fungi find it to be highly favourable media for multiplication.

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.

In summary the potential consequences of engines transitions to a NFS, caused by microbial contamination, may be simply economical, but in some cases may have serious consequences on the natural environment and humans. Thus, better understanding of the physical mechanism that govern this process provides better opportunities for designing a fuel systems for aircraft that are less susceptible to the microbial contamination or developing more robust maintenance tasks for their management and control.

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.

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## **Microbial Decontamination of Fuel Tanks as a Mechanism of the Motion of an Aircraft through MIRCE Space**

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### **Abstract**

*The paper addresses the microbial decontamination of fuel tanks as a physical mechanism of the motion of an aircraft through MIRCE Space, in accordance to MIRCE Science<sup>37</sup>. In cases where microbiological contamination is detected and decontamination needs to be done with biocides, up-to-date instructions in the Aircraft Maintenance Manuals should be followed to ensure that the correct method and dosage is applied. Although in-service problems with this maintenance task are not frequent, the consequences of its incorrect execution could lead to the occurrence of “a serious incident”. The case study analysed in this paper is related to the event of this type that took place at London Gatwick Airport on 26 February 2020. A full understanding of the sequence of actions that led to the occurrence of this negative functionality event is essential for drawing recommendations for the reduction of the probability of human errors during the microbial decontamination process of fuel tanks of an aircraft, some of which are presented in this paper.*

### **3. Introduction**

Millions of gallons of aviation turbine fuel are used daily to power thousands of the aircraft to facilitate thousands of flights all over the world. It is complex mixture of thousands of organic compounds known as hydrocarbons, which is sterile when produced. However, during the transport, storage and in the aircraft fuel tank, it may become contaminated. One of the major contaminants of aviation fuel are microbes, like bacteria and fungi. Contaminated fuel can cause significant damage to the aircraft and engine, which can range from fuel system corrosion, clogging of fuel filtration components, failure of aircraft fuel system instrumentation, and even stopping the fuel supply to the engines during flight and in some cases may even be fatal. In the past several aeroplane crashes have been attributed to the deterioration of aviation fuel caused by microbial contamination. [2]

Microbial contamination is not specific to any one fuel type, diesel, petrol, bio-diesel, kerosene, gasoline, and other fuels used in marine, aviation, automotive and home heating applications are all susceptible. Similarly there is no single specific organism that can be identified as being responsible for degradation and spoilage. As a general

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<sup>37</sup> MIRCE Science is a body of knowledge that studies the motion of functional systems through MIRCE Space resulting from any functionality actions whatsoever and predicts work done and resources needed.[1]

rule, wherever fuel and water come into contact in storage or distribution system microbial contamination is likely to occur.

In the initial stages of contamination the organisms present are predominantly aerobic, using the dissolved oxygen in the water for respiration. As this supply of oxygen is depleted, anaerobic organisms, known as sulphate reducing bacteria, develop. These organisms do not require oxygen for respiration and form corrosive waste products such as hydrogen sulphide.

Once a microbial population becomes established fuel quality rapidly deteriorates. Problems such as haziness, failure to meet specifications, corrosion, filter plugging and additive degradation can occur. All of these problems are related directly to the presence of microorganisms or their associated by-products.

Several factors that affect the presence of microbial contaminants in jet fuel and thus determine to a large extent the quality of aviation fuel, have been determined. Among them, as indicated by numerous studies, the presence of free water is the most important one. However, for various reasons it is almost impossible to prevent the presence of at least minimal amounts of water in jet fuel. Therefore, microbial contamination of turbine fuel is almost inevitable, which requires decontamination actions to take place in order to restore the functionability of the aircraft affected.

The main objective of this paper is to address microbial decontamination of fuel tanks as a potential mechanism of the motion of an aircraft through MIRCE Space, which could have a huge impact on its physically measurable functionability performance, namely work done and resources consumed. Also, based on the real life case study analysed in the paper possible recommendations for the reduction of the probability of human error during the microbial decontamination of fuel tanks are presented, based on the philosophy of MIRCE Science.

## 2. MIRCE Science Fundamentals

The philosophy of MIRCE Science is based on the premise that the purpose of existence of any functionable system<sup>38</sup> is to do a work, which is considered to be done when a measurable function is delivered through time, like miles travelled, units produced, energy supplied and similar. [1]

According to MIRCE Science, at any instant of calendar time, a given functionable system 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 measurable function(s),
- Negative Functionability State (NFS), a generic name for a state in which a functionable system is unable to deliver the expected measurable function(s), resulting from any reason whatsoever.

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<sup>38</sup> Functionable system is a set of mutually related entities that delivers a physically measurable work through a calendar time in accordance to operationally defined rules. [1]

In MIRCE Science a functionability performance of a functionable system is defined by the trajectory of its motion through MIRCE Space. Mathematically, it is a three dimensional space containing functionability points, each representing a discrete functionability state that a functionable system could be found in, probability of being in each of these states along the continuous calendar time.

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

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

MIRCE Mechanics is a part of MIRCE Science that focuses on the scientific understanding of the mechanisms that generate functionability actions that govern the motion of functionable systems through MIRCE Space [1]. A full understanding of these mechanisms is essential for predicting the expected functionability performances using MIRCE Science Equation, like work done and resources consumed.

### 3. Microbial Contamination Treatment and Prevention

Microorganisms that grow in water and use the hydrocarbons from the fuel as a food cause microbiological contamination of fuel in fuel tanks. The most effective means to prevent this contamination is protection of water ingress and accumulation in the fuel tanks is. Thus, keeping fuel tanks clean is one of the best methods to avoid contamination.

Preventive actions against microbial contamination of fuel tanks can be considered as the following three parts<sup>39</sup>:

- **Fuel monitoring program** for the microbes that consists of a periodic testing and sampling of the fuel. The main objective is to minimise the problems by early detection of microbial growth. During this process the procedures that are outlined in appropriate industrial standards and aircraft manufacturer's maintenance manuals should be followed.
- **Maintenance of fuel system** whose main objective is to prevent microbial growth in fuel by reducing the exposure of the fuel to water. There are various ways this could be achieved. [2]
- **Fuel treatment** methods that should control the spreading of microbial growth including decontamination, which is a removal of the already developed biomass or the sludge. When choosing a remover, several factors should be considered namely the solubility of the fuel/water, compatibility with system

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<sup>39</sup> <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)

components, compatibility with fuel and other additives, speed desired to eliminate the microbes, in accordance to regulatory approvals.

In this paper a highly effective “shock dosage” (killing existing growth) microbial decontamination process will be examined and analysed.

#### **4. Microbial decontamination**

In case microbiological contamination is detected and needs to be treated with biocides, maintenance personnel, aircraft owners and operators are expected to follow up-to-date instructions in the engine and aircraft manufacturer’s Aircraft Maintenance Manuals (AMMs) to ensure that the correct method and dosage is applied during the decontamination process.

In case of discrepancies caused by different update cycles of aircraft documentation, it is imperative that the manufacturer should be contacted for further advice.

During the microbial decontamination process appropriate precautions should be taken, which include the following:

- Personal protection equipment (PPE) should be employed to avoid dermal contact, including suitable gloves of butyl rubber or nitrile rubber, safety goggles, and if required, a face shield.
- Treated fuel tanks should be at least 10% full before treatment. Do not dispense into empty fuel tanks
- Used biocides must be treated in accordance to local regulatory requirements and must not exceed recommended dose levels
- The most reliable way to get additive into the fuel system is by metered injection. If the use of an injection system is not possible a batch may be made to pre-dilute the product

#### **5. The biocides**

Harmful or unwanted organisms such as viruses, bacteria, fungi, insects and animals are controlled by biocides through chemical or biological means.

It is important that there are safeguards to ensure that products containing biocides can be used without causing harm to people, the environment or animals. This process is governed by national and international governing organisations, such as:

- In the UK, Health and Safety Executive (HSE) is the UK Authority for biocides that runs two regulatory schemes<sup>40</sup>, which assess the safety of such products and the active substances within them, and puts conditions on the use of these products.
- In the European Union, Biocides Regulation (Regulation 528/2012) covers a very diverse group of products. It repeals and updates the Biocidal Products Directive 98/8/EEC.

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<sup>40</sup> These schemes are: the Biocidal Products Regulations and the Control of Pesticides Regulations.

- In the USA, the Federal Aviation Administration (FAA) that has published a Special Airworthiness Information Bulletin (SAIB), which provides general guidance on the use of biocide jet fuel additives that can be used to supplement existing original equipment manufacturer procedures.

The two most common biocides in use for the decontamination in aviation industry are Biobor JF and Kathon FP1.5.

### 5.1 Biobor JF

Biobor JF<sup>41</sup> is a liquid fuel additive developed in 1965 to combat fungus and other microbial life in hydrocarbon fuels such as home heating, diesel, jet fuels, and light oils. It eliminates growth of harmful slime-producing fungi and algae that clog filters and fuel lines, attack rubber fuel system components and whose waste products aid in the corrosion of metal surfaces.

Biobor JF is easy to use and harmless to the wide variety of fuel system parts, top coatings, sealants and elastomeric materials used.

Some of the physical and chemical properties of Biobor JF are shown in the table below.

Property	Description
pH	Not Applicable
Odour	Aromatic
Evaporation rate	<1 (n-Butyl Alcohol)
Flash point	102°F (38.8°C)
Appearance	Clear liquid
Boiling point	529°F (276.1°C)
Specific gravity	1.05
Hazard class	Hazardous as a flammable liquid

Table 1: Physical and chemical properties of Biobor JF

### 5.2 Kathon FP1.5

Kathon FP 1.5 is biocidal substance that has been notified under the Biocidal Products Directive (BPD) and is registered with the United States Environmental Protection Agency (US EPA). It is a solution of the technical grade of the active ingredient, CMIT/MIT<sup>42</sup>, in dipropylene glycol at a nominal value of 1.5% of active substance. Kathon FP 1.5 is effective against microbial species commonly encountered in fuel systems, including bacteria, yeast, and mould. It is designed to cause inhibition that rapidly becomes irreversible and results in cell death of microbial growth upon contact.

<sup>41</sup> In 1965 scientist and engineers from U.S. Borax and SOHIO created the first aviation fuel biocide and named it Biobor JF<sup>®</sup>

<sup>42</sup> Abbreviated name for KATHON<sup>™</sup> FP 1.5 contains a 3:1 ratio mixture of 5-chloro-2-methyl-(2H)isothiazolone (CMIT) and 2-methyl-3(2H)isothiazolone (MIT).

For fuels that are heavily contaminated, Kathon FP 1.5 is used as a shock biocide. In these cases, doses up to 1000 particles per million (ppm)<sup>43</sup> can be administered according to the BPD. In this case, the residence time is recommended to be a full 24 hours.

Kathon FP 1.5 can also be used in fuels not contaminated with microbial, as a preventative maintenance measure (to guard against bacterial contamination). In those cases, the recommended dosage is 100 to 150 ppm. The biocide should be added in such a manner so as to allow good mixing and uniform distribution of the biocide across the fuel. In such a case the residence time should be at least 12 hours.

Property	Description
pH	4-6
Odour	Mild
Appearance	Yellow, liquid
Molecular weight (g/mol)	149.45 (CMIT), 115.16 (MIT)
Freezing point	< -20°C (-4°F)
Specific gravity	1.04
Hazard Class	Corrosive material

Table 2: Physical & chemical properties of Kathon FP1.5

DuPont, the manufacturer of Kathon FP1.5 announced in March 2020 that they are no longer able to sell it for aviation fuel applications, but many other users, from rail operators to super-yachts, could use it.

## 6. MIRCE Science Analysis of “a serious incident” of G-POWN aircraft

This case study focuses on MIRCE Science analysis of functionability event related to the microbial decontamination of aircraft G-POWN in February of 2020 with objectives to understand actions that led to the occurrence of this negative functionability event, as well as to derived the actions that should be taken in the future for the reduction of the probability of their re-occurrences.

### 6.1 The Aircraft (G-POWN)

The aircraft considered, Airbus A321-211, originated the motion through MIRCE Space in March 2009 as OE-LET in Austria, as a part of Niki Airways fleet. It was equipped with a two SFMI<sup>44</sup> engines. In March 2016 it was purchased by Titan Airways, a passenger and cargo air-charter services company in UK, and continued in-service life as G-POWN.

During its motion through MIRCE Space G-POWN was scheduled to enter a NFS in late January 2020 for an extensive positive functionability action with an Approved Maintenance Organisation (AMO). As a pre-requisite for this PFA, on 23 November

<sup>43</sup> 1 litre of biocide per 1000 liters of aviation fuel.

<sup>44</sup> French-American high-bypass turbofan aircraft engine made by CMF International (CFMI), which is 50-50 joint-owned company of Safran Aircraft Engines (formerly known as Snecma) of France and General Electric (GE) of the United States.

2019 the operator took fuel samples from the aircraft tanks to be tested for microbial contamination<sup>45</sup>, in accordance with the Aircraft Maintenance Manual (AMM).

The samples were sent to a laboratory which determined a moderate level of contamination. The AMM's report states that a second test is required no more than 10 days after the first test and, should this show positive, then biocidal treatment should be applied to the fuel tanks within a further 10 days. A work card for the treatment of the tanks was raised by the operator and sent to the AMO on 8 January 2020 for inclusion in the scheduled PFA. No further microbiological testing was performed.

## 6.2 The scheduled positive functionability action

The aircraft entered the AMO's hangar on 23 January 2020 and the PFA started. The operator's work card requested a biocidal shock treatment for moderate contamination with Kathon FP1.5 biocide in accordance with AMM Task 28-11-00-600-008-A01. The biocidal treatment was not designated a critical maintenance task<sup>46</sup> by the AMO. The task states that fuel should be mixed with Kathon biocide at a concentration of 100 parts per million (ppm) by volume and then the aircraft pressure-refuelled using the onboard automatic control functionality in accordance with AMM Task 12-11-28-650-003-A<sup>47</sup>. The Kathon dosed fuel should remain in the aircraft fuel tanks for 24 hours.

The EASA Part-66 B1 licensed AMO engineer dealing with this task was not familiar with the term 'ppm'. It was not written in expanded form anywhere in the AMM Task or glossary, and the AMM task did not provide instructions about how to perform the calculation of the quantity of Kathon to be use. The engineer searched the Internet for a definition and conversion calculator. Knowing that each wing tank contains 6,200 kg of fuel, based on Internet calculator, he calculated that a quantity of 30 kg of Kathon should be added to each wing tank.

The AMO engineer added 30 kg of Kathon to each wing tank through the overwing apertures and uplifted 6,200 kg of fuel into both wing tanks. In accordance with the AMM task, the engine and APU fuel filters where changed and aircraft was left in situ for 24 hours.

The next day 6,400 kg of fuel was transferred from the wing tanks to the centre fuel tank and again left in situ for 24 hours. All the access panels to the fuel tanks were open to allow work to be carried inside them until 19 February 2020 when the aircraft was moved outside. Once outside, the fuel tanks were leak-checked and treated for moderate microbial contamination. Finally the task card was stamped as complete, with a further task opened to perform a biological contamination check within 10 days, but after at least 5 flights.

The aircraft departed the AMO in PFS and returned to the operator's base on 24 February 2020.

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<sup>45</sup> Task 12-32-28-281-003-A, *Sample Fuel for Microbiological Contamination Analysis*.

<sup>46</sup> EASA Part M, AMC1 M.A.402(h) Performance of CRITICAL MAINTENANCE TASKS.  
<https://www.easa.europa.eu/sites/default/files/dfu/Annex%20I%20to%20Decision%202016-011-R.pdf>  
(accessed 07 April 2020)

<sup>47</sup> Pressure Refuel with Automatic Control

### 6.3 The negative functionability event on 26 February 2020

At 2349 hrs G-POWN's crew of initiated a positioning<sup>48</sup> flight from London Gatwick Airport (Gatwick) to London Stansted Airport (Stansted), by starting the No 2 engine, but they experienced difficulties starting the No 1. Technical Control suggested to pilot to attempt another start, which was successful. As the engine control indications appeared normal, the crew commenced the takeoff at 0009 hrs. At around 500 ft, the No 1 engine began banging and surging. Pilot observed that the engine's control indications were fluctuating, and the aircraft was "yawing... and fishtailing... all over the place" [3]. However, there was no accompanying message from the Electronic Centralised Aircraft Monitoring (ECAM) system. A number of cabin crew saw flames coming from the No 1 engine's tailpipe and attempted to contact flight crew via the interphone. Flying pilot transmitted a MAYDAY call, requesting a return and issued an alert call to the cabin crew. Just after commencing descent, the ECAM message "Eng 2 stall" was displayed three times in quick succession. Co-pilot prepared the aircraft's flight management guidance system for a return and the pilot positioned the aircraft on a 9 nm final approach. He opted to fly slightly above the glide path in order to minimise the thrust required by the engines, and so that he could glide the aircraft to the runway if the engine problems worsened. The aircraft landed at 0020 hrs, with the reverse thrust appearing to function normally. [3]

The Air Accident Investigation Branch (AAIB) of the UK Government classified this NFE as "a serious incident" and began an investigation on 26 February 2020 in accordance with established international arrangements<sup>49</sup>.

### 6.4 Sequence of functionability events preceding the incident flight

On 26 February 2020, G-POWN's first job was a positioning flight from Stansted to Gatwick. At around 0520 hrs, the No 2 engine started normally, but the flight crew experienced problems while starting the No 1. The engineer who was assisting with the engine starts, via an external headset, advised the crew to attempt another start on the No 1 engine, which was successful.

Later in the day, a different crew boarded G-POWN to conduct a return charter trip to Krakow International Airport (Krakow), Poland. The engines operated normally on the outbound flight. At around 2000 hrs, at the beginning of the return flight the No 1 engine required more than one attempt to start successfully. The crew notified the operator of the starting problem via a datalink<sup>50</sup> message from the aircraft after departure from Krakow. During the flight, the ECAM system displayed the message "Eng 2 stall" momentarily on two occasions. On arrival at Gatwick, at around 2230 hrs, the pilot informed the operator's Technical Control department via phone that the No 2 engine stall event and the defect was recorded in G-POWN's technical log. [3]

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<sup>48</sup> Positioning flight – a flight without passengers

<sup>49</sup> The AAIB is being assisted by Accredited Representatives appointed by the Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile in France, the National Transportation Safety Board in the USA, and the Aircraft Accident and Incident Investigation Board in Cyprus. The Accredited Representatives are supported by Technical Advisors from the aircraft and engine manufacturers.

<sup>50</sup> Datalink – A system of text messaging between aircraft and ground stations

The operator's Technical Control instructed an EASA Part-66 B1 licensed engineer, who worked for an EASA Part-145 AMO that provided line maintenance at Gatwick for the operator, to attend the aircraft to troubleshoot the No 2 engine stall. The engineer accessed the troubleshooting manual (TSM) via manufacturer's online system *AIRBUS World: AirN@v Maintenance*. This system had two different applications: *AirN@v* and *airnavX* that was recently introduced to replace *AirN@v*. The operator had granted the AMO access to the operator's data on *AirN@v* but not *airnavX*, so the engineer used *AirN@v* to try and access the applicable troubleshooting procedure. The design of *airnavX* requires the user to filter data to a specific aircraft before going through the troubleshooting process but *AirN@v* does not. The engineer did not filter the TSM for the G-POWN, but accessed the procedure using the TSM table of contents, which enabled him to access the procedures for all the operator's Airbus aircraft. Consequently, the engineer printed and followed TSM procedure 77-11-00-810-815-A<sup>51</sup>, which applied to LEAP-1A32 engines.

However, G-POWN was fitted with the CFM56-5B3/3 engine and the applicable TSM procedure for this engine is 73-00-00-810-866-A<sup>52</sup>, which requires an extensive examination of the engine, including borescope inspections of the high pressure and Stage 1 low-pressure turbine blades. As the no fault was found during the troubleshooting procedure, the engineer signed off the engine stall defect and the Certificate of Release to Service in G-POWN's technical log.

## 6.5 Post incident functionality analysis

In order to understand the mechanisms that generated this "serious incident" several analysis are performed, some of which are briefly presented below.

### 6.5.1 Fuel Analysis

Fuel samples were taken from both wing fuel tanks and water drain valves were subjected to laboratory analysis. The tested fuel was found not to comply with the JET A-1 specification requirements<sup>53</sup> for appearance and water separation characteristics. The fuel samples, once the contents had settled out under gravity, contained a separate brown liquid layer beneath the main fuel layer. Trace element results of the fuel and the bottom brown layer showed similar spectra to a reference Kathon sample, but with a higher water content. The laboratory that conducted the fuel testing concluded that [3]: "The results indicate contamination with undissolved Kathon. It was noted that the bottom layer that is mostly Kathon plus some unknown products and water, suspected to be causing the darker colour than the reference Kathon sample. This is likely due to the glycol type solvent used in Kathon product dissolving polar materials from the fuel and fuel tank surfaces."

### 6.5.2 Engines Analysis

The aircraft's engines were examined visually using a borescope and both exhibited the following findings: "There was no significant damage evident to the fan, low-pressure

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<sup>51</sup> Stall above idle on engine 1(2)

<sup>52</sup> Stall of engine 1 or 2 in flight

<sup>53</sup> 14 DEF STAN 91-091 Issue 11 and AFQRJOS Check List Issue 31.

compressor or high-pressure compressor components, and any minor defects that were identified were within AMM damage limits. The combustion chambers, high-pressure and low-pressure turbine blades were coated in a thin layer of white material that was observed on the turbine blades' convex surfaces. The high-pressure turbine nozzle guide vanes were also coated in the white material." [3]

The borescope inspections performed were unable to collect samples of the white and brown materials from within the engines at the time. Additional examinations are planned that will include inspection of the engines' fuel system components.

### **6.5.3 Kathon FP1.5 quantity analysis**

The AMO engineer who determined the amount of Kathon to be added to the aviation fuel had never performed that task before and did not recognise that the computer assisted calculation was approximately 37 times higher than the recommended dose. To achieve a concentration of 100 ppm by volume, the following calculation should be made: 6,200 kg of aviation fuel uplifted, with a Specific Gravity<sup>54</sup> of 0.8075 (average) equates to 7,678 litres. For the recommended concentration of 100 ppm the correct amount of Kathon to be added is equal to  $7,678 \times 0.0001 = 0.7678$  litres. Using a Kathon Specific Gravity of 1.04 (see table 2) the amount that should be added is 0.7985 kg per wing tank.

Hence, the amount of Kathon added was approximately 37 times greater than the amount recommended. As the manufacturer of the aircraft had not designated this task as a critical task, no additional measures were used to check that it was performed in accordance with the AMM Task.

### **6.5.4 Aircraft Maintenance Organisation Analysis**

According to AAIB [3] the total amount of Kathon available in the AMO stores at Gatwick was 150 kg. However, there was no "alarm bell ringing" when the mechanic working on G-POWN made a material requisition for 60 kg of Kathon. It appears that no control measures were in place at the AMO stores or planning departments to prevent unusually large quantities of chemicals being issued to AMO staff.

### **6.5.6 Aircraft Maintenance Manual Analysis**

The AMM task instructions used the term 'ppm' for which there was no definition within the AMM glossary, and even more, no guidance was provided for the calculation of biocide fuel dosing calculation.

### **6.5.6 Troubleshooting task**

During the three flights on 26 February G-POWN experienced the following two problems:

- difficulties with the start-up of No 1 engine at Stanstead and Krakow

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<sup>54</sup> According to British MoD DEF STAN 91-091 Issue 11 a Specific Gravity of Jet A1 fuel is between 0.775 and 0.84 at 15°C. Thus, 1 kg of Jet A1 will range for a volume of 1.29 to 1.19 litres.

- momentary “Eng 2 stall” messages associated with the No 2 engine on descent into Gatwick.

However, the engineer allocated to deal with G-POWN that evening was tasked with troubleshooting the engine No 2 stall messages.

This was a lost opportunity to detect the abnormal deposits on the high pressure and low-pressure turbine blades. It is probably likely that a borescope inspection would have detected these deposits and, had it done so, it is unlikely that the aircraft would have been released to service.

In summary, the engineer on duty was not tasked with investigating any issues with the No 1 engine. As the symptoms presented by each engine were different no one considered there to be a possible common cause.

## **7. Safety actions taken after the incident event**

Based on the analysis performed several safety related actions have been implemented by regulators and operators. Some of them are briefly addressed below.

### **7.1 Actions by regulators**

The EASA issued Safety Information Bulletin SIB 2020-0616 on 20 March 2020, to notify affected stakeholders of recent air safety-related events involving Kathon biocide and to remind aircraft owners and operators to ensure that the correct method and dosage is used for approved biocide treatment of aircraft fuel systems.

The FAA issued Special Airworthiness Information Bulletin SAIB NE-20-04<sup>55</sup> on 25 March 2020 that contained similar regulatory guidance.

### **7.2 Actions by the manufacturers of the biocide and engines**

- On 10 March 2020 the manufacturer of Kathon discontinued the use of its product for aviation fuel applications.
- On 16 March 2020, CFM, the manufacturer of the G-POWN’s engines, issued Alert Service Bulletin 73-A0296 recommending that operators of CFM56-5B engines suspend the use of Kathon during aircraft fuel system biocide treatments.
- Similar instructions were issued for other variants of the CFM56 engine family, as well as all General Electric turbofan engines<sup>56</sup>.

### **7.3 Actions by the AMO at London Gatwick Airport**

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<sup>55</sup> [https://rgl.faa.gov/Regulatory\\_and\\_Guidance\\_Library/rgSAIB.nsf/dc7bd4f27e5f107486257221005f069d/05f721d6c7272c0986258536005bbe41/\\$FILE/NE-20-04\\_Corrected.pdf](https://rgl.faa.gov/Regulatory_and_Guidance_Library/rgSAIB.nsf/dc7bd4f27e5f107486257221005f069d/05f721d6c7272c0986258536005bbe41/$FILE/NE-20-04_Corrected.pdf) (accessed 9 April 2020).

<sup>56</sup> The discontinuation of Kathon for aviation applications, combined with the inability to use Biobor within the European Union presently, leaves their aircraft operators without an approved biocide treatment.

The AMO that performed the biocide treatment on G-POWN has introduced a new role of ‘technical engineer’. The technical engineer is expected to be an EASA Part-66 B1 licensed engineer, outside of the management chain within the organisation, who will be available to assist other licensed engineers and mechanics with technical queries, such as calculations.

The AMO is also expecting to introduce usage limits in stores so that staff will not be able to withdraw chemicals in quantities that significantly exceed the maximum permitted.

The Gatwick AMO issued a safety and compliance notice highlighting the importance of filtering maintenance data to the specific aircraft when using the TSM via manufacturer’s online system *AIRBUS World*.

#### **7.4 Action by the Operator**

In consultation with the manufacturer, the operator granted the Gatwick AMO access to the *airnavX* system.

### **8. Conclusions**

The main objective of this paper is to address microbial decontamination of fuel tanks as a potential mechanism of the motion of an aircraft through MIRCE Space, in accordance to MIRCE Science.

Although in-service problems with this functionality action are not frequent, the consequences of its incorrect execution could lead to the occurrence of “serious incidents”, which could have a huge impact on functionality performances, namely work done and resources consumed.

The case study analysed in this paper is related to the microbial decontamination of fuel tanks of Airbus G-POWN that took place at London Gatwick Airport on 26 February 2020. A full analysis of the sequence of functionality actions that led to the occurrence of “a serious incident” presented in this paper is essential for the understanding of the actions that should be taken regarding the reduction of the probability of human errors during the execution of this maintenance task, starting with the design of maintenance task and its description in Aircraft Maintenance Manual to the safety practices within Approved Maintenance Organisations, regarding: training of maintenance personnel, creation of technical engineer and usage limits in stores.

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## COVID-19 Pandemic as a Mechanism of the Motion of an Aircraft in MIRCE Mechanics

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### Abstract

*The COVID-19 outbreak has shown that pandemics, like other rarely occurring natural catastrophes, have happened in the past and will happen in the future. Although humans cannot prevent dangerous viruses from emerging, they should be prepared to dampen their consequences for the economy and all of society. The main objective of this paper is to address the COVID-19 pandemic as a novel mechanism of the motion of an aircraft in MIRCE Mechanics, as only then the most effective technological, social and economical actions can be taken by humans to deal with it. Examples of devastating impacts on aviation world-wide are given in the paper, as well as, some of the human and technological solutions taken to cushion their consequences. To assist airlines in the selection process of aircraft types that should be returned to the post pandemic service MIRCE Functionability and Profitability Equations are presented in the paper. They embrace the impact of COVID-19 on the expected positive and negative work, as well as the cost of associated resources, which determine their business existence.*

### 1. Introduction

The philosophy of MIRCE Science is based on the premise that the purpose of existence of any industrial system is to be industrial<sup>57</sup>, which means doing 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. [1]

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

- Positive Industrial State (PIS), a generic name for a state in which an industrial system is doing work,
- Negative Industrial State (NIS), a generic name for a state in which an industrial system is not doing work.

In MIRCE Science a work done by an industrial 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 an industrial state that an industrial system could be found in at any instant of time and the corresponding probabilities.

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<sup>57</sup> Industrial, adj - from Medieval Latin *industrialis*, in relation to Latin *industria* meaning "engaged in, for use in, serving the needs of industries".

The motion of an industrial system through industrial states is governed by the following two types of actions:

- Negative Industrial Action (NIA) that causes occurrences of negative industrial events (NIE) at which industrial systems are compelled to move to NIS.
- Positive Industrial Action (PIA) that causes occurrences of positive industrial events (PIE) at which industrial systems are compelled to move to PIS.

MIRCE Mechanics is a part of MIRCE Science that focuses on the scientific understanding of the mechanisms that generate positive and negative industrial actions, which uniquely define a time evolution of industrial systems through MIRCE Space [1]. The minimum sufficient “physical scale” that enables scientific understanding of the mechanisms that govern positive and negative actions is between  $10^{-10}$  of a metre (the level of the atoms) and  $10^{+10}$  of a metre (at the level of the solar system). A full understanding of these mechanisms is essential for the predictions of expected performance of industrial systems using MIRCE Science Equations, like works done and resources consumed.

## 2. COVID-19 Pandemic

According to the World Health Organisation (WHO) a pandemic is “the world-wide spread of a new disease”, which is infectious and contagious.

As humans learned to live in-groups forming communities where they live close to each other and also travel across the seas, numerous diseases have spread around the world. Throughout history there have been numerous pandemics that claimed the lives of thousands, even millions of people. The top ten pandemics that affected humanity are presented in Table 1<sup>58</sup>.

<b>Pandemic</b>	<b>Duration</b>
Antonine Plague	165 - 180
The Black Death	1347 - 1352
Small Pox Pandemic	1870 - 1874
Cholera	1817 - 1824
Russian Flu	1889-1890
Spanish Flu	1918-1919
H3N2 Pandemic	1968 - 1970
HIV/AIDS	1981-??
SARS	2002 -2004
COVID-19 Pandemic	2019 - current

Table 1: Top ten pandemics throughout the human history

<sup>58</sup> <https://www.worldatlas.com/articles/10-pandemics-throughout-history.html>  
(accessed 23.11.2020)

The global pandemic caused by the newly discovered severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has caused world-wide suffering and death of unimaginable magnitude from coronavirus disease 2019 (COVID-19).

The effects from the SARS-CoV-2 crisis on human health, health care systems and the global economy have been profound. The major cause of mortality from COVID-19 is acute respiratory failure from acute respiratory distress syndrome (ARDS), although a number of patients with the disease are showing cardiovascular issues such as congestive heart failure, cardiac arrhythmias and vascular thrombosis, as well as brain dysfunction. [3]

In order to make copies of themselves viruses must enter the cells of their hosts, which can be humans, copies are then released by the host cells and enter into circulation in the body, infecting still more cells. Then propagate through the world via host emissions such as respiratory droplets and infect new people. [4]

Transmission of respiratory infections such as COVID-19 is primarily via virus-laden fluid particles (i.e. droplets and aerosols) that are formed in the respiratory tract of an infected person and expelled from the mouth and nose during breathing, talking, coughing and sneezing. Droplets larger than a critical size settle faster than they evaporate, and so contaminate surrounding surfaces. [5]

Droplets smaller than this size evaporate faster than they settle, so forming droplet nuclei that can stay airborne for hours and may be transported over long distances.

Human-to-human transmission of COVID-19 occurs primarily via three routes:

- large droplets that are expelled with sufficient momentum so as to directly impact the recipients' mouth, nose or conjunctiva;
- physical contact with droplets deposited on a surface and subsequent transfer to the recipient's respiratory mucous;
- inhalation by the recipient of aerosolised droplet nuclei from the expiratory ejecta that are delivered by ambient air currents.

The first two routes associated with large droplets are referred to as the 'droplet' and 'contact' routes of transmission, whereas the third is the so-called 'airborne' transmission route. Respiratory infections hijack our respiratory apparatus to increase the frequency and intensity of expiratory events, such as coughing and sneezing, which are particularly effective in generating and dispersing virus-carrying droplets. [5]

### **3. Impact of COVID-19 on Aviation**

At the beginning of the 2020 the world's airlines were operating around 24,000 passenger jets with at least 50 seats. Today that number is lower by approximately 80%. The impact of COVID-19 on UK passenger air transport movements is drastically reduced, as shown in Figure 1 [10].

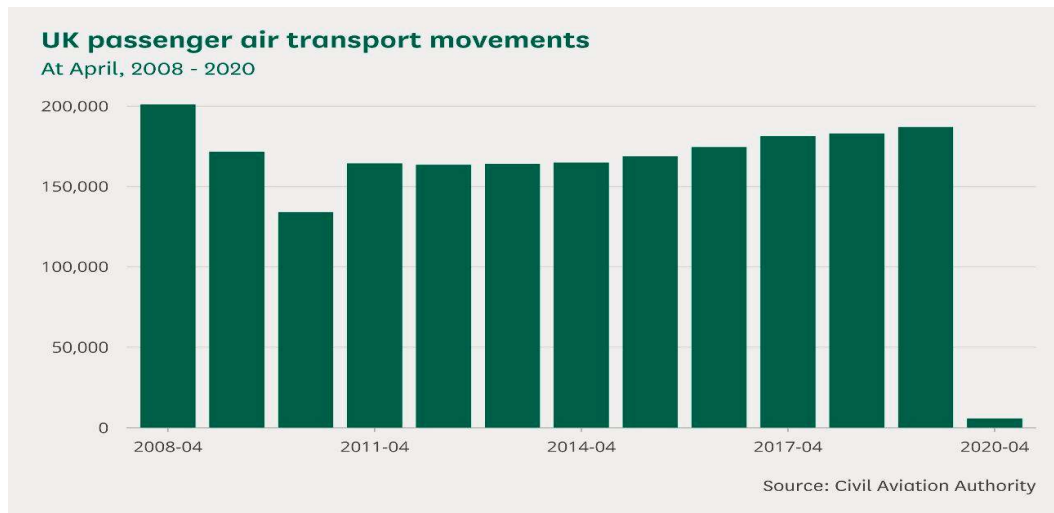


Figure 1: UK passenger air transport movements

The drastic reductions of flights in commercial aviation happened in the past due to some of the following negative mechanisms that generated NIE:

- design problems:
  - grounding of Boeing B737 MAX by aviation safety authorities world-wide, following two fatal accidents that involved the plane's anti-stall system,
  - grounding of Rolls Royce Trent 1000-powered aircraft (B787) due to cracking problems in the intermediate pressure section of the turbine,
  - grounding of Concorde after the crash outside Paris in which 113 people died.
- natural phenomena: volcano eruptions, earthquakes, fires, bird strikes and similar,
- weather conditions: tornadoes, hurricanes, blizzards, fog, and floods,
- political situations: wars and economical embargoes

The commonality in all of the above mentioned cases is the fact that there have been demands for work done by airlines (delivery of commercial flights), but they could not deliver the expected work (flights) due to safety and reliability reasons. However, the drastic reduction in the number of global commercial flights in 2020 is due to a totally different reason. Airlines and their fleets are in positive industrial state ready to deliver safe and reliable flights, but there is no demand for flights by the flying public, due to the fear of the further spread of COVID-19, by individuals, health and other governmental organisations.

Although humans cannot prevent dangerous viruses from emerging, they should be prepared to dampen their consequences for the economy and all of society. The main objective of this paper is to address the severe impacts of COVID-19 on the commercial aviation across the globe and to present the best technological, social and economical actions taken by humans to deal with it. Examples of devastating impacts on aviation and transportation industries are given in the paper, as well as, the human and technological measures taken to cushion their consequences.

#### 4. COVID-19 pandemic generated negative industrial events in aviation

Aircraft are designed in accordance to the laws of science and engineering to transport humans and cargo between chosen destinations through the air. Given satisfactory weather conditions, each airworthy aircraft is in a PIS, which means it is able to safely and reliability deliver expected transpiration work.

The business plan of each airline, world wide, expect that each aircraft in their fleet will safely and reliably deliver between 3500 and 4500 flying hours per calendar year. Hence, the types of aircraft in their fleets are determined by their ability to attract passengers on the routes chosen to fly. All of these factors together determine the price of each ticket, in the way that the revenue generated by flying passengers and cargo is greater than the cost of the resources associated with a delivery of the business plan.

From the beginning of 2020 the Covid-19 pandemic caused havoc in each airline, as their respective aircraft are not delivering flights in accordance to the business plan. By the end of 2020 it became clear that no airline in the world had managed to deliver the expected flying hours from their airworthy aircraft. The end of the year business reports will reveal the final statistics, but the estimated revenue loss, due to the outbreak of COVID-19, for the first six months of 2020 is around \$314 billion<sup>59</sup>.

The remaining part of the paper will examine the causes of those losses as well as the measures that the global aviation has taken to deal with the totally new business reality.

#### **4.1 Impact of the Covid-19 Pandemic on flight safety**

Although the global reduction in commercial air travel, due to the Covid-19 pandemic, has in many ways eased pressure on commercial aviation, in some cases it had the opposite effect on safety. The drastic drop in airline passengers has triggered an unusual type of incidents that are affecting flight safety, according to publicly available reports as well as government, industry and union officials<sup>60</sup>.

Details of incidents have begun to trickle out through NASA's Aviation Safety Reporting System<sup>61</sup> (ASRS), which posts anonymous field reports after validating their authenticity. They include pilots reporting that:

- unusually light airliners behaved unexpectedly, such as climbing so fast that they exceeded assigned altitudes or couldn't maintain cabin air pressure.
- one nearly empty passenger jet, according to the crew "climbed like a rocket," prompting them to exceed their assigned altitude
- some aircraft have scraped their tails on takeoff<sup>62</sup>,

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<sup>59</sup> <https://www.inaa.org/covid-19-economic-impact-of-pandemics-on-aviation/#:~:text=Covid-19%3A%20Economic%20Impact%20of%20Pandemics%20on%20Aviation%20July,firing%20line%20of%20a%20potentially%20devastating%20financial%20crisis.> (accessed 6.12.2020)

<sup>60</sup> Alan Levin, Bloomberg, June 12, 2020

<sup>61</sup> <https://asrs.arc.nasa.gov/report/caveat.html?formType=general#:~:text=NASA%20has%20established%20an%20Aviation%20Safety%20Reporting%20System,described%20in%20detail%20in%20FAA%20Advisory%20Circular%2000-46E.>

<sup>62</sup> A pilot for an unnamed airline filed a ASRS report in spring 2020 detailing an onboard smoke event. "[An] air carrier captain reported smelling a burning smell during cruise," the report's summary says. "Post-flight maintenance briefing advised the pilots that alcohol from wipes may be shorting out wires." The unnamed airline reported that the issue had turned up on "several" aircraft.

- some have gone off course or strayed close enough to other aircraft to prompt mid-air collision alerts
- the boarding process went so fast that the crew forgot to finish safety paperwork
- normal flight routines are being disrupted as thousands of airliners are parked, some of them on runways at major airports.

#### **4.2 Impact of the COVID-19 pandemic on existing aircraft cleaning procedures**

As a result of the COVID-19 pandemic after each landing each airworthy aircraft moves to NIS. This is due to health and safety risks, as it is possible that the residual COVID-19 droplets on the accessible surfaces in the aircraft cabin, including the toilets, could infect passengers boarding it for the next flight. [6]

Aircraft manufacturers have published procedures on how to clean aircraft and what products to use for years. Events such as SARS and the current COVID-19 pandemic have prompted them to issue reminders and, as lessons are learned, provide updates. However, an Airline Pilots Association report issued in spring of this year cited reports of non-compliance at 16 U.S. carriers and one in Canada. Most of the issues concern the frequency and thoroughness of the aircraft-interior disinfecting and the materials being used [7]. For example, pilots have been provided with hand wipes that are not on the Environmental Protection Agency's E-list, which tracks products known to work against the novel coronavirus.

In the US the FAA and other regulators are hesitant to mandate aircraft-cleaning protocols, referring instead to health agency guidance, which focuses largely on aircraft cabins. Instructions on cleaning flight decks, such as in the International Civil Aviation Organisation guidance on protecting cargo pilots issued on 11 May 2020, refer to manufacturers' recommendations.

Despite not enforcing social distancing while seated, United Airlines is committed to ensuring its planes are cleaned thoroughly between flights. The airline recently extended its cleaning procedures to include robots. The robots will spray antibacterial liquid over all the surfaces that passengers touch. This includes the toilets and the tray tables, as well as, overhead bins, seats, armrests and overhead air filters.

This deep clean will not be used in between each flight, but on a weekly base.

#### **4.3 Impact of the COVID-19 pandemic on usage of toilets on commercial flights**

Since the creation of the multi class cabin, passengers are allowed to use toilets in their ticketed determined cabin only. However, starting from 1 November 2020, based on feedback from both passengers and crew, United Airlines has changed this policy. Hence, passengers are allowed to use the first class toilets, regardless of which class tickets they are travelling, as a way to reduce queuing and crowding around toilets. Although the cabin crew advise the passengers to "use the restroom located in your cabin when possible", when there is overcrowding of one toilet passengers can move around the cabin to use a different toilet, even if it means passing from economy into first class<sup>63</sup>. The altered policy allows flight attendants more flexibility to let customers

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<sup>63</sup> [https://simpleflying.com/united-airlines-first-class-toilet/?utm\\_source=Biblio](https://simpleflying.com/united-airlines-first-class-toilet/?utm_source=Biblio)

use another toilet during certain situations. That may include when there is a line for one toilet but not another, when the service cart is in the aisle, etc.

Other airlines such as American have long allowed passengers to use whichever toilet they choose. However, a Delta airline restricts passengers to the toilet in their class.

#### **4.4 Impact of the COVID-19 pandemic on personal protection equipment for Chinese cabin crew**

The Civil Aviation Administration of China (CAAC), in its latest edition of Technical Guidelines for Epidemic Prevention and Control for Airlines, are suggesting cabin crew wear disposable diapers. The advice is meant to limit the use of toilets while flying to and from high-risk destinations<sup>64</sup>. The 38-page document contains special recommendations for charter flights to and from regions where infections exceed 500 in every one million people. They include, among other things, goggles, disposable shoe covers and nappies.

The Personal Protection Equipment (PPE) recommendations also list surgical masks, double-layer disposable gloves, goggles, disposable caps, disposable protective clothing, and disposable shoe covers. Cockpit crew should also wear masks and goggles but are exempt from the nappy request.

The CAAC advises that the last three rows of the cabin on high-risk flights be designated as an emergency quarantine area. The document also requires the airline to divide the rest of the cabin into sections, which include a “clean area,” a buffer zone, and a passenger sitting area, each of which are to be divided by disposable curtains.

Chinese domestic aviation has made a remarkable recovery. It is already back to near-full capacity from 2019. On December 9th, the entire country of 1.39 billion people recorded only 12 new coronavirus cases. Its economy appears to have succeeded in creating the much-desired V-shaped recovery more optimistic projections had been foreseen at the beginning of the crisis.

#### **4.5 Impact of the COVID-19 pandemic on the decisions of where to ground aircraft**

When bookings collapsed for fear of coronavirus, airlines world wide, grounded majority of their aircraft. Hasty grounding meant that only a few of the more than 700 locations where aircraft are now stored were designed for long-term storage. The Mitiga Meteorological and Aerosol Contaminants Index<sup>65</sup> assesses many airports where aircraft are now stored as high in corrosion risk, extreme in temperatures, or contaminated with sea salt, dust or sulphur dioxide. Singapore and Jakarta are especially bad for stored aircraft.

However, there is a trade-off in grounding decisions. Airport storage costs more and has higher risk of damage from unfavourable environments, but it enables airline mechanics to perform the storage maintenance. In contrast, desert or dry-region storage

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<sup>64</sup> <https://simpleflying.com/chinese-cabin-crew-nappies/>

<sup>65</sup> <https://www.twu557.org/index.php/10-latest-news/579-aw-mro-online-tough-decisions-on-grounded-ac>

cost less and is better for aircraft, but requires ferry costs and expenses for contractors for executing required maintenance tasks.

Needles to say that storage also poses technical challenges, like: updating software in remote locations, implementation of time-limited tasks and ADs<sup>66</sup>.

When the aircraft is in PIS, but in passive mode, it still has to be maintained. It is necessary to rotate the tires, to rotate the engines, check all the fluids, the oils, and all the lubricants. So obviously, all of these maintenance events will continue to be accomplished, as part of the business of an airline.

OEMs have been working with airlines to find efficient ways of doing maintenance on grounded jets, keeping them safe while saving man-hours. They are addressing calendar-time tasks and looking for opportunities to combine tasks.

#### **4.6 Impact of the COVID-19 pandemic 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, the 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<sup>67</sup>, 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.

EasyJet has increased testing from once per year to once every 14 days, and the airline is testing in 21 locations instead of one. For many operators, the more frequent testing means more samples to be send the laboratory, which is where many test providers still process samples. To take fuel test samples, send them to labs, and wait for the results ordinarily takes 4-10 days. Today, when aircraft are scattered around airfields away from home bases, the process inevitably takes longer and requires more resources.

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<sup>66</sup> An airworthiness directive (commonly abbreviated as AD) is a notification to owners and operators of certified aircraft that a known safety deficiency with a particular model of aircraft, engine, avionics or other system exists and must be corrected.

<sup>67</sup> <https://conidia.com/industries/aviation/>

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 injection carts, availability of the additive, and also simple things like being able to access aircraft that are parked nose to tail on taxiways.

## 5. Impact of the COVID-19 pandemic on the aircraft type retirement

The current pandemic has severely impacted international travel demand, particularly the large-cabin segment of the market. Figure 2<sup>68</sup> clearly illustrates the drastic drop in the daily flying hours of the two “sky giants”.

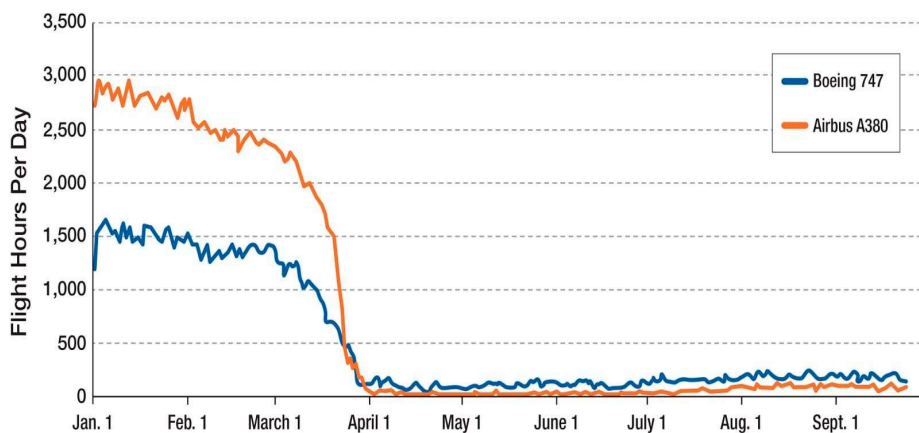


Figure 2. Daily flights hours of A380 and B747 during the first 9 months of 2020

### 5.1 Impact of the COVID-19 pandemic on the retirement of A380

The A380, as the world's largest commercial passenger aircraft, has been more negatively impacted than any other type, with several national flag carriers recently announcing full retirements of their A380 fleets.

In the context of the current COVID-19 crisis and its impact on anticipated activity levels, the Air France-KLM group announces today the definitive end of Air France Airbus A380 operations. The group had previously planned to phase out its super-jumbo fleet by the end of 2022 as part of a broader strategy of rationalising and simplifying its fleet in a bid to improve effectiveness and reduce cost. Air France, the first European airline to operate the A380 retired its last one in June 2020, having once operated as many as 10. The overall impact of the A380 phase-out amounts to a write-down of €500 million and the group said that would be booked in the second quarter of 2020 as a non-current cost/expense. Air France said A350s and Boeing 787s would replace the A380s.

Lufthansa, which has already offloaded half its 14 A380s, does not expect to fly the remaining airframes until at least 2022 and meanwhile will keep them in deep storage.

<sup>68</sup> Source: Aviation Week Fleet Discovery, Commercial passenger aircraft only

Outside of Europe, the future of the aircraft in the fleets of Etihad, Qatar Airways and Thai Airways has also been the subject of discussion since the COVID-19 outbreak.

The early retirement of the A380 type of aircraft is a totally unexpected development for the commercial aviation community, starting with the designers, manufactures and operators. Normally, all significant design decisions are made on the expectation that each aircraft type will stay in operation for 25 years. Hence, all design compromises, between mutually competing engineering and management decisions are based on around 80% occupancy rate per flight over the life span of 25 years. Certainly, this is far from the COVID-19 impacted destiny of A380, which entered into service only in 2007 and as of May 2020, according to Airbus, there were approximately 228 of the aircraft in service with 14 operators.

## **5.2 Impact of COVID-19 pandemic on the retirement of B747**

The future life of the B747, also known as the “Queen of the Skies” is similar to that of the A380. British Airways is one of the world's largest users of the Boeing 747, receiving its first Boeing 747-100 in 1971. The latest version, the B747-400, was delivered in 1989.

On 17 July British Airways announced the immediate early retirement of their fleet of 30 Boeing 747-400s. The aircraft had been due to retire gradually over the next few years, with the last planes exiting the company by 2024. However, no more commercial flights are expected now for the airline's fleet of Boeing 747s, subject to consultation with the relevant unions.

In the communication to staff, British Airways said, “They are an airliner of another era, however, and they burn far more fuel than the latest generation of planes and, logically, require more frequent and detailed attention from our engineering team. They rely on high passenger load factors and high premium demand to make them commercially viable. Subject to proper consultation, their early retirement would be accelerated over the coming months, and we would not expect any more commercial flights.. The proposal to retire the entire fleet of these iconic aircraft is nothing short of heartbreaking for those of us that grew up watching them fly all over the world.”

The exit of the aircraft will affect hundreds of British Airways pilots that are only qualified to fly the aircraft specifically.

## **6. Use of MIRCE Science Equations for the post the COVID-19 fleet selection**

When bookings collapsed for fear of coronavirus grounding aircraft was a painful, but easy business decision for airlines. However, when the recovery begins, airlines must decide<sup>69</sup>:

- which and how many aircraft to put back into service immediately,
- how to get them back most economically,
- where and how to store the aircraft not needed soon,

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<sup>69</sup> <https://www.twu557.org/index.php/10-latest-news/579-aw-mro-online-tough-decisions-on-grounded-ac> (accessed 1.12.2020)

- which aircraft to retire and how to gain the most value out of it.

Answers to the above listed questions are rather complex, as there are many factors that need to be considered under the veil of uncertainties. A common guess is that no more than 5,000 of the currently parked aircraft will return to service by the end of 2021. That would leave more than 8,000 aircraft to find more permanent homes than the cold or humid airports.

MIRCE Science Equations are mathematical expressions of the motion of industrial systems through MIRCE Space, developed by Knezevic [1]. They enable predictions of the expected work to be done by operationally defined industrial 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 an industrial system being in PIS, at a given instant of time  $t$ , is defined by the MIRCE Functionability Equation, [8] thus:

$$y(t) = P(PIS, t) = \sum_{i=1}^{\infty} P(PIS^i, t) = \sum_{i=1}^{\infty} [O^{i-1}(t) - F^i(t)]$$

where:

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

The positive work done,  $PW(T)$ , by an industrial system during the stated interval of time  $T$ , can be calculated by making use of the following expression:

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

The numerical value of the above expression, when applied to each operationally defined aircraft type, presents the amount of time it is expected to be in PIS delivering flying hours and generating revenue.

Correspondingly, the negative work done,  $NW(T)$ , by a given aircraft type, presents the amount of time it is expected to be in NIS consuming: maintenance man-hours, storage hours and necessary resources (material, facilities, energy, equipment and similar) during the stated interval of time  $T$ , can be calculated by making a use of the following expression:

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

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

## 6.1 MIRCE Profitability Equation

The creation of the MIRCE Functionability Equation enabled the development of the MIRCE Profitability Equation [9] that links the revenue and cost sides of business, by integrating the consequences of system engineering decisions, adopted business methods and project management decisions.

According to MIRCE Science, the expected revenue of a given industrial 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 and the amount of the work done by the system, thus:

$$Rev(T) = HI \times PW(T) \quad [MU]$$

In general terms, the cost of doing positive work during the stated period of time<sup>70</sup>,  $CPW(T)$ , which is equal to the sum of the 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 an industrial system spends in PIS, thus:

$$CPW(T) = CPW_{fix}(T) + HC_{PW} \times PW(T) \quad [MU]$$

Equivalent cost for doing negative work (maintenance and storage), during the stated period of time<sup>71</sup>,  $CNW(T)$ , which is equal to the sum of the 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 an industrial system spends in NIS, thus:

$$CNW(T) = CNW_{fix}(T) + HC_{NW} \times NW(T) \quad [MU]$$

Finally, the profit expected to be generated by a given industrial system, during the stated period of time,  $PROFIT(T)$ , could be calculated by making use of the MIRCE Profitability Equation, thus:

$$\begin{aligned} PROFIT(T) &= Rev(T) - C(T) \\ &= HI \times PW(T) - [CPW(T) + CNW(T)] \quad [MU] \end{aligned}$$

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

It is necessary to stress that the above-presented equations are applicable only when the mechanisms of the motion of an industrial system through MIRCE Space are known.

<sup>70</sup> 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.

<sup>71</sup> 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.

COVID-19 is one of those that were not known until the beginning of 2020. Consequently business plans of airlines world-wide are for several orders of magnitude off the target, measured in flying hours delivered, revenue generated, number of aircraft grounded and those retired from active service.

## 8. Conclusions

The main objective of this paper is to address the impact of the COVID-19 pandemic as a mechanism of the motion of an aircraft through MIRCE Space, which is a mathematical reality of the observed physical realities, experienced in aviation world during 2020.

The COVID-19 outbreak has shown that pandemics, like other rarely occurring natural catastrophes, have happened in the past and will happen in the future. Although humans cannot prevent dangerous viruses from emerging, they should be prepared to dampen their consequences for the economy and all of society.

Examples of devastating impacts on aviation world-wide are given in the paper, as well as, some of the human and technological solutions taken to cushion their consequences.

To assist airlines in the selection process of aircraft types that should be returned to the post pandemic service MIRCE Functionability and Profitability Equations are presented in the paper. They embrace the impact of COVID-19 on the expected positive and negative work, as well as the cost of associated resources, which determine their business existence. However, the above-presented equations are applicable only when the mechanisms of the motion of an industrial system through MIRCE Space are known. As COVID-19 pandemic was not known until the beginning of 2020 business plans of airlines world-wide are for several orders of magnitude off the target, measured in flying hours delivered, revenue generated, number of aircraft grounded and those retired from active service.

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## MIRCE Science Question: Digital or Analogue Visual Displays of Dynamic Information for Humans?

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### Abstract

*Visual Displays of Dynamic Information (VDDI) represent the interface that machines use to communicate their dynamic functionality state to humans. This paper tries to address the question of the selection between the two main types of VDDI available, digital or analogue, and identify what are some of the most important factors that may affect this selection. In that aid the paper briefly covers how the displays and VDDI are classified, their uses and objectives, the factors that could affect the selection process and finally a comparison between digital and analogue VDDI. The quantitative assessment of the impact of VDDI on the human elements of functionable systems could be determined by making use of MIRCE Functionability Equation. It enables to predict the impact of each feasible options of VDDI on the expected work to be delivered by the system.*

### 1. Introduction

In system engineering the term human factors engineering is used to designate a body of knowledge related to the collection of data and principles about human characteristics, capabilities, and limitations in relation to machines, jobs, and environments taking account the safety, comfort, and productiveness of human users and operators<sup>72</sup>. The term human factors engineering is used mainly in the North American continent. In Europe, Japan, and most of the rest of the world the prevalent term is ergonomics, a word formed from the Greek words, *ergon*, meaning “work,” and *nomos*, meaning “law.” Despite minor differences in emphasis, the terms human factors engineering and ergonomics may be considered synonymous. The terms were used in the 1920s and '30s to refer to problems of human relations in industry, an older connotation that has gradually dropped out of use. Some specialised groups prefer such labels as bioastronautics, biodynamics, bioengineering, and manned-systems technology; these represent special emphases whose differences are much smaller than the similarities in their aims and goals.

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<sup>72</sup> The principles of human factors engineering are concerned with human performance, behaviour, and training in human-machine systems; the design and development of human-machine systems; and systems-related biological or medical research. Because of its broad scope, human-factors engineering draws upon parts of such social or physiological sciences as anatomy, anthropometry, applied physiology, environmental medicine, psychology, sociology, and toxicology, as well as parts of engineering, industrial design, and operations research. <https://www.britannica.com/topic/human-factors-engineering> (access 11.06. 2020)

The main problem with the system engineering approach to human factor is that operators, maintainers and users are considered as an independent part of a system. For example no human is a part of reliability block diagram<sup>73</sup>, despite numerous evidences that humans had caused major accidents and failures. Hence, pilots, drivers, operators, maintainers and other humans that actively participate in the life of systems are not considered as an integral part. To deal with this anomaly, and a few others, deeply imbedded in system engineering, MIRCE Science<sup>74</sup>, has been created as an independent body of knowledge that studies and predicts the behaviour of functionable systems. According to Knezevic [0], functionable system is “a set of mutually related entities put together to do a functionability work in accordance to physical laws and given functionability rules.” The work is considered done when a measurable function is delivered through time. As, humans play different part in the working of systems, they are considered and an integral part of functionable system, and as such are included in the functionability block diagram of functionable systems.

For example a motorcar is created to do a transporting work of people and cargo from one point to another, with expected speed, fuel consumption and other measurable performance. A refinery is built to do a work consisting of transforming crude oil into a variety of refined products as petrol, jet fuel, asphalt, oil, sulphur, etc. When these systems are performing their expected functions, humans participating in their operation need information about the functionability states of its consisting elements, to plan and execute all actions required to maintain the system in working state.

One of the many ways that systems use to communicate their functionability state to the humans, whether the system is a radio, a car, industrial plant or spaceship, is through visual displays. They provide the mechanism for the flows of information from non-cognitive to cognitive elements of a functionable system. The visual displays enable humans to monitor the parameters that are direct indication of the functionability performance of the system.

According to James [2] the basic purpose of all displays is to provide answers to questions. For example, in the case of a car, the speed gauge informs the drivers about the speed, at any moment, which they use to control the vehicle speed within the required limits, or the fuel gauge enables drivers to determine when to refuel. In the case of the refinery the manometer at the discharge of certain pump or the thermocouple at the outlet side of a heat exchanger will give critical information about how these devices are functioning, enabling humans to control or take corrective measurements in the event of a problem. The generic name for all equipment used to monitor parameters subject to change with time and inform humans about the functionability state of functionable systems is the Visual Displays of Dynamic Information (VDDI).

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<sup>73</sup> A Reliability Block Diagram (RBD) is a method of modelling that is performed to assess how components and sub-system failures combine to cause system failure. The diagram can be analysed to predict the availability of a system and determine the critical components from a reliability viewpoint.

<sup>74</sup> MIRCE Science comprises of mathematical axioms, equations and methods that enable predictions of expected functionability performance of each feasible option of the future functionability system to be done, based on the time-dependent interactions between: physical properties of consisting components and applied functionability rules regarding operation, maintenance and support processes.

Given that the VDDI play a very important role in working of functionable systems the important question arises: “What method should be used to present visual information to humans in order that they are adequately, easily and timely understood, analogue or digital? Hence, the main purpose of this paper is to attempt to provide the answer the question raised, in accordance to MIRCE Science.

## 2. Overview of Visual Displays of Dynamic Information

Generally speaking, visual displays to humans take two forms: digital and analogue. In display’s terminology, the digital display presents the information directly in numbers or digits. With the analogue display the humans have to interpret the information from the position of a pointer on a scale, from the shape, position or inclination of a picture on the screen, or from some other indication which is analogous to the real state of the functionable system [3].

One of the most common examples for digital and analogue displays, familiar to everyone, is in the wristwatch. The traditional analogue display represented by the circle with printed numbers where arms to point the hours, minute and seconds. The other option is the digital wristwatch, where the time is presented by digits (numbers) in a Liquid Crystal Display (LCD) or similar. The selection between a digital or analogue wristwatch could be considered as a matter of personal preference and style. However, it could not be always said for the complex functionable systems, where numerous factors have to be considered in order to select the one that best suits the requirements.

For the purpose of this paper, the VDDI are classified in the following three main groups:

- **Quantitative:** This type of displays are a must when the actual values of the variable measured is required to be known with certain degree of precision. The quantitative VDDI, according to Sanders [6] can be of three types:
  - Fixed scale with moving pointer (analogue)
  - Moving scale with fixed pointer (analogue)
  - Digital display, which according to Pankove [7], can be:
    - Light-Emitting Diodes (LED),
    - plasma, Liquid-Crystal Display (LCD),
    - Electrochromic Displays (ECD)
    - Electrophoretic Displays (EPID).
- **Qualitative:** The qualitative types of VDDI are used when precision is not required. For example, the machine temperature in degrees centigrade, as the operator may simply need to know whether is hot, neutral or cold, or whether is safe, dangerous or critical. This type of display is mostly analogue and used as a form of check reading. Kelly [5] indicates that qualitative displays usually represent a physical analogy between the display and that which it provides information about. If the spatial correspondence is such that the display actually resembles that which it represents, the display is said to be “pictorial”.

- **Computerised VDDI:** As Hancock [8] argues, the development of micro chip technology, has led directly to more complex and interactive machines, complicating the problem of designing machines that are operable by human users. As systems get more complex, there are more cognitive tasks, more complex application and more interactive interfaces. Thus, the importance of the new concept of intelligent interfaces. Although is beyond the scope of this paper, it is important to be aware of the existence of this type of display. The computerised display can have numerous variants. Those used in industrial plants show digital, analogue, qualitative and quantitative information, if required, all of them simultaneously. The information can be presented, customised and can be changed at any moment to suit the needs of the user, all in one monochromatic or colour screen. This type of displays also offer the possibility of presenting the information in a representational or mimic form, with schematics and figures that intent to represent the parts of the system or variables that are being shown. Another advantage of this type of displays is that through the use of “touch screen” capabilities is possible to access more detailed information of a particular item in a fully logical and intuitively sequence form for the operator. Even though this type of displays is most of the times related to automated type of process, it can also include the capability of taking control actions directly from the display. An example could be shutting down an equipment that shows non acceptable levels of a relevant condition parameter.

### 3. Uses of Visual Displays of Dynamic Information

In order to select the adequate VDDI, it must be clearly defined what is the user expected to do with the display, this is, what is the intended use of the VDDI and what is the objective of using it. The selection of the VDDI should consider how the users will interact to achieve the desired requirement, observing their limitations.

According to James [2] the most important objectives of using VDDI, seen through the human perspective are as following:

- Improve decision-making (human nature is subjective).
- Improve understanding (gain insight of a problem or situation).
- Clarify complex relationships (relationships, conflicts, correlation, extrapolations, quick clearly and correctly comprehended).
- Reduce reaction times (detecting trends, conflicts and exceptions, planning for contingency).
- Improve co-ordination (between diverse operations).
- Improve availability of information.
- Improve control of the system.
- Simplify operations (simplicity, if equipment is difficult or inconvenient to use, it won't be used effectively)
- Provide flexibility (system able to adapt to changing requirements).

The selection process of the VDDI, will be briefly described below, in accordance to the MIRCE Science.

#### **4. Elements of selection process of VDDI type during the design**

Although every industry usually has some basic isolated guidelines for the selection of VDDI, particularly for systems that are designed in a recurrent manner, there is no a generic recipe for the selection process. Every case may has its own characteristics from operational, maintenance, logistics, etc. perspectives, in different environments, and all these characteristics can be related with ergonomic considerations, the possible combination of factors are almost infinite. Then, every situation must be evaluated with the people involved in operation and maintenance under intended circumstances, having human elements of functionable systems in mind is crucial for the selection of the VDDI.

From the information provided by Sanders [6] is possible to infer some aspects to be considered in the selection of the VDDI, these may include graphics, access, size, colours, arrangement, scales, environmental conditions and nature of function/process. These factors could influence the selection of the analogue or digital VDDI, and are briefly discussed below.

##### **4.1 Graphics**

The types of questions that the Design Team should be focussed on regarding the selection of VDDI are of the following nature:

- Does the user will require qualitative or quantitative information?
- Are symbols required?
- What is the nature of the process to be monitored?
- If a digital VDDI is considered what type is the best?
- What type of matrix shall be used?
- Does a mimic panel solve the situation from the user, operational and economical point of view?
- There are requirements of control associated with the displays to be used?

For example, in the case of VDDI used for cars is important to enable the driver to easily differentiate one display from another, like speedometer and rev. counter that are usually of the same size. This can be done using symbols associated with the VDDI and avoiding situations in which the driver may confuse two VDDI.

##### **4.2 Access and size**

Most of the VDDI are able to receive a remote signal, mechanical, electrical or digital from a sensing instrument, Hence, they don't have to be installed directly on the device whose parameter is being measured. The location (distance, viewing angle, etc.) of the operator in relation with the location of the VDDI is a factor to be considered when selecting between digital or analogue,, which in turns determines the diameter of the round analogue display or the size of the numbers in a digital one?. James [2] indicates that no matter how large displays get, people wish they were bigger. One cannot make the general statement that "the bigger the better", in fact, James indicates that an study compared a large purpose display for many people to view simultaneously with individual displays in front of each user. He concluded that there was some need for

both. As Sanders [6] points out, to determine the size of the display, there are proven methods, including tables, depending on the reading distance and other factors.

#### **4.3 Colours and illumination**

Depending on the nature of the parameter to measure some colours are more convenient than others. There are some practices for the selection of colours associated to VDDI. Bailey [9] indicate some recommendations such red for abnormal/undesirable condition, yellow for warning, green for normal, etc. If the use of colours is required for an easier reading of the parameter measured, then strong consideration should be taken towards the use of analogue VDDI. The use of colours is particularly important in quantitative and qualitative VDDI, since they help to interpret quickly the functionality state of the parameter measured. The use of different colours in digital VDDI (blue, green, amber, red, etc.) can help to differentiate parameters, but they are not of much help.

The illumination of the VDDI is important, particularly if the system is intended to use at night or in places with poor illumination. Direct or indirect illumination shall be considered for both analogue and digital VDDI. The incandescent digital displays have an advantage in this situation since it does not require extra illumination at night, but if it is located outdoors, it does require adequate power during the day to overcome the brightness of the solar light in order to enable its reading.

#### **4.4 Scales**

The scale of the VDDI, especially in the analogue type of display should be carefully selected, not only foreseeing the expected range of operation, but also considering that the operator should easily read from it and differentiate from other displays. Some practices for the selection of scales are indicated by Bailey [9]. The Design team should consider the selection of VDDI that uses colours in their scales for the already discussed advantages. This is particularly important when selecting analogue qualitative type of VDDI, where the different ranges of operation could be identified by the use of different colours. In digital VDDI, the scale (increments) represents the precision that the display has to measure determined parameter. Most of the times, the process will dictate what is the required scale. For example, an aircraft digital altimeter measuring altitude in 5 [feet] increments could be acceptable, but increments of 5 [gallons] in a digital meter of a petrol pump, would probably be not acceptable for the petrol station owner. Kelly [5] indicates some techniques for display scale determination and some recommended scales for various devices.

#### **4.5 Nature of function or process**

Depending on the nature of the process one type of display may have more advantages over others, again the important issue is to select the one that best suits the user, considering also related aspects as environment, maintenance, costs, etc. For example, analogue VDDI is an easy way of doing quick “check readings” whilst a digital VDDI could be a good choice for a parameter that need to be counted in a cumulative or historical way, such the odometer of a care. Nevertheless, the type of interaction user-display should be also considered: the length of the time the user will be interacting

with the display. Is important to avoid that the users get tired of seeing a display not “eye-friendly”.

#### **4.6 Arrangement**

It is critical to situate adequately the different types of displays of a system. The preference should be to group them in logical ways, according to sub-process, or criticality of the nature of the parameter. Kelly [11] indicates that the arrangement of the VDDI should be made according to the following priority:

- Function
- Importance
- Use sequence
- Frequency of use

The adequate location of the analogue VDDI enable the use of concepts such “positional concordance for the reading of multiple normal operating values” which is exposed by Sanders [6]. This concept can be useful when the user wants to verify the normal functioning of a system or part of it with a quick look at the set of VDDI. For example, if a certain number of analogue VDDIs are groped together and are of similar sizes and the normal value of the parameter that each of the displays is measuring is positioned so that the arm of the display points in the same direction (say 12 o'clock in a round dial) then, instead of a series of random positioned pointers, the user could see, if everything is normal, a group of fairly aligned pointers, then any pointer out of alignment would be easily identified from the group. This type of arrangement is useful even for not so complex systems, such a automobile with a set of three VDDI.

#### **4.7 Environment**

Awareness of the environment where VDDI is going to be used is of vital importance, especially if it will be outdoors, exposed to weather conditions or extreme operational conditions. In that case it is crucial to assess will the operator be able to withstand the environmental conditions during its reading.

Also, it is important to assess will it be safe environment, and if not, how to provide protection for the user. At certain locations environmental conditions could affect users to make correct readings (illumination, heat, noise, vibration, wind), so the selection between digital or analogue VDDI became safety significant issues.

### **5. The Final selection of the VDDI**

One of the main decisions that the design team has to make, is the selection of the VDDI, between digital and analogue. Today, most of new systems incorporate the use of chip technology to control their functions and performance. A direct way to communicate the information about their state is through digital output, their basic language. Also the chip and digital display technology is becoming increasingly popular and more affordable, some digital displays are now cheaper than their analogue equivalents. As Osborne [3] argues, the experiments done by Murrell [10], tend to point that digital displays produces less reading errors and faster reading times (when a value

is required) that their analogue counterparts. The digital clock can be read faster than the conventional clocks, with one tenth of the errors. From this affirmation, the impression may be gained, so far, that numerical information should always be presented digitally. Digital displays, however, have their weak side, particularly when the task requires some degree of “check reading”, when the display is used as a predictor or when the rate of change of the information is fast.

The natural world where we live is mostly a “world of analogies”. For thousands of years, humans have been used to see and understand all phenomena through analogies, seeing relative and gradual movements among parts. The digital presentation of information is entirely arbitrary and conceptual. This may be one of the main reasons why, humans may feel more comfortable reading analogue displays that enables them to use their intuition. The digital displays require an additional effort to actually “read” a value in a display and then find the meaning of its value against some referential scale that the user has to know, for the value to have some meaning. This is expressed by Kelly [11] when he points that “digital displays employs symbols such as numbers that can have no meaning to the person unfamiliar with the code or convention. One who is familiar with the code or convention, however, is able to interpret the information. In the other hand, with the analogue display, the user gets an instantaneous picture of what is going on with the variable, and the use of pictorial type analogue displays, the user requires minimum interpretation, as the nature of the analogy is obvious”.

In comparing the advantages and disadvantages of digital and analogue VDDI, Osborne [3] made the conclusions that are presented below.

### **5.1 Check reading**

Murrell [10] discuss a data from a survey of ships, which indicates that 18% of the dials of steam boilers were used for quantitative reading, whereas over 75% for some form of checking.

The digital displays lack of the perceptual information offered by the analogue type (for example the angle between a pointer and the “north”) so the only way that the check reading can be done with digital is comparing numbers. For this reason, in certain cases, digital displays may increase both the time needed to read the instrument and the number of errors made during the task. This was demonstrated by Conell [12].

### **5.2 Spatial clues for prediction**

“Speed and accuracy is only half of the problem. Very often the operator has to translate what he sees into appropriate action” [13]. For example a digital clock may indicate that time is 11:40 a.m., an analogue clock indicating the same time enables quick spatial prediction, showing that there is 20 minutes left to reach 12, with no further calculation.

### **5.3 Blurring**

When the values to be read change too quickly, it may be difficult to read them from a digital display. In this case the spatial clues provided by the pointer in an analogue display may help the operator in making his reading.

From the previous analysis, it seems that there is not a simple answer when it comes to decide between a digital and analogue VDDI, there is not a recipe to follow. Every case must be evaluated considering its particular factors, some of them were discussed previously in this paper. Some times a digital VDDI will be the best solution for a particular situation, like recording quantitative information such the number of gallons of fuel pumped to a ship in a refinery pier. In other situation an analogue display will be the best solution, like when check reading is required using a manometer in a pressure vessel to determine if the pressure level is in a safe range. The final decision relays on the design group, that work together with user and maintenance personnel. This group will have to find what is the best type of display for every situation, is mainly an engineering decision. The merits of analogue and digital displays are summarised by Osborne [3] in Table 1.

<b>Function</b>	<b>Analogue</b>	<b>Digital</b>
Quantitative reading	Best is precise reading is not required, or if tasks contains predictive or checking components.	Best for accurate reading of slow changing values, poor if task contains predictive or checking components.
Qualitative reading	Best for warnings, checking and prediction, useful to have visual coded areas.	Poor
Setting and tracking	Best	Poor

**Table 1.** Merits of analogue and digital displays in relation to intended function.

## 6. Example if VDDI selection

To illustrate some considerations on the selection of VDDI, an example for a passenger car will be briefly considered.

The selection of VDDI for a car represents a situation where, from the human's point of view, there are some particular considerations:

- Most of the times, the user is not a specialised operator (has not received any training on the VDDI of the car) and may be or not familiarised with the automobile VDDI (if for example the user is renting a car).
- The user not only has to deal with the driving task which takes most of his attention, but also is responsible for reading and interpreting the parameters of the car through the VDDI at the same time.

During the driving, the user will have to check the values of the displays to assure the required functioning of the car. This situation represents a problem because he will have to take his sight out of the road while driving to read the displays (speed, petrol, oil pressure, temperature, voltage, amperage, etc.) just to assure that every thing is running within the expected range/value. At an speed of 60 MPH a car covers about 27 meters in one second. If the driver spends, say 3 seconds "reading" displays, the car would have run more than 80 meters with the driver not looking at the road. This is a

potentially dangerous situation. If an obstacle suddenly appears in front of the car while the driver is not looking, even 1 second could make the difference between an accident and an evasive manoeuvre. For this reason there is not enough time for the driver to read every gauge, instead he has to take short “looks” at instruments, he actually does “check reading”. This is one of the main considerations that guide the selection of the VDDI in a car. Thus, the analogue VDDI should be the best suited for this task of check reading.

The car industry has almost 100 years of experience designing automobiles and selecting their VDDI. A quick research was done to find out the preference of car manufacturers in the use of VDDI, see table 2. [14]

<b>Make and Model</b>	<b>Type of VDDI</b>
Ford Escort	Analogue
Citroën 2CV6 Special	Analogue
Volvo 480 ES	Analogue
Peugeot 205 GR	Analogue
Fiat Uno 70S	Analogue
Nissan Blue Bird	Analogue
Toyota Corolla GL	Analogue
Rover 218 SLD	Analogue
BMW 325 tds	Analogue
Mazda XEDOS9	Analogue
Rover 216 Gsi	Analogue
Renault Laguna	Analogue

**Table 2.** Type of VDDI used by a random sample of automobiles.

From the sample of 12 cars, Zavala [14] found that all of them use analogue type of VDDI for all dynamic parameters that require measurement, with the exception of odometers which were mechanical or electronic digital type of display. As a result of this short research it is evident that there is a preference for the use of analogue VDDI in cars. This is the expected result, since the design of the control panel of most cars is done for humans, which are an integral part of transportation work expected to be done by them, in accordance to MIRCE Science. When the user looks at an analogue VDDI a quick look is enough to locate the position of the arm of the display, and with the aid of a colour scale or qualitative indication, is possible to get an instant feeling of the parameter value. This is particularly important in parameters with high rate of change, like for example the tachometer. It would be very difficult to read values of RPM in a digital tachometer whilst changing gears, without taking the eyes out of the road for long periods of time (and still not been able to read a particular value due to “blurring”). The user, usually does not require to do any check reading on the odometer while driving, is mostly used for maintenance purposes, this is the reason why it does not matter if it is in a digital presentation.

The regular user finds easier to get information of the car parameters through the use of analogue VDDI. Also the fact that the driver only need approximate information for most of conditions of the car (with exemption of speed, which has to be controlled

closely to avoid speeding ticket) encourages the use of qualitative analogue displays for parameters such as oil pressure, water temperature, voltage, amperage, etc.

## 7. Quantitative assessment of the impact of VDDI on work done

As of now, there is not a unique answer to the question which of which VDDI is better to use in a new system. The selection of the VDDI between digital and analogue is a trade off process that could be successfully supported by the quantitative evaluation of each design solution. That is possible by making use of MIRCE Functionability Equation. [15] It is able to consider each process during the life of a functional system where VDDI are used and calculate the cumulative impact of all of them on the work done by the system and the cost of resources expected to be consumed.

## 8. Conclusions

Visual Displays of Dynamic Information (VDDI) represent the interface that machines use to communicate their dynamic functionability state to humans.

The main objective of this paper was to address the question of the selection between the two main type of VDDI available, digital or analogue, and identify what are some of the most important factors that may affect this selection. In that aid the paper briefly covered how the displays and VDDI are classified, their uses and objectives, the factors that could affect the selection process and finally a comparison between digital and analogue VDDI are made. As no definite answer was found in existing literature, the author introduced MIRCE Functionability Equation [15] as a method for quantitative assessment of the impact of VDDI on the human elements of functional systems. Thus, the main conclusion of the paper is that for each feasible application of VDDI a quantitative assessment of the expected work and resources demanded has to be performed and the most compromising option selected, in accordance to the given criteria.

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