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

Richard F.W. Bader (1931 – 2012)
Grand Fellow of the MIRCE Akademy

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

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

Editor:
Dr J. Knezevic, President MIRCE Akademy

Editorial Board:
Fellows of the MIRCE Akademy

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Mirce-mechanics

According to Einstein ***"**Everything that the human race has done and thought is concerned with the satisfaction of felt needs*".

During the history of civilisation needs for transporting, communicating, navigating and many others have been satisfied by transpiration, communication, navigation and other human created systems. The mechanics of the functioning of maintainable systems are well-understood processes, which are predictable by the laws of natural sciences, such as: Newton's laws of motion, Coulomb's law of solid friction, Hook's law of stress and strain, Maxwell's law of electrodynamics, Boltzmann's law of thermodynamics, to name a few.

Needs satisfying systems are constructed by assembling a well-defined number of parts in a precise and preestablished way. As they are functioning in predetermined linear chains of cause and effect, their performance measured through speed, acceleration, power, range, energy usage, capacity and similar is also predictable. The reason for the predictability of the system design-in functionality performance is the fact that they are based on the physical and chemical processes that are characterised by certainty, continuity, reversibility, separability and independence of time, location and humans.

Regarding the long-term satisfaction of human needs, the ability of a system to function beyond the delivery day is an essential property of its in-service performance. Due to complex interactions between consisting parts and impacts from environment and humans, disturbances of mechanical, electrical, chemical, thermal, radiant and other types are created, some of which cause occurrence of events that prevent systems from functioning. Thus, to provide the flow of functionality through time maintenance tasks like servicing, repairs, overhauls, replacements and similar are undertaken by humans, making them maintainable systems. Thus, from the point of view of the ability to function during the in-service life, known as f**unctionability**[1]**,** maintainable systems could be in a positive or a negative functionability state, at any instant of time.

Experience teaches us that unlike quantitative information regarding the design-in functionality performance of a system that is available on the delivery day, the in-service functionability performance is not. Instead, years later the statistics for various functionability measures become available. The reason for this is the fact that they are emerging properties of the complex interactions between system in-service processes, which are characterised by indeterminism, discontinuity, irreversibility, inseparability, and dependence on time, location and humans.

To scientifically understand processes and mechanisms of the motion of maintainable systems through functionability states during in-service life resulting from any causes whatsoever and to develop laws and rules that enable predictions of emerging functionability trajectory to be made in 1999 Dr Knezevic established the MIRCE Akademy at Woodbury Park. Staff, Fellows, Members and students of the Akademy study in-service behaviours of maintainable systems to:

- Determine the patterns of the motion of functionability through the life of maintainable systems and to measure emerging functionability properties.
- Understand mechanisms of the motion of functionability through the life of maintainable systems, within the physical scale from 10^{-10} to 10^{10} metre,
- Define the mathematical scheme for the prediction of emerging functionability measures for a given: maintainable system in a given in-service conditions.

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

A generated body of scientific knowledge constitutes Mirce-mechanics whose axioms, formulas, methods and rules enable predictions of the emerging functionability trajectory of the future transportation, communication, navigation and many other maintainable systems to be made.

Content

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Mirce-mechanics Philosophy

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

Inspired by the work of scientists and equipped with the methods of their studies, the author of this paper during last 40 years focused on systematic and objective studies of the in-service life of transportation, communication, energy and similar human created and managed systems. Hence, this paper addresses the generic knowledge of the motion of functionability of operational systems through time, obtained through observational principles and quantitative reasoning under the name of Mirce-mechanics.

1. Introduction

Fundamental problems, such as those connected with reality, existence, knowledge, values, reason, mind, and language are subject of the study of Philosophy. It is distinguished from other ways of addressing such problems by generally systematic approach based on the reliance on rational argument. In more casual speech, by extension, "philosophy" can refer to "the most basic beliefs, concepts, and attitudes of an individual or group

Natural philosophy or the philosophy of nature (from Latin philosophia naturalis) was the philosophical study of nature and the physical universe that was dominant before the development of modern science. Natural philosophy pertains to the work of analysis and synthesis of common experience and argumentation to explain or describe nature. In 1577 University of Padua appointed Jacopo Zabarella as the world first professor of Natural Philosophy.

Natural science historically developed out of philosophy when acquiring knowledge through experiments under the scientific method, which thanks to Galileo Galilei involved quantitative reasoning and explanations about nature, became its own specialised branch of study apart from natural philosophy.

Modern meanings of the terms science and scientists date only to the 19th century. The naturalist-theologian William Whewell was the one who coined the term "scientist." The Oxford English Dictionary dates the origin of the word to 1834. Before then, the word "science" meant any kind of well-established knowledge and the label of scientist did not exist. Some examples of the application of the term "natural philosophy" to what is today known as "natural science" are Isaac Newton's 1687 scientific treatise, which is known as The Mathematical Principles of Natural Philosophy and Lord Kelvin and Peter Guthrie Tait's 1867 treatise called Treatise on Natural Philosophy which helped define much of modern physics.

Inspired by the work of scientists and equipped with the methods of their studies, the author of this paper during last 40 years focused on systematic and objective studies of the in-service life of transportation, communication, energy and similar human created and managed systems. Hence, this paper addresses the generic knowledge of the in-service life of systems obtained through observational principles and quantitative reasoning under the name of Mirce-mechanics.

2. Concept of Functional System

According to Einstein **“***Everything that the human race has done and thought is concerned with the satisfaction of felt needs*”.

Although the felt needs cover a very large spectrum of solutions, the word system is commonly used as a generic name for all of them. The most commonly used systems in daily life are:

- Aeronautical and aerospace: systems, which are created to satisfy the need for air transport, through supersonic and subsonic aircraft (jet, vertical take-off), spacecraft, missiles, rockets, remotely piloted vehicles, space labs, and similar.
- Agricultural: systems, which satisfy the need for production, processing, handling and storage of food and related products, like: tractors, combines, barns, silos, granaries, processing buildings, freezers and many others.
- Structural: systems, which are created to satisfy needs for large office buildings, manufacturing plants, sporting arenas, and housing complexes and so on.
- Chemical process and processing systems, which facilitate production of chemicals such as plastics, paints, synthetics, alkalise, dyes, polymers, insecticides, fungicides, oil, fuel, and many other comparable outputs.
- Civil engineering: systems, like highways, bridges, tunnels, dams, canals, waterways, sanitary and sewage treatment, disposal, water and gas networks, airports, railway stations, hotels, shopping centres, and many others, which are created as a result of specific human needs.
- Electrical and electronic systems, which are created in response to the need for creation, transfer and utilisation of energy. This includes electrical power systems, control systems, computer systems, communication systems, electronic systems (radar, navigation, fire control, missile guidance, signal processing equipment etc.), electro optical devices, instrumentation appliances, as well as small electrical/electronic components (transistors, semiconductors, switches, etc.).
- Mechanical: systems, main tasks of which are to convert energy into useful mechanical forms. This covers both, power-generating machines and machines that transform or consume this power in order to perform a particular function. Typical examples of mechanical systems are: engines, turbines, motors, control mechanisms, transportation systems (automobiles, bicycles, trains, space vehicles, etc.), refrigeration and air-conditioning systems, propulsion systems (steam, gas, nuclear) and cryogenic systems.
- Metallurgical, mining and materials: systems, which are created as a response to the need for dealing with various forms and applications of metals, alloys, and materials in general. These tasks are related to the initial location and evaluation of various materials from earth, the accomplishment of land reclamation after the mining and extraction functions have been completed, extraction of commodities (ores) into basic metals or comparable alloys. Some of the tasks accomplished by these systems are related to the changing the chemical physical characteristics of metals (extrusion, reforming, hardening and similar).

- Nuclear: systems, which are created to deal with all aspects of fission and fusion reactions (initiation, control of reactive materials, storage, disposal, decontamination) in order to provide power generation and medical applications.
- Ocean, marine and nautical: systems, which are manifested through existence of ships, submarines, hydrofoils, underwater sea laboratories, sea towers and similar marine structures.
- Petroleum: systems, which basically deal with the need for exploration, location, development and recovery of petroleum resources through tasks like drilling, separation, processing, transportation, and storage of crude oil, gases and related products.

In summary needs for transporting, defending, communicating, racing, entertaining, heating, navigating, and similar functions have been manifested by the human race throughout the history. Satisfaction of these needs, generally speaking, come from systems, which are collections of the related components and necessary resources that jointly have the ability to deliver required function with a measurable performance and attributes.

2.1 The Science of Functionality

Through centuries, especially during 100 years the scientific community has provided a larger number of laws that describe physical phenomena needed to be understood by engineers and managers in the process of creating systems, from agricultural to astronomical. Those scientific laws and methods have been presented to engineers and managers in "bundles of knowledge" named as thermodynamics, fluids mechanics, material science, electronics and similar through their professional education and qualification processes.

The theoretical foundations of systems are laws of science that describe observable natural phenomena, known to humans so far. Among them laws of motion are the most significant from the point of view of functionality of a system. Some of them are very briefly addressed in this paper as the scientific foundation for the development of the laws of the motion of functionability. Hence:

- **Thermodynamics** is the branch of science that describes the macro scale properties of a fluid. One of the principle results of the study of thermodynamics is the conservation of energy; within a system, energy is neither created nor destroyed but may be converted from one form to another. The most general form for the conservation of energy is given by the Navier-Stokes equation. This formula includes the effects of unsteady flows and viscous interactions.

- **Fluid Mechanics i**s a branch of physics that studies the effects of forces and energy on liquids and gases. One branch of the field, hydrostatics, deals with fluids at rest; the other, fluid dynamics, deals with fluids in motion and with the motion of bodies through fluids. Liquids and gases are both treated as fluids because they often have the same equations of motion and exhibit the same flow phenomena. The subject has numerous applications in fields varying from aeronautics and marine engineering to the study of blood flow and the dynamics of swimming.

- **Electronics** deals with electrical circuits that involve active electrical components such as vacuum tubes, transistors, diodes and integrated circuits, and associated passive electrical components and interconnection technologies. Commonly, electronic devices contain circuitry consisting primarily or exclusively of active semiconductors supplemented with passive elements; such a circuit is described as an electronic circuit. The ability of electronic devices to act as switches makes digital information processing possible.

- **Materials science** is an interdisciplinary subject, spanning the physics and chemistry of matter, engineering applications and industrial manufacturing processes. It is at the core of nanotechnology, the production of machines and devices at molecular levels, which is likely to drive the next technological revolution.

- **Mechanics** is an area of science concerned with the behavior of physical bodies when subjected to forces or displacements, and the subsequent effects of the bodies on their environment. The scientific discipline has its origins in Ancient Greece with the writings of Aristotle and Archimedes. During the early modern period, scientists such as Galileo, Kepler, and especially Newton, laid the foundation for what is now known as classical mechanics. It is a branch of classical physics that deals with particles that are either at rest or are moving with velocities significantly less than the speed of light.

- **Electromagnetism** is the study of the electromagnetic force which is a type of physical interaction that occurs between electrically charged particles. The electromagnetic force usually manifests as electromagnetic fields, such as electric fields, magnetic fields and light.

- **Quantum mechanics** is the science of the very small: the body of scientific principles that explains the behaviour of matter and its interactions with energy on the scale of atoms and subatomic particles

In summary, scientific principles and concepts expressed through the laws, equations and formulas are the bedrock of any engineering creation. They have achieved that status by providing accurate predictions for all engineering and management concepts, scenarios and “dreams”.

3. In-service Life of Functional System

3.1 Birth of a System

At the end of production or construction process, when all consisting components are assembled together and relationships between them established, a new system is “born” with capability do deliver all expected functionality characteristics. That unique, infinitesimally short instant of time, is denoted as t=0, to mark the beginning of the system operational process. Thus, each system will have its own “birth” time, which is very important from the system life point of view. At that instant the system is, for the very first time in its life, able to satisfy users’ needs by delivering functionality (function, performance and attributes). Hence, functionality characteristics of the system are inherited from the design and manufacturing processes and as such cannot be changed during the system life, apart from implementing some modifications and redesigns.

For example, in 1969, engineers and managers of the Boeing Corporation have deliver to the world first wide body aircraft, named Boeing 747, series 100 with the following functionality characteristics:

Passengers	
3-class configuration	366
2-class configuration	452
1-class configuration	N/A
Cargo;	6,19ft^{3} = 30 LD-1 containers
Engines maximum thrust	Pratt & Whitney JT9D-7A, 46,500 lb (20,925 kg) Rolls-Royce RB211-524B2, 50,100 lb (22,545 kg) GE CF6-45A2, 46,500 lb (20,925 kg)
Maximum Fuel Capacity	48,445 U.S. gal (183,380 litre)
Maximum Takeoff Weight	735,000 lb (333,400 kg)
Maximum Range	6,100 statute miles (9,800 km)
Cruise Speed at 35,000 feet	Mach 0.84, 555 mph (895 km/h)
Basic Dimensions	
Wing Span	195 ft 8 in (59.6 m)
Overall Length	231 ft 10.2 in (70.6 m)
Tail Height	63 ft 5 in (19.3 m)
Interior Cabin Width	20 ft (6.1 m)

Figure 1; Functionality Performance of a Boeing 747-100

Thus, it is expected that each Boeing 747-100 series aircraft have the same functionality, as shown in Figure 1, under identical environmental conditions, because the laws of nature are independent of time and the location in the universe,

After the “birth” a system is ready to deliver required function. For that to happen a system needs to engage in an operational process, which could be defined as a flow of operational tasks performed to deliver functionality of a system.

3.2 System Operational Process

Despite the fact that all systems exist in order to perform a desired function, all of them will perform a function only when engaged into the operation process. The process of operation is defined as: *a flow of operational tasks necessary to be performed in order to deliver system function.* [2]

Successful execution of operational tasks required some resources like trained personnel, material, facilities, equipment, tools, operational manuals, energy and similar. These resources will be termed System Operational Resources, SOR. For example, a commercial aircraft can only deliver transportation function when adequately trained crew is available to perform the required tasks in the cockpit and the cabin, and when the resources like fuel, runways, air traffic controls, and similar are available. Thus, the needs for transportation through the air, of the passengers chosen to fly to a given destination, are satisfied when the allocated aircraft and all necessary resources are simultaneously available during the entire duration of the flight. It is necessary to stress that all of these tasks are performed in the physical environment uniquely defined by its latitude, longitude and altitude, which is control by some political system governed by its own laws and rules at a given interval of calendar time.

When a system is placed in environment, all motion usually comes to a standstill as a result of various kinds of friction, differences of electrical or chemical potencial are equalised, substances which tend to form a chemical compound do so, temperature becomes uniform by heat conduction. After that the whole system fades away into dead, inert lump of matter. A permanent state is reached, in which no observable events occur. The physicist calls this the state of thermodynamiical equilibrium or of maximum entropy. [3]

3.3 The concept of Failure

However, experience teaches us that in-service behaviour of systems is dominated by phenomena like fatigue, operator induced errors, corrosion, creep, foreign object damage, a faulty weld, bird strike, perished rubber, carburettor icing, to name just a few. These phenomena are generated by energy exchanges between the components of the system and interactions of the system with the natural and human environment.
Resulting phenomena are losses of the design-in function or performance, which is commonly known as system failures. Hence, each new system when experienced the very first lost of function or performance seizes to satisfy human needs. This practically means that needs for transporting, communicating, defending, heating, cooling, projecting and many others cannot be satisfied any more. Hence, products with such properties would become undesirable objects as racing cars in the garage do not win races and neither commercial aircraft on the ground delivers passengers and cargo through the air.

In order to restore the ability of a system to perform a function it is necessary to perform required maintenance tasks. The process during which the ability of the system to perform a function is restored, is known as maintenance process, and is defined as the flow of maintenance tasks, selected and performed by the user in order to retain or restore functionality of the system during its life.

3.4 The concept of Maintenance Process

There are a large number of systems, the functionability of which has to be maintained during the utilisation process by the user. The process during which the ability of the system to perform a function is maintained, is known as maintenance process, and is defined as *'the flow of maintenance tasks, selected by the user to meet a specific business objectives, performed by the user in order to maintain the functionability of the system during its operational life'* [2].

It is necessary to stress that resources are needed to facilitate this process. Most frequently used resources are spares, material, trained personnel, tools, equipment, manuals, facilities, software, etc. As the main task of these resources is to facilitate the maintenance process they will be termed Maintenance Resources (MR).

Faced with this truth, over the centuries, humans have learned to change this situation by performing actions like cleaning, repairing, replacing, modifying, “cannibalising”, overhauling and similar. These actions brought systems in the states in which they become satisfying felt needs and desirable again by their owners and users. Needles to say, that when systems start performing needs satisfying function again, the energies exchange processes between consisting components and systems with natural and human environment starts again that eventually lead to the loss of function and performance. New situations initiate execution of like cleaning, repairing, replacing, modifying, "cannibalising", overhauling and similar actions, which turn no desirable systems into desirable and the whole cycles is repented until the decision has been made to discontinue satisfying needs with in that way.

3.5 The Support Process

Already it has been pointed out that in order to successfully conduct the operation and maintenance process some resources are needed. The process during which all necessary resources for operation and maintenance are provided is known as support process, and is defined as '*the flow of support tasks, selected by the user to meet the specific business objectives, performed by the user, in order to provide the resources needed for the execution of operation and maintenance plan'*.[2]

It is necessary to stress that the logistics process, as any other process, requires resources for its completion. Most frequently required resources are trained personnel, equipment, facilities, software, etc. As the main task of these resources is to support process they will be termed Support Resources (SR).

4. The concept of Functionability

The development of science started when people began to study phenomena not merely observing them. People developed instruments and learned to trust their readings, rather than to rely on their own perceptions. They recorded the results of their measurements in the form of numbers. Supplied with these numbers they began to seek relationships between them and to write down in the form of formulas. Then the formulas became the only things they came to trust when they began to predict things they could not physically experience.

However, people communicate with each other by means of words, not formulas. Hence, when they want to speak about new phenomena they have to invent concepts that correspond to them. Even though these concepts are often quite extraordinary, people become accustomed to them and learn to apply them correctly and even create images for themselves that they associate with the new concepts.

Consequently, the main objective of this paper is to present the concept of the functionability created by the author in 1993 [3]. Today, functionability plays the central role in Mirce-mechanics.

Functionability is defined as in-service property of systems related to their ability of being functional through time, resulting from occurrences of all atomic, environmental or human actions. Hence, the motion of functionability is generated by the complex interactions between some of the following contributors:

- Structure of a system
- Construction of a system
- In-service rules and policies (operational, maintenance and support)

- Environmental conditions (operational, maintenance and support)

From functionability point of view, at any instant of time a system can be in one of the following two states:

- Positive Functionability State, PFS, which is the state of being functional
- Negative Functionability State, NFS, which is the state of not being functional

The motion of the system through functionability states is governed by the occurrence of functionability events, which are classified as:

- Positive Functionability Events, PFE, which cause the transition from NFS to PFS
- Negative Functionability Events, NFE, which cause the transition from PFS to NFS

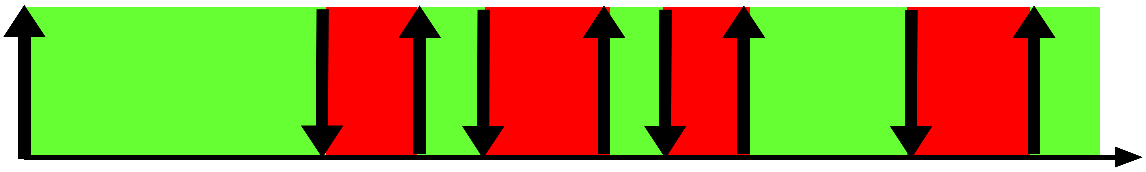

Figure 3: Functionability Events, Positive (arrows up) and Negative (arrows down)

Consequently, the life of a system could be Life of a System is the motion of system through functionability states in time

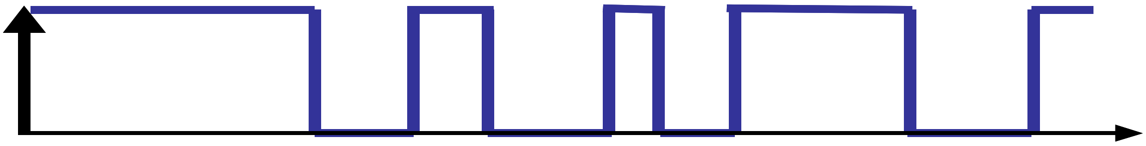

Figure 4: Functionability profile from a hypothetical system

The pattern generated by the motion of functionability through functionability states, in respect to the passage of time, forms the Functionability trajectory, which uniquely defined the degree of satisfaction of human needs by each system created and operated.

4. Concept of Functionable System

Based on the brief analysis of in-service life of a need satisfying system it became obvious that a large number of operational, maintenance and support tasks are necessary to be completed in order to “keep a system in-service”. As all of these tasks have been performed by humans, these systems are going to be called systems in order to be differentiated from the natural systems. Hence, a system is defined as: *a collection of components put together to perform at least one measurable function together with a set of actions required to be performed to maintain it in the positive functionability state through time.*

To illustrate the in-service processes described above a life of the very first Boeing 747 will be used, as an example. It started its in-service life in 1970 as the Pam Am asset with a tail number N747PA. During the 22 years of in-service life the list of major operation and maintenance statistics has been compiled and presented in the table below:

Work done by the system	• $37x10^6$ miles flown • $4x10^6$ passengers carried • $80x10^3$ hours air borne • $40x10^3$ take-off and landings made
Work done to the system	• $975x10^6$ liters of fuel loaded to the system • $806x10^3$ man-hours of maintenance consumed • $9,98x10^3$ individual X-ray frames of film used for structural inspections for metal fatigue and corrosion • 5 times had the metal skin, on its superstructure, wings and belly replaced • 2100 tyres replaced • 350 brake systems replaced • 125 engines been fitted • 4 times the passenger compartment and lavatories been replaced

Figure 2: In-service performance of a Boeing 747 registration N747PA

Comparing the data provided in the Figure 1 and 2, both of which related to the Boeing 747, it is clear that the data shown in Table 1 are measures of functionality performance of each Boeing 747 ever produced, whereas the data given in Table 2 a unique for the Boeing 747 that is registered in USA under the following tale number of N747PA.

Consequently, it is logical to ask the questions what are equivalent in-service performance measures for all other Boeing 747. Unfortunately the answer to this question can be only provided at the end of in-service life of each aircraft of this type.

Unlike deign and production engineers that have a large number of scientific laws to draw from, life cycle engineers and managers have none. Existing equations of motion, some of which are briefly presented at the beginning of this paper, are not able to even the address the above questions, not because they are incorrect, but because they are not created to address these phenomena. Consequently, without ability to provide accurate and reliable answers to those questions the future of life cycle and management is not existent.

5. Birth of Mirce-mechanics

> *"If you watch a glacier from a distance, and see the big rocks fallings into the sea, and the way the ice moves, and so forth, it is not really essential to remember that it is made out of little hexagonal ice crystals. Yet if understood well enough the motion of the glacier is in fact a consequence of the character of the hexagonal ice crystals. But it takes quite a while to understand all the behaviour of the glacier (in fact nobody knows enough about ice yet, no matter how much they've studied crystal). However, the hope is that if we do understand the ice crystal we shall ultimately understand the glacier."*
>
> Richard Feynman, “The Character of Physical Law”

The development of science started when people began to study phenomena not merely observing them. People developed instruments and learned to trust their readings, rather than to rely on their own perceptions. They recorded the results of their measurements in the form of numbers. Supplied with these numbers they began to seek relationships between them and to write down in the form of formulas. Then the formulas became the only things they came to trust when they began to predict things they could not physically experience.

As mentioned earlier, during the history human needs for transporting, navigating, communicating, cooling, heating, sheltering and many others have been satisfied by a work done by transportation, navigation, communication, refrigeration, and many other systems. Their design-in performance in terms of speed, capacity, frequency, power and similar physically measurable quantities can be accurately predicted during the design process and tested at the delivery, as they are functioning in accordance to well understood laws of natural sciences, such as: Newton's laws of motion, Coulomb's law of solid friction, Hook's law of stress and strain, Maxwell's law of electrodynamics, Boltzmann's law of thermodynamics, to name a few, which are characterised by certainty, reversibility and independence of time, location and humans.

However, main concerns of the owners and users of those systems are related to how much work they will be doing during their lives and how much effort should they put in to keep it going. Unfortunately, creators and developers of systems do not provide answers to these questions on the delivery day. Instead, years later the statistics for various measures become available. The reason for this is the fact that in-service behaviour of these systems is govern by the complex interactions of between the laws of science, human rules and environmental impacts, which are characterised by indeterminism, irreversibility, inseparability, and dependence on time, location and humans.

To rationally address questions of the amount of work done by transportation, communication, heating and many other similar systems during their lives and develop a body of knowledge for prediction of in-service performance, Dr Knezevic has established the MIRCE Akademy at Woodbury Park, Exeter, UK, in 1999. Staff, Fellows, Members and students of the Akademy have endeavoured to subject in-service lives of these systems to the laws of science and mathematics to:

- Determine the trajectory of the work done in time that is defined by the sequence of occurring functionability[2] events like failures of consisting parts, repairs, inspections, tests, environmental impacts, human actions/errors, legal/safety regulations and similar.
- Understand mechanisms that lead to the occurrence of functionability events starting from atomic structure of matter all the way up to the solar system, which covers a physical scale ranging from 10^{-10} to 10^{10} metre.
- Define a computational scheme for the quantitative prediction of the work expected to be done by a given system on one hand and the work required to be done to a given system on the other[3], during the expected in-service life.

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

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[2] Knezevic, J., Reliability, Maintainability and Supportability – A probabilistic Approach, Text and Software package, pp. 291, McGraw Hill, London 1993. ISBN 0-07-707691-

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

In summary, a body of science based knowledge comprising of axioms, mathematical equations and computational methods that enable quantitative predictions to be made of the work expected to be done by a given system and the work expected to be done to a given system during its in-service life, constitutes Mirce-mechanics.

6. Concept of Motion in Mirce-mechanics

Motion is one of the most complex concepts of science. The images it creates in our minds are diverse as the “jiggling” of atoms and molecules to the movement of planets, and beyond.

Since the earliest years of science the only idea of motion imagined was that of mechanical motion, so there is a tendency to view all other kinds of motion in terms of the concept of trajectory. As the science progressed, this naturally became impossible, for instance when the attempt was made to conceive the electrical motion. It could be possible, of course, to think in the case of a high-voltage transmission line that wire is the “trajectory” of the electric signals. However, such a mental picture would have no practical purpose, as the electromagnetic waves could not have been viewed as a liquid flowing through the wires.

Consequently, the question by which the motion of functionability through the life of systems is to be described must contain only those quantities that can be measured physically. Research performed shown that it could only be seen as the change in the functionability state of a system through time. Hence, a life of any system could be viewed as a sequence of occurrences of positive and negative functionability events that “move” systems through functionability states.

In summary, in Mirce-mechanics the motion of functionability is perceived as the change in the functionability state of a system in relation to functionability state variables, with respect to the passage of time. Functionability state variables are measures of functionality performance of a system uniquely determined by the functionability states of consisting components and system structure.

It is focused on the understanding of the mechanisms of the motion of functionability phenomena that leads to the occurrence the functionability events as statistical methods do not study the causes of statistical behaviour. Consequently, the systematic studies are applied to understand phenomena that cause: occurrence of any functionability events whatsoever.

6.1 Positive Functionability Processes

All physical processes that cause the motion of a component or a module from the negative to positive functionability states are known as positive functionability processes, PFP, and they could be categorised as following [8]:

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

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

In summary a large number of maintenance tasks is performed by humans to maintain system in functionable state during its in-service life.

6.2 Negative Functionability Processes

To understand the actions and mechanisms that generate negative functionability events analysis of over tens of thousands of components, modules and assemblies of systems in defence, aerospace, transportation, motorsport, nuclear, communication and other industries, had been studied at the MIRCE Akademy, as these phenomena have a profound impact on all aspects of the in-service life on any system.

Thus, all physical processes that cause the motion of a system from the positive to negative functionability states are known as negative functionability processes, NFP, and they could be categorised as following:

- Potential NFP are those that are generated by mechanisms related to acting in-service stresses, generated by mechanical, electrical, thermal, radiation, chemical and other types of energy which potentially might occur and consequentially exceed that strength of components and modules subjected to them. Typical examples are foreign object damage (birds, hail, rain, snow, volcanic ashes, etc.), lightening, abuse by operator (pilots, driver and user errors), single event upset and similar, that potentially could take at any instant of time during the life of a system.

- Cumulative NFP are those that are generated by irreversible processes resulting from mechanical, electrical, thermal, radiation, chemical and other type of energy that inevitably take place during the life of a system. A typical processes of this type of damage are corrosion, fatigue, creep, friction, abrasion and similar.

- Inherent NFP are generated by mechanical, electrical, thermal, radiation, chemical and other types of energy, that have been introduced into system prior to the beginning of operation process through activates associated with manufacturing, transportation, maintenance, storage and similar processes.

It is necessary to stress that components of a systems could be exposed to more that one negative functionability process during their in-service life.

6.3 Physical Scale on Mirce-mechanics

For years, research studies, international conferences, summer schools and other events have been organised in order to understand just a physical scale at which functionability phenomena should be studied and understood. In order to understand the motion of functionability it is necessary to understand the mechanisms of the motion. That represented a real challenge. Answers to the questions “what is the real cause of say, fatigue, the wind direction change, suncups formation on the blue ice runway, faulty weld, bird strike, perished rubber, maintenance induced error, carburettor icing”, to name just a few, have to be provided. Without accurate answers to those questions the prediction of their future occurrences is not possible, and without ability to predict the future, the use of the word science becomes inappropriate.

After a numerous discussions, studies and trials, it has been concluded that any serious studies in this direction, from Mirce-mechanics point of view, have to be based between the following two boundaries:

- the “bottom end” of the physical world, which is at the level of the atoms and molecules that exists in the region of 10^{-10} of a metre ;
- the ”top end” of the physical world, which is at the level of the solar system that stretches in the physical scale around 10^{+10} of a metre.

This range is the minimum sufficient “physical scale” which enables scientific understanding of relationships between system operational processes and system operational events. In other words, this is the physical range within which, the system operational processes mentioned above (fatigue, the wind direction change, suncups formation on the blue ice runway, bird strike, perished rubber, carburettor icing) take place and as such they could be understood and predicted.

6.4 Mirce-mechanics Axioms

Based on the extensive research of the motion of functionability through the lives of a large number of systems the following axioms have been developed:

Axiom 1: *System starts in-service life in positive functionability state*

Axiom 2: **S***ystem stays in a given functionability state until it is compelled to change it by an imposing event.*

Axiom 3: *The probability of occurrence of a negative functionability event at any instant of in-service life of a system is greater than zero.*

Axiom 4: *The probability of a human error during participation in any functionability process during the in-service life of a system is greater than zero.*

The above axioms are the bed rock for all calcinations and predictions in Mirce-mechanics. It is necessary to stress that there are many statements that do not result from these axioms and do not negate them. The statement “it is a beautiful aircraft” or “it is cheaper to outsource maintenance” do not result from any axioms nor do negate any axiom. Hence, the axioms divide all statements regarding the motion of systems in-service life in respect to functionability states, into three mutually exclusive groups:

1. True statement, which means that it is in accordance to the axioms
2. False statement, which means contradicts any of the axioms
3. Not related, which means that does not come from, nor contradicts, any axiom.

These axioms also limit the scope of the application of Mirce-mechanics, which is correct, as it does not cover the whole spectrum of in-service life on systems.

7. Work Done by a System

Humans have created systems to satisfy their needs for variety of functions. Based on the argument presented above, a life of a system could be viewed as a sequence of occurrences of functionability events that cause the change of the state of a system. The pattern generated by the motion of functionability through functionability states, in respect to the passage of time, forms the Functionability trajectory, as shown in the Figure below.

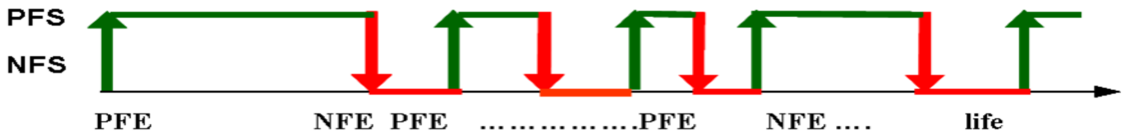

Figure 2: Functionability profile from a hypothetical system

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

The significance of the functionability trajectory is that the area covered by it defines the work done by a systems, as systems is able to satisfy human needs during the stays in PFS. Hence, the work done by a system, expressed through measures like tonnes per year, miles per day and similar, is proportional to the length of time that system spends in PFS, as illustrated by the Figure 3.

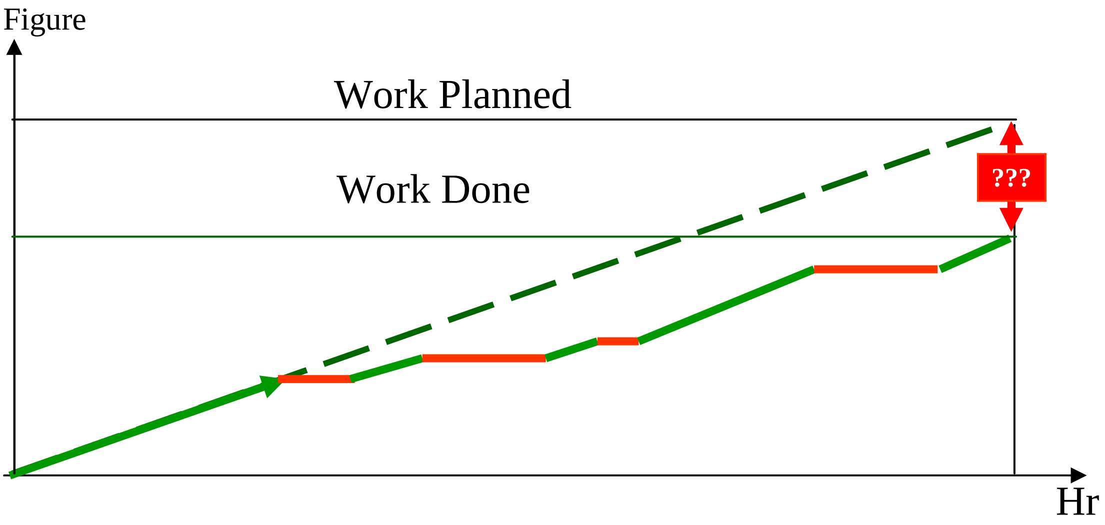

Figure 3: Worked Planned and Done by a Hypothetical System

It is necessary to point out that the work done by system is only a part of the full picture, as there is a work that need to be done to the system in order to keep it going through time. This type of the work is also part of the study of Mirce-mechanics, as they are mutually related.

8. Impact of Mirce-mechanics to Engineering and Management Processes

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

- Every scheduled flight will leave on time with a probability of at least 0.97 or in other words, it is acceptable to have no more than three delays, on average, out of 100 flights;
- The direct maintenance cost will not exceed 25 % of the purchase cost with a probability of 0.95;
- The probability that the production line will be fully operational during the specified in-service time will be not less than 0.88;
- In system consisting of several systems, at least 90% of them will be operational at all times with a probability not less than 0.925;
- The mission reliability will be greater than 0.98 for missions shorter than 500 hours;
- There should be 5 failures among 1000 systems, on average, during the first 10 years of service, with a probability of 0.975.
- Each 10 hour flight will be successfully completed with probability of 0.995, during the first 20 years of operation

Consequently, the only way to address the work done formulated in the way above is to use the approach of Mirce-mechanics provided in this paper to evaluate engineering and management options, at the time when fundamental and irreversible decision are made regarding future systems.

9. Conclusions

Natural philosophy was distinguished from the other precursor of modern science, natural history, in that the former involved reasoning and explanations about nature (and after Galileo, quantitative reasoning), whereas the latter was essentially qualitative and descriptive.

This paper clearly demonstrates that functionability performance of any human made and managed system is very much different from its functionality performance, which are accurately predictable by the proven laws on natural sciences. Hence, there is a need for the development of science based methods for the predictions of the motion of functionability through the life of systems and associated measures of in-service performance.

This paper also demonstrates that functionability performance is the time dependent property of the system and its motion is manifested through the sequence of transitions through positive and negative functionability states resulting from any natural or human actions.

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Mathematical Principles of Mirce-mechanics

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

Abstract

Scientific principles and concepts expressed through the laws, equations and formulas are the bedrock for the prediction of the deign-in functionality performance of any engineering creation. However, there is no equivalent when the in-service functionability performance predictions have to be made. Hence, Mirce-mechanics has been created at the MIRCE Akademy to fulfil the roll. The main purpose of this paper is to present the development and application of mathematical principles of Mirce-mechanics that are the bedrock for the prediction of the functionability performance of engineering systems.

1. The Concept of Functionality

According to Einstein **"***Everything that the human race has done and thought is concerned with the satisfaction of felt needs*".

During the history of civilisation needs for transporting, communicating, navigating and many others have been satisfied by transpiration, communication, navigation and other human created systems. As they are functioning in accordance to the laws of science, which are independent of time, place and human impact, their design-in performance, like speed, acceleration, power, fuel consumption and many others, are accurately predictable. [1]

2. The Science of Functionality

The theoretical foundations of designing systems are laws of science that describe observable natural phenomena, known to humans so far. Among them laws of motion are the most significant from the life cycle engineering and management point of view, in respect to functionality of a system. Some of them are very briefly addressed in this paper as the scientific foundation for the development of the laws of the motion of functionability.

> **Newton's laws of motion** are three physical laws that form the basis for classical mechanics. These laws describe the relationship between the forces acting on a body and the motion of that body. They were first compiled by Sir Isaac Newton in his work *Philosophiæ Naturalis Principia Mathematica*, first published on July 5, 1687.Newton used them to explain and investigate the motion of many physical objects and systems, from the "apple" to planets.
>
> **Kepler's laws of planetary motion** are three astronomical laws that describe the motion of planets around the Sun. From them it is possible to accurately predict either what the position of the planet is at a given time, or the time when the planet is in a given position.

Maxwell's equations are a set of four partial differential equations that relate the electric and magnetic fields to their sources, charge density and current density. Their individual names, equations and descriptions are given in the table below.

Name	Equation	Describe
Gauss's law:	$\nabla \times E = \frac{\rho}{\varepsilon_0}$	How charges attract/repel
Gauss's law for magnetism:	$\nabla \times B = 0$	No isolated magnetic poles
Maxwell–Faraday equation (Faraday's law of induction):	$\nabla \times E = -\frac{\partial B}{\partial t}$	Changing magnetism produces electricity
Ampere’s law (with Maxwell's extension):	$\nabla \times B = \mu_0 J + \mu_0 \varepsilon_0 \frac{\partial E}{\partial t}$	Changing electricity produces magnetism

Navier–Stokes equations, describe the motion of fluid substances. These equations arise from applying Newton’s second law to the motion of fluid, together with the assumption that the fluid stress is the sum of a diffusing viscous term (proportional to the gradient of velocity), plus a pressure term. The general form of the equations of the motion of fluid, being written for an arbitrary portion of the fluid, is:

.

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla p + \nabla \cdot \mathbb{T} + \mathbf{f},$$

The equations are useful because they describe the physics of many things from modelling the weather, ocean currents, water flow in a pipe, air flow around a wing and motion of stars inside a galaxy. In their full and simplified forms help with the design of aircraft and cars, the study of blood flow, the design of power stations, the analysis of pollution, and many other things.

Boltzmann transport equation, is used to study the motion of physical quantities such as heat and charge through fluid, and thus to derive transport properties such as electrical conductivity, Hall conductivity, viscosity, and thermal conductivity. It is defined by the following expression:

$$\frac{\partial f}{\partial t} + \frac{\partial f}{\partial \mathbf{x}} \cdot \frac{\mathbf{p}}{m} + \frac{\partial f}{\partial \mathbf{p}} \cdot \mathbf{F} = \left. \frac{\partial f}{\partial t} \right|_{\mathrm{coll}} .$$

Physicists today use the equation to model gases in everything from nuclear power stations to galaxies

Heisenberg's equation of motion was the first complete and correct definition of quantum mechanics, branch of physics that study the motion of subatomic particles. It extended the Bohr model of atom by describing how the quantum jumps occur, by interpreting the physical properties of particles as matrices that evolve in time. The Heisenberg equation of motion, named after Werner Heisenberg who formulate it in 1925 in the following repression:

$$\mathrm{i}\hbar\,\frac{dv_t}{dt} = [v_t, H_t].$$

Schrödinger equation describes how the quantum state of a physical system changes in time. It is as central to quantum mechanics as Newton's laws are to classical mechanics. In the standard interpretation of quantum mechanics, the quantum state, also called a wavefunction or state vector, is the most complete description that can be given to a physical system. The equation is named after Erwin Schrödinger, who constructed it in 1926, and it was formulated in the following form:

$$i\hbar\frac{\partial}{\partial t}\Psi = \hat{H}\Psi$$

Solutions to Schrödinger's equation describe not only molecular, atomic and subatomic systems, but also macroscopic systems, possibly even the whole universe

In summary, scientific principles and concepts expressed through the laws, equations and formulas are the bedrock of any engineering creation. They have achieved that status by providing accurate predictions for all engineering and management concepts, scenarios and “dreams”.

3. Concept of a System

At the end of production or construction process, when all consisting components are assembled together and relationships between them established, a new physical system is “born” with capability to deliver all expected functionality characteristics. That unique, infinitesimally short instant of time, is denoted as t=0, to mark the beginning of the system operational process. Thus, each system will have its own “birth” time, which is very important from the system life point of view. At that instant the system is, for the very first time in its life, able to satisfy users’ needs by delivering functionality (function, performance and attributes). Hence, functionality characteristics of the system are inherited from its design process and cannot be changed during the system life, apart from implementing some modifications and redesigns.

However, experience teaches us that in-service performance of these systems is dominated by phenomena like fatigue, operator induced errors, corrosion, creep, foreign object damage, a faulty weld, bird strike, perished rubber, carburettor icing, to name just a few. These phenomena generate energy exchanges between systems and environment, leading to the loss of the design-in function or performance. Hence, maintaining the deign-in performance beyond the delivery day requires actions like troubleshooting, repairs, replacements, modifications, diagnostics, “cannibalisations” and similar to be performed.

In summary, any entity that satisfies human needs by performing a measurable function whose design-in functionality is maintained by humans is defined as a engineering system.

4. The Concept of Functionability

Thus, the ability of being functional through time, known as **functionability,** is an essential in-service property of engineering systems.

From functionability point of view, at any instant of time a system can be in one of the following two states:

1. Positive Functionability State, PFS, which is the state of being functional
2. Negative Functionability State, NFS, which is the state of not being functional

The motion of the system through functionability states is governed by the occurrence of functionability events, which are classified as:

- Positive Functionability Events, PFE, which signifies the transition from NFS to PFS
- Negative Functionability Events, NFE, which signifies the transition from PFS to NFS

Consequently, the life of a engineering system could be considered as motion of system through functionability states. The pattern generated by the motion of functionability through functionability states, in respect to the passage of time, forms the functionability trajectory.

5. Functionability Questions

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

- How many Negative Functionability Events are going to occur?
- What types of Negative Functionality Events are going to occur?
- What frequencies of Negative Functionability Events are going to be?
- How the cause of Negative Functionability Event will be detected?
- How long systems are going to be in Negative Functionability State?
- How long systems are going to be in Positive Functionability State?

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

In summary, without ability to provide accurate answers to functionability questions design engineering and project management are not in the position make the trade off between the cost of resources required to maintain systems in positive functionability states and the consequential losses while they are in negative functionability states.

6. Concept of Mirce-mechanics

The development of science started when people began to study phenomena not merely observing them. People developed instruments and learned to trust their readings, rather than to rely on their own perceptions. They recorded the results of their measurements in the form of numbers. Supplied with these numbers they began to seek relationships between them and to write down in the form of formulas. Then the formulas became the only things they came to trust when they began to predict things they could not physically experience.

Consequently, to address functionability questions the author established the MIRCE Akademy in 1999. Staff, Fellows, Members and students of the Akademy study in-service behaviour of engineering systems to:

- Physically observe the emerging trajectory of the motion of functionability through the life of engineering systems and to measure emerging in-service performance
- Scientifically understand mechanisms that cause the motion of a functionability through the life of engineering systems, within the physical scale from 10^{-10} to 10^{10} metre [2,3,4,5]
- Mathematically define the scheme for the prediction of in-service performance of a given design-in system, for a given in-service conditions and rules.

A science based body of knowledge, formulated through axioms, formulas, methods, rules and algorithms for predicting the in-service performance of the future systems, resulting from their motion through the functionability states in respect to time constitutes Mirce-mechanics.

The ability to simultaneously predict the design-in functionality performance and in-service functionability performance of the future systems is of fundamental importance for the engineers, managers, investors, regulators and other specialists who are responsible for the satisfaction of the "human felt needs", in reliable, economical and safe manner, for the future transportation, communication, defence, energy, entertainment and many other functions delivered by engineering systems.

7. The Concept of Motion in Mirce-mechanics

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

Consequently, the question by which the motion of functionability through the life of engineering systems is to be described must contain only those quantities that can be measured physically. Research performed shown that it could only be seen as the change in the functionability state of a system through time. Hence, a life of any engineering system could be viewed as a sequence of occurrences of positive and negative functionability events that "move" systems through functionability states.

In summary, in Mirce-mechanics the motion of functionability is perceived as the change in the functionability state of a system in relation to functionability state variables, with respect to the passage of time. Functionability state variables are measures of functionality performance of a system that uniquely determine the functionability states of a system.

Results of experiments and observations performed thus far unquestionably lead to conclusion that the deterministic regularity found in the continuous motion of functionality, such as speed, acceleration and similar, studied by classical mechanics, cannot be found in respect to the motion of functionability through time. What can be found is discrete motion with statistical variability, as shown in Figure 1.

Thus, functionability trajectories, generated by similar individual systems, under similar circumstances vary among them self, to the degree that no two trajectories are identical. Therefore, the proven formulas of Newtonian mechanics that govern the motion of macroscopic bodies through time cannot be used for predicting the motion of functionability through time, as far as the functionability trajectory is concerned

The relative frequency histogram of the motion of functionability through the life of sample size of 497 systems at specific instances of time is obtained by using well-known statistical expression:

$$y'(t) = \frac{\text{Number fo systems in PFS @ t}}{\text{Total Number of Systems Orserved}} \qquad 1.$$

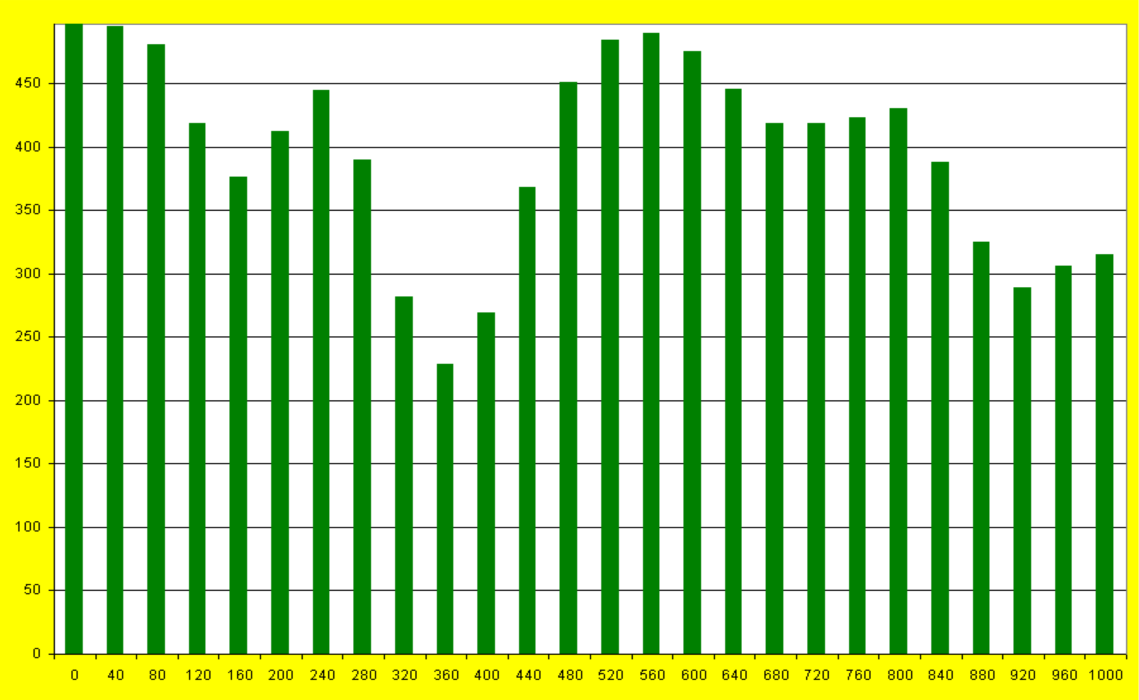

Figure 1: Relative Frequency Histogram of the Motion of Functionability through the life of 497 Systems at specific instances of time

At the stated period of operational time, as shown in Table 2, the following statistics has been observed for a given sample of 497 systems of this type

Tst	MNNE(Tst0	MNPE‘Tst)	W_{by}(Tst)	W_{to}(Tst)	y(Tst)
300	1.31	1.02	265.51	84.49	0.702
650	2.32	2.16	535.18	114.82	0.849
750	2.87	2.71	621.84	128.16	0.843
900	3.84	3.46	741.47	153.53	0.624
1000	4.77	4.38	797.77	202.23	0.647

Table 2: Functionability Statistics of the in-service behaviour of of 497 Systems at specific instances of time

Clearly, functionability histograms and other in-service statistics can be produced only after the data have been generated, which means after the events. However, the objective of Mirce-mechanics is to develop equation that will be able to predict the data that are going to be observed, in the similar manner as the predictions made by Newton’s, Maxwell’s, Schrödinger’s become confirmed by the future events.

8. Probabilistic Motion

The laws of probability are just as rigorous as other mathematical laws. However, they do have certain unusual features and clearly delineated domain of application. For example, it can be readily verify that in the case of a large number of systems failure phenomena will occur in a specific number of the cases, and the law is more accurate the more systems are observed. However, this accurate knowledge will be of no help in predicting the occurrence of functionability events in each individual case. This is what distinguishes the laws of probability: the concept of probability is valid only for an individual event and it is possible to work out a number that corresponds to it. However, it can only be measured when identical tests are repeated a great number of times. Only then can the measured value, the probability, be used to assess the occurrence of each individual functionability event, which is one of the possible outcomes of the test.

The unusual features of the laws of probability have a natural explanation. In fact, most probabilistic events are results of quite complex physical processes, which in many cases cannot be studied or understood in all of its intricacy. Such inability takes its toll, as it is only possible to predict with certainty the average result of numerous identical tests. Thus, for each functionability event it is only possible to indicate its likely outcome.

Probabilistic predictions of the functionability trajectory are based on the framework of the sequence of occurrences of Positive and Negative Functionability Events, whose individual and cumulative times are measured as shown in the Figure below.

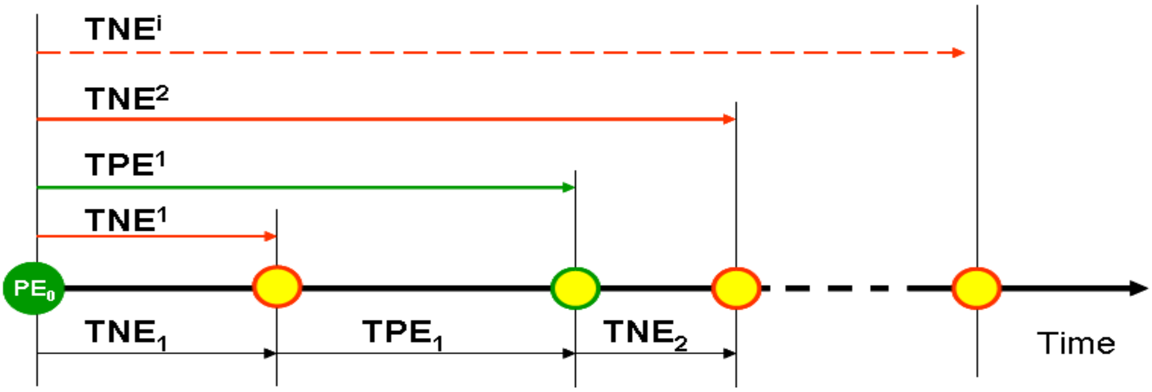

Figure 2: Individual and Cumulative Times to Functionability Events

Based on the Figure 2, the following functions are used:

Negative Function, F*i(t)*, which defines the probability that the ith NFE will take place before or at instant of time t is defined in the following way:

$$F_i(t) = P(TNE_i \leq t) = \int_0^t f_i(t)dt, \qquad i = 1, \infty . \qquad 2.$$

Positive Function, O*i(t)*, which define the probability that the ith PFE will take place before or at instant of time t is defined by the following expression:

$$O_i(t) = P(TPE_i \leq t) = \int_0^t o_i(t)dt, \qquad i = 1, \infty . \qquad 3.$$

Probability distribution that defines this event is uniquely determined by the physical properties of the process that generate positive functionability event (replacement, repair, calibration, modification and similar) [9].

Sequential Negative Function, F*(t)*, which defines the probability that the ith sequential NFE will take place before or at instant of time t, is defined as:

$$F^i(t) = P(TNE^{\mathrm{i}} \leq t) = \int_o^t M^{i-1}(x)dF_i(t-x), \qquad i = 1, \infty . \qquad 4.$$

Sequential Positive Function, O*(t)*, which defines the probability that the ith sequential PFE will take place before or at instant of time t: is presented in the following manner:

$$O^i(t) = P(TPE^{\mathrm{i}} \leq t) = \int_0^t F^i(x)dM_i(t-x), \qquad i = 1, \infty . \qquad 5.$$

Equations 4 and 5 define the sequence of functionability events for any system.

Having determined the probability distribution and its governing parameters of the times to subsequent functionability event, positive and negative, it is possible to develop a mathematical scheme that will provide opportunity to predict the future sequence of functionability events for any given system.

This is the essence of the Mirce-mechanics, which is the only theory available to design engineers to quantitatively predict the consequences of all of their decisions on in-service behaviour of their future systems.

9. Mathematical Principles of Mirce-mechanics

The trajectory of functionability is uniquely defined by the sequence of functionability events, from the birth of the system to its decommissioning. Thus, the fundamental equation of Mirce-mechanics, the functionability equation *y (t)*, that defines the probability of a system being functionable at a given instant of time t is defined as:

$$y(t) = P(PFS @ t) = \sum_{i=0}^{\infty}\left[P(PFS^i @ t)\right] = \sum_{i=0}^{\infty}\left[P\left(TPE^i \le t\right) - P\left(TNE^{i+1} \le t\right)\right]$$

Making use of equations 3 and 4, while bearing in mind that $O_0(0) = 1$, as a system starts its life in positive functionability state, the above expression of functionability equation could be presented in its final form:

$$y(t) = 1 - \varphi(t) + \mu(t) \qquad 6.$$

where:

$\varphi(t) = \sum_{i=1}^{\infty} P(TNE^i \le t) = \sum_{i=1}^{\infty} F^i(t)$, is the expected number of negative functionability events that will take place from the birth of a system to the stated instant of time t.

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

The author developed this expression and named it Mirce Functionability Equation. It defines the trajectory of the motion of functionability through the life of engineering systems.

The unit of functionability, determined by the Mirce Functionability Equation, is 1 Senna [1S]. It quantifies the amount of certainty of a given engineering system being in positive functionable state at a given instant of time**.**

Making use of the equation 6 it is also possible to calculate the expected time that system will spend in PFS during a stated interval of calendar time, which is Mirce-mechanics' is known as the work done by the system, $W_{by}(t)$, through the following equation:

$$W_{by}(t) = \int_0^t y(t)dt \qquad \mathbf{7}$$

Correspondently, it is possible to derive the expression for the prediction of the work done to the system during its stays in NFS, which mainly is related to the time take for the executions of maintenance tasks, scheduled and unscheduled. Hence, the probability of a system being in negative functionability state at any instant of time, denote with n(t), could be calculated in accordance to this equation:

$$n(t) = P(NFS @ t) = \mu(t) - \varphi(t) \qquad 8$$

As the system at any instant of time must be in either positive or negative functionability state, according to the second axiom of probability, the sum of probabilities of these two mutually exclusive events must be equal to 1, as the following expression confirms.

Thus the work done to the system during a stated period of calendar time, $W_{to}(t)$, could calculated in accordance to the following equation:

$$W_{to}(t) = \int_{0}^{t} n(t)dt \qquad \mathbf{9}$$

Making use of existing observational data related to the in-service behaviour of a sample of 497 systems, operating in similar environmental and utilisation conditions, the probability laws that drive shapes of positive and negative functions defined by the equations 2-5 where determined. The obtained functions are shown in Figure 3, where the green lines represent positive functions and the read lines represents negative functions.

The functionability trajectory, calculated in accordance to the expression 6 is shown with a black line in the Figure 3.

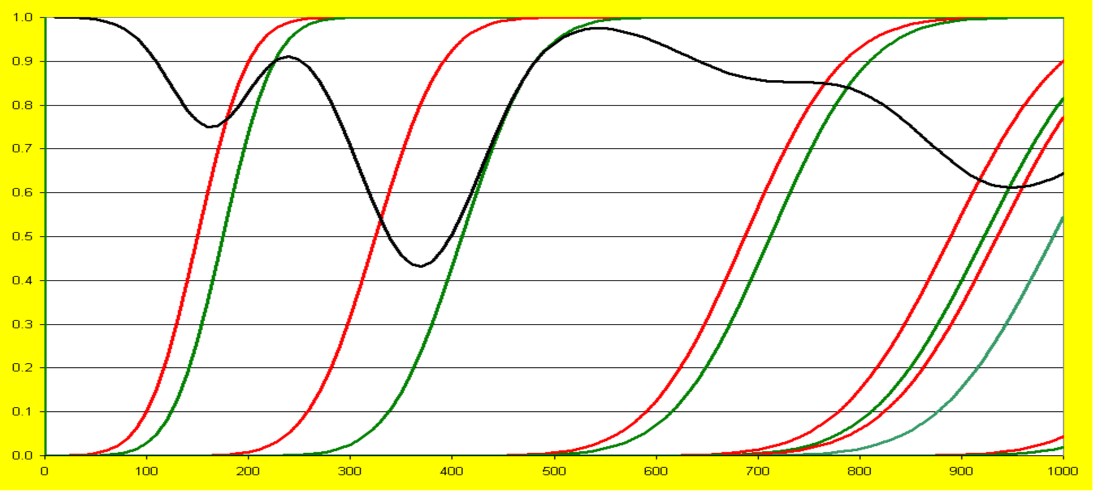

Figure 3: Functionability profile calculated by Mirce Functionability Equation (6) for the Example shown in Figure 1.

At the stated period of operational time, as shown in Table 3, the following functionability measures have been calculated by making of Mirce-mechanics Mathematics presented above.

Tst	MNE(T_{st})	MPE(T_{st})	W_{by}(T_{st})	W_{to}(T_{st})	y'(T_{st})
300	1.32	1.02	263.13	36.87	0.709
650	2.35	2.13	533.28	116.72	0.883
750	2.90	2.74	620.15	123.85	0.853
900	3.87	3.49	738.39	161.61	0.626
1000	4.80	4.45	797.43	202.57	0.652

Table 3: Predicted Functionability measure for the Example shown in Table 2.

Making use of equations 7 and 9 it possible to calculate the work done by a given system as well as the work done to a given system for entire its in-service life.

For the example run through this paper the $W_{by}(t)$ and $W_{to}(t)$ have been calculated and presented in Figure 4, where:

- Broken green line represents a theoretical work done by a system, which means for a system that never makes a transition to the negative functionability state, which is in contrast to the 3rd axiom of Mirce-mechanics

- Solid green line represents the work done by the system through in-service time starting from the introduction to the service.
- Solid red line represents the work done to the system from the introduction to the service

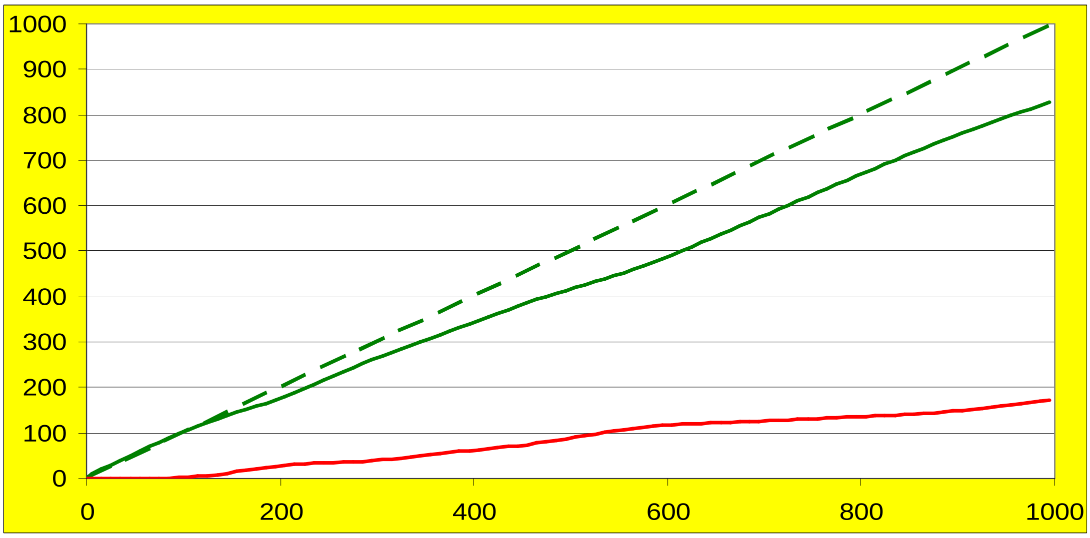

Figure 4: Predicted work done by the system and to the system

10. The Impact of Mirce Functionability Equation on System Engineering and Management Process

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

- Every scheduled flight will leave on time with a probability of at least 0.97 or in other words, it is acceptable to have no more than three delays, on average, out of 100 flights;
- The direct maintenance cost will not exceed 25 % of the purchase cost with a probability of 0.95;
- The probability that the production line will be fully operational during the specified in-service time will be not less than 0.91;
- In system consisting of several systems, at least 90% of them will be operational at all times with a probability not less than 0.925;
- The mission reliability will be greater than 0.98 for missions shorter than 500 hours;
- There should be 5 NFEs among 1000 systems, on average, during the first 10 years of service, with a probability of 0.95.
- Each 10-hour flight will be successfully completed with probability of 0.995, during the first 20 years of operation

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

11. Conclusion

Like in the classical mechanics, where the continuous uniform motion is natural state of the macro world that is fully defined and predictable by Newton's equations, or in quantum mechanics where the continuous motion is also natural state of a micro world fully described and predictable by Schrodinger equation, in Mirce-mechanics continuous change in the functionability states is a natural state of engineering systems during they in-service life, which is fully defined and predictable by mathematical principle of Mirce Mechanics presented here.

This paper also demonstrates that functionability performance is the time dependent property of the system and its motion is manifested through the sequence of transitions through positive and negative functionability states initiated by the occurrences of functionability events.

Finally, the mathematical scheme of Mirce-mechanics presented in this paper is the scientific foundation of the System Engineering and Management predictions and analysis regarding the motion of functionability through the life of engineering system.

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Mirce Supportability Equation

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

Abstract

Scientific principles and concepts expressed through the laws, equations and formulas are the bedrock for the prediction of the design-in functionality performance of any engineering creation. However, there is no equivalent when the in-service supportability performance predictions have to be made. Hence, Mirce-mechanics has been created at the MIRCE Akademy to fulfil the roll. The main purpose of this paper is to present the development of the Mirce Supportability Equation that is the bedrock for the prediction of the supportability performance of engineering systems.

1. Introduction

During the history of civilisation needs for transporting, communicating, navigating and many others have been satisfied by transpiration, communication, navigation and other human created systems, commonly known as engineering systems. As they are functioning in accordance to the laws of science, which are independent of time, place and human impact, their design-in performance, like speed, acceleration, power, fuel consumption and many others, are accurately predictable. [1]

However, experience teaches us that in-service performance of these systems is dominated by phenomena like fatigue, operator induced errors, corrosion, creep, foreign object damage, a faulty weld, bird strike, perished rubber, carburettor icing, to name just a few. These phenomena generate energy exchanges between systems and environment, leading to the loss of the design-in function or performance. Hence, maintaining the design-in performance beyond the delivery day requires actions like troubleshooting, repairs, replacements, modifications, diagnostics, "cannibalisations" and similar to be performed. Thus, all human created collections of entities that are able to deliver at least one measurable function whose functionability is maintained by humans' actions are known as engineering systems [2].

Generally speaking, from functionability point of view, at any instant of time a engineering system can be in one of the following two states [3]:

3. Positive Functionability State, PFS, during which is able to deliver functionality.
4. Negative Functionability State, NFS, during which is not able to deliver functionality.

The motion of the system through functionability states is governed by the occurrence of functionability events, which are classified as:

- Positive Functionability Events, PFE, which cause the transition from NFS to PFS
- Negative Functionability Events, NFE, which cause the transition from PFS to NFS

Consequently, the life of a engineering system could be considered as motion of system through functionability states. The pattern generated by the motion of functionability through functionability states, in respect to the passage of time, forms the functionability trajectory, which is defined by Mirce Functionability Equation [4].

$$y(t) = 1 - \varphi(t) + \mu(t)$$

where $\varphi(t)$ and $\mu(\mathrm{t})$ are expected number of negative and positive functionability events, respectively, that will take place from the birth of a system and a given instant of time t.

However, in this scheme all activities that take place during the stay of a system in the NFS are considered together. Mathematically it does make sense, but a physical analysis of maintenance and support activities clearly shows that they are very distinguishable processes. Hence, the main objective of this paper is to delineate their boundaries and develop a mathematical equation for predicting the motion of engineering systems through support process, which is the time during which no maintenance action can take place due to lack of necessary resources.

2. Concept of Operational Process

Act of the birth of a system initiates the utilisation process that consists of the following three processes:

i) Operation process during which the expected function(s) is performed and users' needs satisfied.
ii) Maintenance process during which the functionability of the system is maintained/restored by the user/owner.
iii) Support process during which all necessary resources for the operation and maintenance of the system are provided.

Clearly, each of the above mentioned processes are planned and managed in accordance to the business objectives and plans of the system's owners and users.

It is necessary to stress that all three processes are interdependent, as the operation process determines the load and regime of the system which directly affects the process of change in condition, and these affect the maintenance process. On the other hand, both the operation and maintenance processes, drive support process, which is connected with the cost of provision of necessary resources for their successful completion and the consequential cost of lost revenue due to inability of the system to perform a function, which should be taken into consideration when determining the process of operation.

3. The Support Process

Already it has been pointed out that in order to successfully conduct the operation and maintenance process some resources are needed. The process during which all necessary resources for operation and maintenance are provided is known as support process, and is defined as [1]:

> 'the flow of support tasks, selected by the user to meet the specific business objectives, performed by the user, in order to provide the resources needed for the execution of operation and maintenance plan'.

It is necessary to stress that the logistics process, as any other process, requires resources for its completion. Most frequently required resources are trained personnel, equipment, facilities, software, etc. As the main task of these resources is to support process they will be termed Support Resources (SR). Generally speaking, the main characteristic, which quantifies the logistic support process, is the number of demands for resources, which in majority of cases quantifiable with discrete random variables.

4. Support Resources

The resources needed for the successful completion of every operation and maintenance action are commonly known as support resources. They could be grouped into the following categories [5]:

- Supply Support
- Test and Support Equipment
- Transportation and Handling
- Personnel and Training
- Facilities
- Data
- Computer Resources

Each of these categories identified are briefly described below.

4.1 Supply Support

Supply support is the generic name, which includes all spares, repair parts, consumables, special supplies, and related inventories needed to support the operation and maintenance processes. Considerations include each operation and maintenance task and each geographical location where spare/repair parts are distributed and stocked; spares demand rates and inventory levels; the distances between stocking points; procurement lead times; and the methods of material distribution.

4.2 Test and Support Equipment

This category includes all tools, special condition monitoring equipment, diagnostic and checkout equipment, metrology and calibration equipment, maintenance stands, and servicing and handling equipment required to support scheduled and unscheduled maintenance actions associated with the system or product. Test and support equipment may be classified as "peculiar" (newly designed and/or off-the-shelf items peculiar to the system under development) or "common" (existing items already in the inventory).

4.3 Transportation and Handling

This element of support includes all provision, containers (reusable and disposable), and supplies necessary to support packaging, preservation, storage, handling, and/or transportation of system, test and support equipment, spares and repair parts, personnel, technical data, and mobile facilities. In essence, this category basically covers the initial distribution of products and the transportation of personnel and materials for operation and maintenance purposes.

4.3 Personnel and Training

Personnel required for the installation, checkout, operation, handling, and sustaining the maintenance of the system (or product) and its associated test and support equipment are included in this category. Maintenance personnel required for each operation and maintenance are considered. Personnel requirements are identified in terms of quantity and skill levels for each operation and maintenance function by level and geographical location. Formal training includes both initial training for system/product familiarisation and replenishment training to cover attrition and replacement personnel. Training is designed to upgrade assigned personnel to the skill levels defined for the system. Training data and equipment (e.g. simulators, mock-ups, and special devices) are developed as required, to support personnel training operations.

4.4 Facilities

This category refers to all special facilities needed for completion of operation and maintenance tasks. Physical plant, real estate, portable buildings, housing, intermediate maintenance ships, calibration laboratories, and special depot repair and overhaul facilities must be considered. Capital equipment and utilities (heat, power, energy requirements, environmental controls, communications, etc.) are generally included as part of the facilities.

4.5 Data

System installation and checkout procedures, operation and maintenance instructions, inspection and calibration procedures, overhaul procedures, modification instructions, facilities information, drawings, and specifications that are necessary in the performance of system operation and maintenance functions are included herein. Such data not only cover the system but also the test and support equipment, transportation and handling equipment, training equipment, and facilities.

4.6 Computer Resources

This facet of support refers to all computer equipment and accessories, software, programmes, tapes, disks, drives, data bases and so on, necessary for the performance of system operation and maintenance functions. This includes both, operation assisting and maintenance diagnostic aids.

5. The Concept of Negative Time in Support

In order to explain the physical meaning of supportability, it is necessary to establish the link between the operational and maintenance processes and the additional length of time during which systems are in NFS. Thus, supportability can be graphically presented as shown in Figure 1.

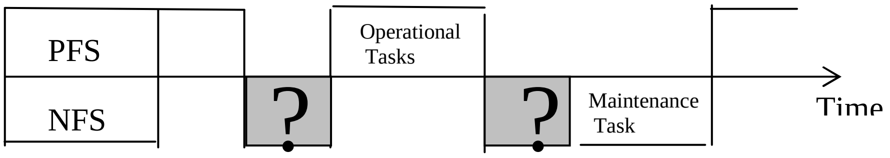


Figure 1.The Concept of Supportability in the life of Engineering Systems

Despite this being only an illustrative attempt to define the concept of supportability, it also suggests that the capability of an item to be supported during the execution of operational and maintenance tasks could be numerically defined through the shaded area. This means that supportability is indirectly proportional to the area considered, and that the more supportable systems have smaller area, and vice versa. It is necessary to stress that the size of the area considered depends on a large number of factors, like complexity of design, size, quantity, and standardisation of all support resources addressed above.

Thus, supportability can be quantitatively expressed through the length of time during which a system is in the NFS and neither operational nor maintenance actions cannot be performed, due to lack of essential support resources (spares, material, personnel, facilities, software, equipment, tools, and similar).

Experience teaches that the time spend in NFS due to provision of support resources , denoted as TPS_s has a statistical nature resulting from the variability and complexity of all influential factors to the support process. It is therefore reasonable to say that it is impossible to give a deterministic answer regarding the additional length of time during which any specific item will spend in the NFS. It is only possible to assign a probability that it will happen within a given interval of time, or that a certain percentage of support actions will, or will not, be completed during a specific time interval.

6. Logistics Support Questions

The Logistics management function in any organisation is fully dedicated towards the provision of the resources needed for the successful completion of the tasks within operation and maintenance process. As such, the logistics function is to select, acquire, and deliver the right resources in the right place at the right time, based on existing information related to the system technical effectiveness and the users’ business plan. Therefore, the main objective of the logistics function is to provide the most satisfactory answers to some of the following questions:

- When hardware should be acquired?
- When spare parts stock should be established?
- When training of operation and maintenance personnel should be started?
- When maintenance facilities are going to be needed?
- What is required for operation?
- What is required for maintenance?
- What is required for storage and transportation?
- Where spare parts should be stocked?
- Where maintenance shops should be located?
- Where repair facilities should be set up?
- Who can restore the product?
- Who will operate the product?
- Who will train the personnel?
- How the information to effectively operate the system could be obtained?
- How the information to maintain the system could be obtained?
- How all of this could fit in the budget available?

Certainly the list of possible questions is much longer, but those above are representative. Clearly, logistics management and planning is a very difficult and complex function because resources incur the cost on the one hand, but the lack of them could have a detrimental impact on the system operational success.

7. Concept of Mirce-mechanics

The development of science started when people began to study phenomena not merely observing them. People developed instruments and learned to trust their readings, rather than to rely on their own perceptions. They recorded the results of their measurements in the form of numbers. Supplied with these numbers they began to seek relationships between them and to write down in the form of formulas. Then the formulas became the only things they came to trust when they began to predict things they could not physically experience.

Consequently, to address functionability questions the author established the MIRCE Akademy in 1999. Staff, Fellows, Members and students of the Akademy study in-service behaviour of engineering systems to:

- Physically observe the emerging trajectory of the motion of functionability through the life of engineering systems and to measure emerging in-service performance.
- Scientifically understand mechanisms that cause the motion of functionability through the life of engineering systems, within the physical scale from 10^{-10} to 10^{10} metre.
- Mathematically define the scheme for the prediction of in-service performance of a given design-in system, for a given in-service conditions and rules.

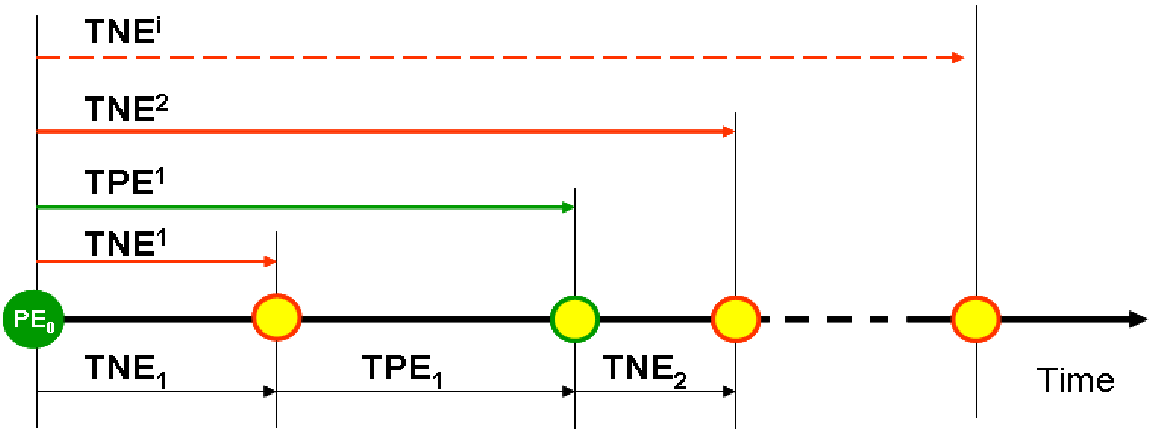
A science based body of knowledge, formulated through axioms, formulas, methods, rules and algorithms for predicting the in-service performance of future systems, resulting from their motion through the functionability states in respect to time constitutes Mirce-mechanics.

The ability to simultaneously predict the design-in functionality performance and in-service functionability performance of future systems is of fundamental importance for the engineers, managers, investors, regulators and other specialists who are responsible for the satisfaction of the “human felt needs”, in a reliable, economical and safe manner, for the future transportation, communication, defence, energy, entertainment and many other functions delivered by engineering systems.

8. Probabilistic Motion

The unusual features of the laws of probability have a natural explanation. In fact, most probabilistic events are results of quite complex physical processes, which in many cases cannot be studied or understood in all of its intricacy. Such inability takes its toll, as it is only possible to predict with certainty the average result of numerous identical tests. Thus, for each functionability event it is only possible to indicate its likely outcome.

Probabilistic predictions of the functionability trajectory are based on the framework of the sequence of occurrences of Positive and Negative Functionability Events, whose individual and cumulative times are measured as shown in the Figure below.



Based on the Figure 2, the following functions are fully defined:

- Negative Function, F$_i(t)$, which defines the probability that the ith NFE will take place before or at instant of time t is defined in the following way:

$$N_i(t) = P(TNE_i \le t), \qquad i = 1, \infty . \qquad 2.$$

- Positive Support Function, O$_{si,i}(t)$, which defines the probability that the ith PFE$_{s,}$, will take place before or at instant of time t is defined in the following way:

$$O_{s,i}(t) = P(TPE_{s,i} \le t), \qquad i = 1, \infty . \qquad 3.$$

- Positive Maintenance Function, O$_i(t)$, which define the probability that the ith PFE$_{m,i}$ will take place before or at instant of time t is defined by the following expression:

$$O_{m,i}(t) = P(TPE_{m,i} \le t), \qquad i = 1, \infty . \qquad 3.$$

- Probability distribution that defines this event is uniquely determined by the physical properties of the process that generate positive functionability event (replacement, repair, calibration, modification and similar) [9].

- Sequential Negative Function, F^i (t), which defines the probability that the ith sequential NFE will take place before or at instant of time t, is defined as:

$$F^i(t) = P(TNE^i \le t), \qquad i = 1, \infty . \qquad 4.$$

- Sequential Support Function, $O_s^i(t)$, which defines the probability that the ith sequential PFE will take place before or at instant of time t: is presented in the following manner:

$$O_s^i(t) = P(TPE_s^i \le t), \qquad i = 1, \infty . \qquad 5.$$

Having determined the probability distribution and its governing parameters of the times to subsequent functionability event's positive and negative, it is possible to develop a mathematical scheme that will provide opportunity to predict the future sequence of functionability event's in general, and supportability relevant events in particular, for any given engineering system.

This is the essence of the Mirce-mechanics, which is the only theory available to design engineers to quantitatively predict the consequences of all of their decisions on in-service behaviour of their future systems.

9. Mirce Supportability Equation

The trajectory of functionability is uniquely defined by the sequence of functionability events, from the birth of the system to its decommissioning, as defined by equation 1. Thus, the mathematical scheme that uniquely defines the trajectory of engineering systems through the support sector of NFS$_s$, denoted as $n_s(t)$, is defined as:

$$n_s(t) = P(NFS_s @ t) = \sum_{i=1}^{\infty}\left[P(NFS_s^i @ t)\right] = \sum_{i=1}^{\infty}\left[P\left(TNE^i \le t\right) - P\left(TPE_s^i \le t\right)\right]$$

Making use of equations 3 and 4, the above expression of functionability equation could be presented in its final form:

$$n_s(t) = \varphi(t) - \mu_s(t) \qquad 6.$$

where:

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

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

The author developed this expression and named it Mirce Supportability Equation. It defines the trajectory of the motion of a engineering system through a given support process. For each given instant of time t, the supportability equation quantifies the probability of a system being in support part of the NFS.

The trajectory of the motion of a hypothetical engineering system through a hypothetical support process is shown in the Figure 2.

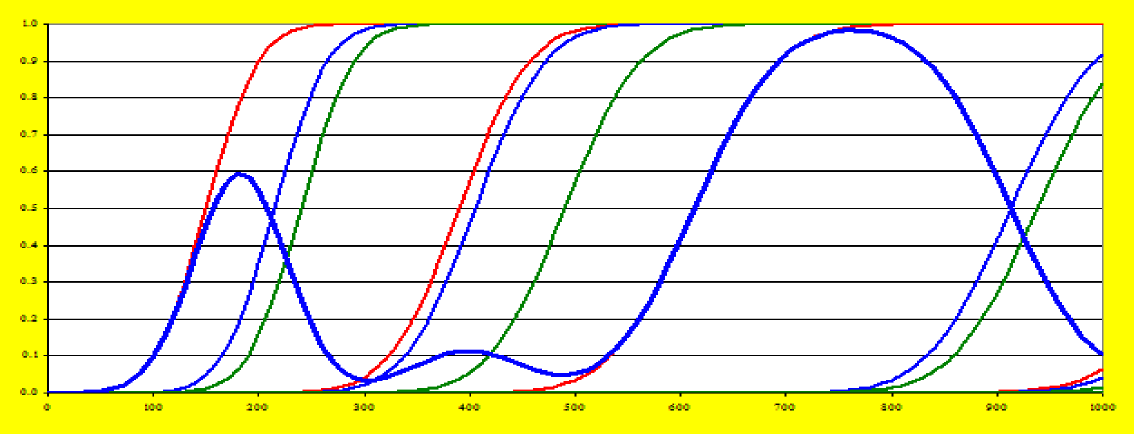


Figure 2: Supportability Function for a hypothetical Maintainability System

10. Time in Support

Answers to supportability questions raised earlier are uniquely deterring by the length of the time that engineering systems spend in the NFS during their life. Hence, to compare all possible support policies and strategies it is essential to quantify their impact on the time that system will be spending in the NFS should each of them is adopted.

Making use of the Mirce Supportability Equation presented above, it is possible to calculate the expected time that system will spend in NFS during a stated interval of time, TIS(t)], for each possible support policies. The numerical value of the time required is equal to the area under supportability function within a given interval of time, thus:

$$TIS(t) = \int_0^t n_s(t)dt \qquad \textbf{7.}$$

The cumulative time spend in B_mFS for a hypothetical engineering system through a hypothetical maintenance process is shown in the Figure 3.

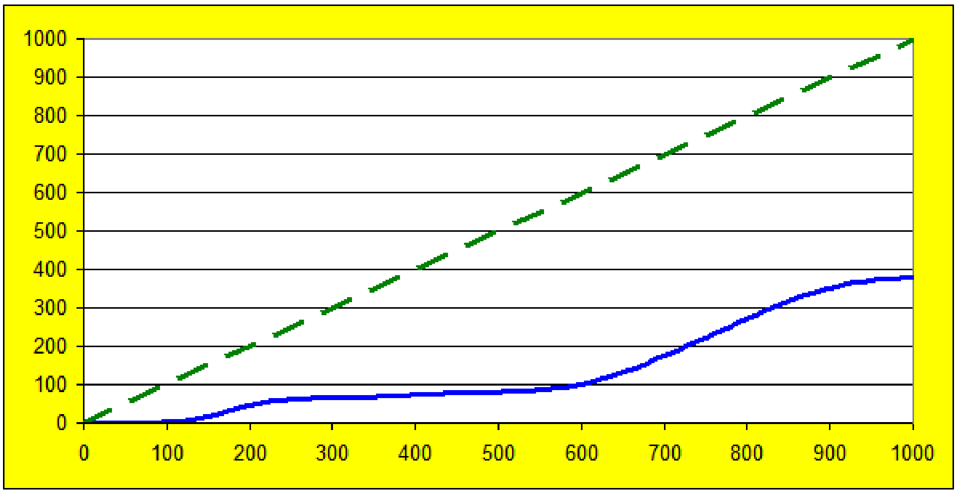


Figure 3: Time in Maintenance of a Hypothetical Engineering System

Several other measures of the motion of a engineering system through support process, which are essential for the system engineering and management decision making process could be derived and calculated from the mathematical scheme presented.

Analytical solutions for the Mirce Functionability Equation are seldom possible due to inability of mathematics to deal with the large number of functions and their interactions. These types of problems are not specifically related to the Mirce-mechanics; they are common to all scientific disciplines of this nature, as it is a known mathematical fact that the integral equations do not have analytical solutions. [6]

However, it is necessary to develop computational methods to deal with the mathematical difficulties, as it is unacceptable to simplify observed reality of system in-service behaviour in order to cope with mathematical limitations. Dubi [9] successfully applied the Monte Carlo simulation method to this type of computational problems.

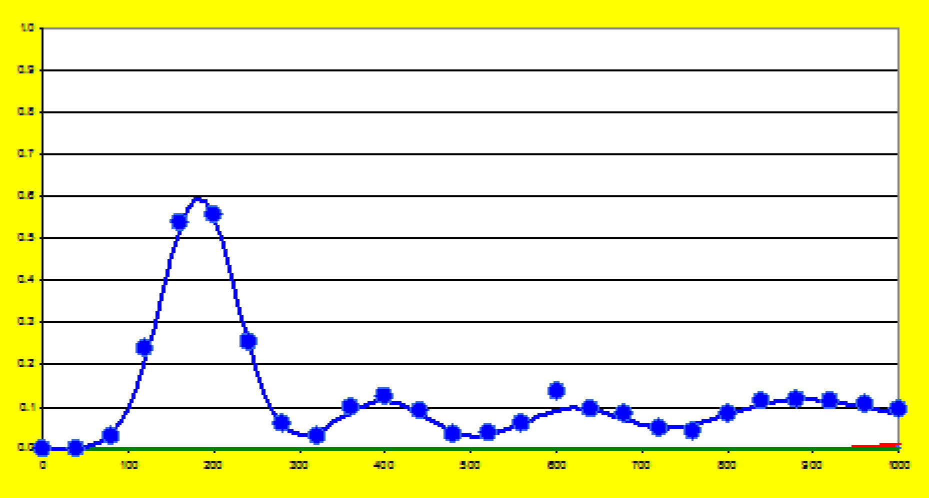


Figure 4: Supportability Trajectory Calculated Analytically (solid line) and by Monte Carlo Simulation (dots) for a hypothetical Engineering System

11. The Impact of Mirce Supportability Equation on System Engineering and Management Process

Although science has to be truthful, rather then useful, Mirce Supportability Equation presented in this paper provides a tool for supportability and logistics engineers, managers, technicians and analysts in industry, government and academia to predict the motion of the future systems through supportability states for each of feasible options, for a given configurations, in-service rules and conditions, in order to manage functionability events in the way that the functionability performance is delivered through the life of system, at least investment in resources and environmental impact. The capabilities of accurate predictions have been anticipated and hoped for during last 50 years among many professionals who were seeking a seat at the system engineering table, led by defence and aerospace industries.

12. Conclusion

In classical mechanics continuous uniform motion is a natural behaviour of the macro world that is fully defined and predictable by Newton's equations. However, in Mirce-mechanics continuous and non-uniform change in the functionability states is a natural behaviour of engineering systems during their in-service life, which is fully defined and predictable by mathematical principle of Mirce-mechanics [4].

The main objective of this paper, which was to delineate the boundaries between systems stays in support part and in maintenance part of the NFS and develop a mathematical equation for predicting the motion of engineering systems through support process. The task has been successfully completed by developing the expression for the Mirce Supportability Function. It enables accurate predictions to be made, regarding the stay of a system in a support part of NFS, for each maintenance policy and logistics support strategy identified. Part of the mathematical scheme of Mirce-mechanics presented, in this paper, is the scientific foundation of the Supportability Engineering and Management predictions and analysis regarding the motion of functionability through the life of engineering system, as an integrated part of the system engineering process, which did not exist thus far.

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Mirce Maintainability Equation

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

Abstract

Scientific principles and concepts expressed through the laws, equations and formulas are the bedrock for the prediction of the design-in functionality performance of any engineering creation. However, there is no equivalent when the in-service maintainability performance predictions have to be made. Hence, Mirce-mechanics has been created at the MIRCE Akademy to fulfil the roll. The main purpose of this paper is to present the development of the Mirce Maintainability Equation that is the bedrock for all the predictions related to the maintenance process and related maintenance policies for a given maintainable systems.

1. Introduction

During the history of civilisation needs for transporting, communicating, navigating and many others have been satisfied by transpiration, communication, navigation and other human created systems, commonly known as engineering systems. As they are functioning in accordance to the laws of science, which are independent of time, place and human impact, their design-in performance, like speed, acceleration, power, fuel consumption and many others, are accurately predictable. [1]

However, experience teaches us that in-service performance of these systems is dominated by phenomena like fatigue, operator induced errors, corrosion, creep, foreign object damage, a faulty weld, bird strike, perished rubber, carburettor icing, to name just a few. These phenomena generate energy exchanges between systems and environment, leading to the loss of the design-in function or performance. Hence, maintaining the design-in performance beyond the delivery day requires actions like troubleshooting, repairs, replacements, modifications, diagnostics, “cannibalisations” and similar to be performed. Thus, all human created collections of entities that are able to deliver at least one measurable function whose functionability is maintained by humans’ actions are known as engineering systems [2].

Generally speaking, from functionability point of view, at any instant of time a engineering system can be in one of the following two states [3]:

5. Positive Functionability State, PFS, during which is able to deliver functionality.
6. Negative Functionability State, NFS, during which is not able to deliver functionality.

The motion of the system through functionability states is governed by the occurrence of functionability events, which are classified as:

- Positive Functionability Events, PFE, which cause the transition from NFS to PFS
- Negative Functionability Events, NFE, which cause the transition from PFS to NFS

Consequently, the life of a engineering system could be considered as motion of system through functionability states. The pattern generated by the motion of functionability through functionability states, in respect to the passage of time, forms the functionability trajectory, which is defined by Mirce Functionability Equation [4].

$$y(t) = 1 - \varphi(t) + \mu(t)$$

where $\varphi(t)$ and $\mu(\mathrm{t})$ are expected number of negative and positive functionability events, respectively, that will take place from the birth of a system and a given instant of time t.

However, in this scheme all activities that take place during the stay of a system in the NFS are considered together. Mathematically it does make sense, but a physical analysis of maintenance and support activities clearly shows that they are very distinguishable processes. Hence, the main objective of this paper is to delineate their boundaries and develop a mathematical equation for predicting the motion of maintainable systems through bad functionability state due to execution of scheduled and unscheduled maintenance actions.

2. The Maintenance Process

The process, during which the ability of the system to perform a function is maintained, is known as *maintenance process*, and it is defined as [3]: *The set of maintenance tasks performed by the user in order to maintain the functionability of the system during its utilisation.*

When analysing the objectives of the maintenance tasks performed during a maintenance process, it is possible to classify as following:

- *Reduction of the rate of change in condition* which results in the extension of the length of the operational life of a system. Typical examples are: washing, cleaning, painting, filtering, adjustment, lubrication, calibration, and similar.

- *Assurance of the required reliability and safety* which reduces the probability of occurrence of failure. The most common activities of this kind are: inspection, detection, examination and testing.

- *Provision of the optimal rate of consumption* of the items, like fuel, lubricant, tyres, and so forth, which contributes to the cost effectiveness of the operation process.

- *Restoration of the functionability* of the system, after the transition to the *SoFa* has occurred. The most frequently performed activities in order to restore functionability are: replacement, repair, refurbishment, renewal, and so on.

It is necessary to stress that some resources are needed to facilitate these processes. Most frequently used resources are spares, material, trained personnel, tools, equipment, manuals, facilities, software, etc. As thee main task of these resources is to facilitate the maintenance process, they will be called *maintenance resources*, [6].

3. Concept of Maintenance Task

According to Ben-Daya at el 2009, “A Maintenance task is a set of activities that need to be performed in a specified manner, usually by humans, for functionality of the item/system to be maintained.”

In accordance to the Maintenance Program Development Document MSG-3, revision 2, published in 1993 [2], maintenance tasks could be categorised in the following categories:

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

It is necessary to stress that some resources are needed to facilitate the successful completion of the maintenance task. As the main function of these resources is to facilitate the maintenance process they will be called maintenance resources. The resources needed for the successful completion of every maintenance task, could be grouped into following categories:

- Maintenance Personnel, MP: a generic name for trained and qualified humans required for the installation, checkout, handling, and sustaining maintenance of the item/system and its associated test and support equipment are included in this category.
- Maintenance Material, MM: a generic name which includes all spares, repair items, consumables, lubricants, special supplies, and related inventories needed for the execution of a maintenance task;
- Maintenance Test and Support Equipment, MTE: a generic name for all tools, special condition monitoring equipment, diagnostic and check-out equipment, metrology and calibration equipment, maintenance stands and servicing and handling equipment required for the execution of a maintenance task

- Maintenance Facilities, MF: a generic name for all facilities needed for completion of maintenance tasks, such as buildings, portable repair shops, inspection pits, dry dock, housing, maintenance shops, calibration laboratories, and special repair and overhaul facilities

- Maintenance Data, MD: a generic name for all necessary technical information required for check-out procedures, maintenance inspection and calibration procedures, overhaul procedures, modification instructions, facilities information, drawings and specifications that are necessary in the performance of system maintenance functions.

At the same time it is important to stress that each task is performed in a specific working environment that could make a significant impact on the quality of the execution of each task. The main environmental factors could be grouped as follows:

- Space impediment (which reflects the obstructions imposed on maintenance personnel during the task execution which requires them to operate in restricted positions)
- Climatic conditions (rain/snow, solar radiation, humidity, temperature, and similar situations, which could make a significant impact on the task completion.
- Platform on which maintenance task is performed (board of the ship/submarine, space vehicle, off-shore platform and similar).

4. Measures of Maintenance Task

Like all other physical phenomena that have to be measured in order to be understood, a maintenance task has to be measured. For that purpose, Knezevic 1997 created the concept of the Duration of a Maintenance Task, DMT, and associated measures of a maintenance task, thus:

- Maintainability Function, denoted as M(t), represents the probability that the maintenance task considered will be successfully completed before or at the specified moment of elapsed time t, thus:

$$M(t) = P(DMT \leq t) \qquad 1.$$

- Percentual Duration of Maintenance Task, DMT_p, represents the duration of a maintenance task by which a given percentage of maintenance tasks considered would be successfully completed. It is the abscissa of the point whose coordinate presents a given percentage of task completion. Mathematically, DMT_p can be represented as:

$$DMT_p = t, \text{ for which, } M(t) = P(DMT \leq t) = p \qquad 2.$$

The most frequently used is DMT_p measure is DMT_{90} time which presents the duration of the restoration time by which 90 percent of maintenance trials will be completed, thus:

$$DMT_{90} = t, \text{ for which, } M(t) = P(DMT \leq t) = 0.9$$

- Expected Duration of a Maintenance Task, denoted as MDMT, represents the expectation of the random variable DMT, which can be used for calculating this characteristic of a maintenance process, thus:

$$E(DMT) = MDMT = \int_0^\infty [1 - M(t)]dt \qquad 3.$$

It is necessary to stress that above presented measures of maintenance tasks that are related to the maintenance tasks that are completed without faults or errors during their executions.

5. Measures of Maintenance Process

In literature, maintainability is defined as ability of a system to be maintained, which refers to ease, accuracy, safety and economy of the performance of maintenance actions. However, maintainability measures used in literature are related to specific maintenance task related to the individual items, Mean Corrective maintenance time, Mean Preventive maintenance time, Maximum Active corrective maintenance time and similar [5].

In order to address the motion of functionability through the life of maintainable systems it is necessary to embrace all maintenance tasks together, as irrespective which one tasks is question, the system is in NFS. Thus, in Mirce-mechanics the maintainability of maintainable systems is measured through the time that system spends in B_mFS due to execution of maintenance tasks during a given interval of in-service time.

6. Concept of Mirce-mechanics

The development of science started when people began to study phenomena not merely observing them. People developed instruments and learned to trust their readings, rather than to rely on their own perceptions. They recorded the results of their measurements in the form of numbers. Supplied with these numbers they began to seek relationships between them and to write down in the form of formulas. Then the formulas became the only things they came to trust when they began to predict things they could not physically experience.

Consequently, to address functionability questions the author established the MIRCE Akademy in 1999. Staff, Fellows, Members and students of the Akademy study in-service behaviour of engineering systems to:

- Physically observe the emerging trajectory of the motion of functionability through the life of engineering systems and to measure emerging in-service performance.
- Scientifically understand mechanisms that cause the motion of functionability through the life of engineering systems, within the physical scale from 10^{-10} to 10^{10} metre.
- Mathematically define the scheme for the prediction of in-service performance of a given design-in system, for a given in-service conditions and rules.

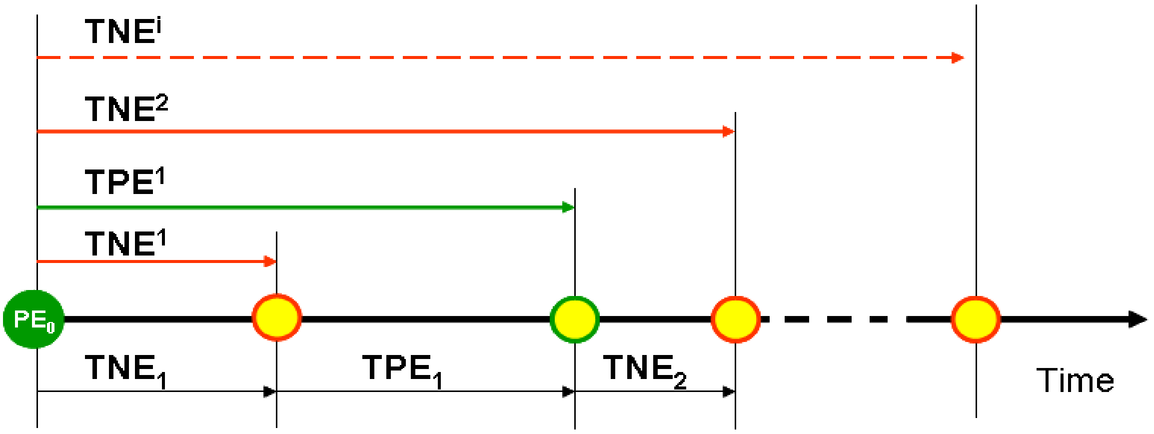
A science based body of knowledge, formulated through axioms, formulas, methods, rules and algorithms for predicting the in-service performance of future systems, resulting from their motion through the functionability states in respect to time constitutes Mirce-mechanics.

The ability to simultaneously predict the design-in functionality performance and in-service functionability performance of future systems is of fundamental importance for the engineers, managers, investors, regulators and other specialists who are responsible for the satisfaction of the “human felt needs”, in a reliable, economical and safe manner, for the future transportation, communication, defence, energy, entertainment and many other functions delivered by engineering systems.

7. Probabilistic Motion

The unusual features of the laws of probability have a natural explanation. In fact, most probabilistic events are results of quite complex physical processes, which in many cases cannot be studied or understood in all of its intricacy. Such inability takes its toll, as it is only possible to predict with certainty the average result of numerous identical tests. Thus, for each functionability event it is only possible to indicate its likely outcome.

Probabilistic predictions of the functionability trajectory are based on the framework of the sequence of occurrences of Positive and Negative Functionability Events, whose individual and cumulative times are measured as shown in the Figure below.



Based on the Figure 2, the following functions are fully defined:

- Negative Function, $F_i(t)$, which defines the probability that the ith NFE will take place before or at instant of time t is defined in the following way:

$$N_i(t) = P(TNE_i \le t), \qquad i = 1, \infty . \qquad 2.$$

- Positive Support Function, $O_{si,i}(t)$, which defines the probability that the ith $PFE_{s,}$, will take place before or at instant of time t is defined in the following way:

$$O_{s,i}(t) = P(TPE_{s,i} \le t), \qquad i = 1, \infty . \qquad 3.$$

- Positive Maintenance Function, $O_i(t)$, which define the probability that the ith $PFE_{m,i}$ will take place before or at instant of time t is defined by the following expression:

$$O_{m,i}(t) = P(TPE_{m,i} \le t), \qquad i = 1, \infty . \qquad 3.$$

- Probability distribution that defines this event is uniquely determined by the physical properties of the process that generate positive functionability event (replacement, repair, calibration, modification and similar) [9].

- Sequential Negative Function, F^{i} *(t),* which defines the probability that the ith sequential NFE will take place before or at instant of time t, is defined as:

$$F^{i}(t) = P(TNE^{\mathrm{i}} \le t), \qquad i = 1, \infty . \qquad 4.$$

- Sequential Support Function, $O_s^i(t)$, which defines the probability that the ith sequential PFE will take place before or at instant of time t: is presented in the following manner:

$$O_s^i(t) = P(TPE_s^i \le t), \qquad i = 1, \infty . \qquad 5.$$

Having determined the probability distribution and its governing parameters of the times to subsequent functionability event's positive and negative, it is possible to develop a mathematical scheme that will provide opportunity to predict the future sequence of functionability event's in general, and supportability relevant events in particular, for any given engineering system.

This is the essence of the Mirce-mechanics, which is the only theory available to design engineers to quantitatively predict the consequences of all of their decisions on in-service behaviour of their future systems.

8. Mirce Maintainability Equation

The trajectory of functionability is uniquely defined by the sequence of functionability events, from the birth of the system to its decommissioning, as defined by equation 1. Thus, the mathematical scheme that uniquely defines the trajectory of maintainable systems through the maintenance sector of NFS, denoted as $n_m(t)$, is defined as:

$$n_m(t) = P(N_m FS @ t) = \sum_{i=1}^{\infty}\left[P(N_m FS^i @ t)\right] = \sum_{i=1}^{\infty}\left[P\left(TPE_s^i \le t\right) - P\left(TPE_m^i \le t\right)\right]$$

Making use of equations 3 and 4, the above expression of functionability equation could be presented in its final form:

$$n_s(t) = \mu_s(t) - \mu_m(t) \qquad 6.$$

where:

$\mu_s(t) = \sum_{i=1}^{\infty} O_s^i(t)$ is the expected number of support related functionability events that will take place from the birth of a system and a given instant of time t.

$\mu_m(t) = \sum_{i=1}^{\infty} O_m^i(t)$ is the expected number of maintenance related functionability events that will take place from the birth of a system and a given instant of time t.

The author developed this expression and named it Mirce Maintainability Equation. It defines the trajectory of the motion of a maintainable system through a given maintenance process. For each given instant of time t, the maintainability equation quantifies which quantifies the amount of certainty of a given maintainable system being B$_m$FS.

The trajectory of the motion of a hypothetical maintainable system through a hypothetical maintenance process is shown in the Figure 2.

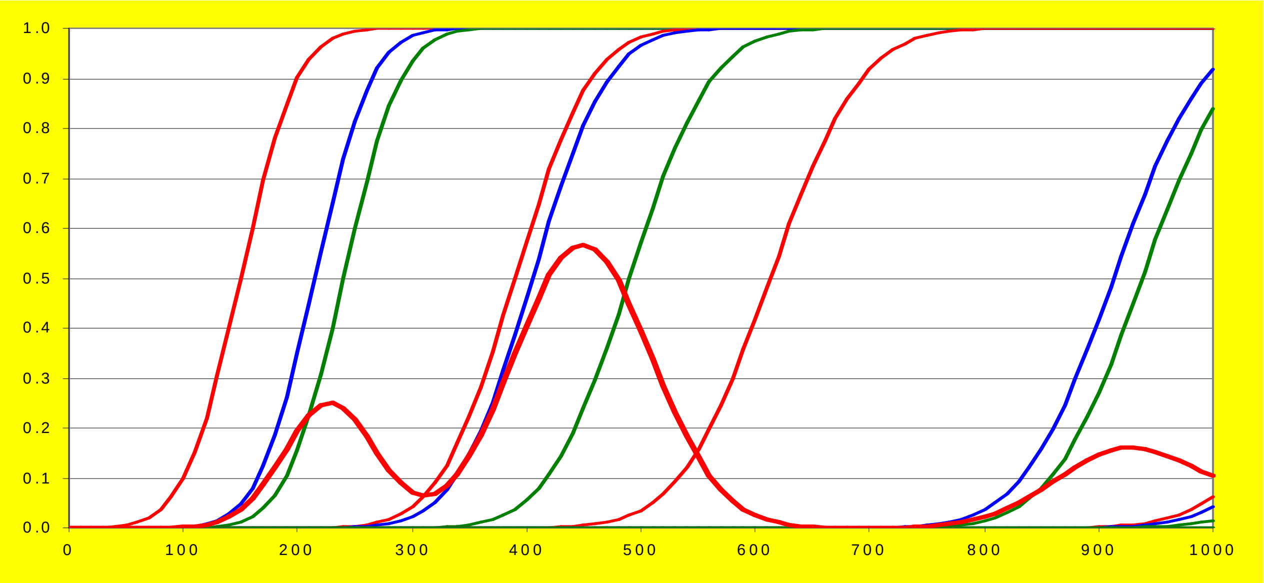


Figure 2: Maintainability Function for a hypothetical Maintainability System

9. Time in Maintenance

Answers to maintainability questions raised earlier are uniquely deterring by the length of the time that maintainable systems spend in the NFS during their life. Hence, to compare all possible support policies and strategies it is essential to quantify their impact on the time that system will be spending in the NFS should each of them is adopted.

Making use of the Mirce Maintainability Equation presented above, it is possible to calculate the expected time that system will spend in B_mFS during a stated interval of time, TIM(t)], for each possible maintenance policy and strategy. The numerical value of the time required is equal to the area under maintainability function within a given interval of time, thus:

$$TIM(t) = \int_0^t n_m(t)dt \qquad \textbf{7.}$$

The cumulative time spend in B_mFS for a hypothetical maintainable system through a hypothetical maintenance process is shown in the Figure 3.

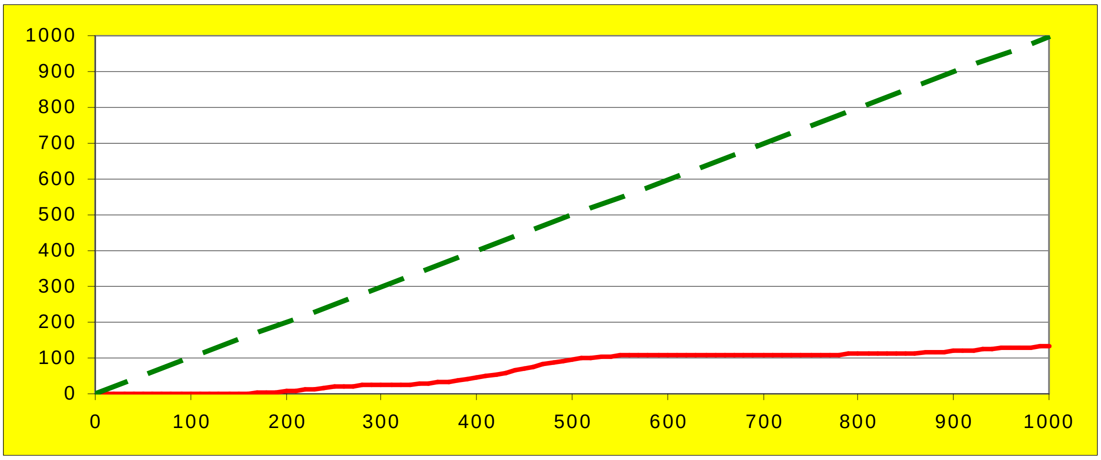


Figure 3: Time in Maintenance of a Hypothetical Maintainable System

Several other measures of the motion of a maintainable system through maintenance process, which are essential for the system engineering and management decision making process could be derived and calculated from the mathematical scheme presented.

Analytical solutions for the Mirce Maintainability Equation are seldom possible due to inability of mathematics to deal with the large number of convolution functions and their interactions. These types of problems are not specifically related to the Mirce-mechanics; they are common to all scientific disciplines of this nature, as it is a known mathematical fact that the integral equations do not have analytical solutions. [7]

However, it is necessary to develop computational methods to deal with the mathematical difficulties, as it is unacceptable to simplify observed reality of system in-service behaviour in order to cope with mathematical limitations. Dubi [7] successfully applied the Monte Carlo simulation method to this type of computational problems.

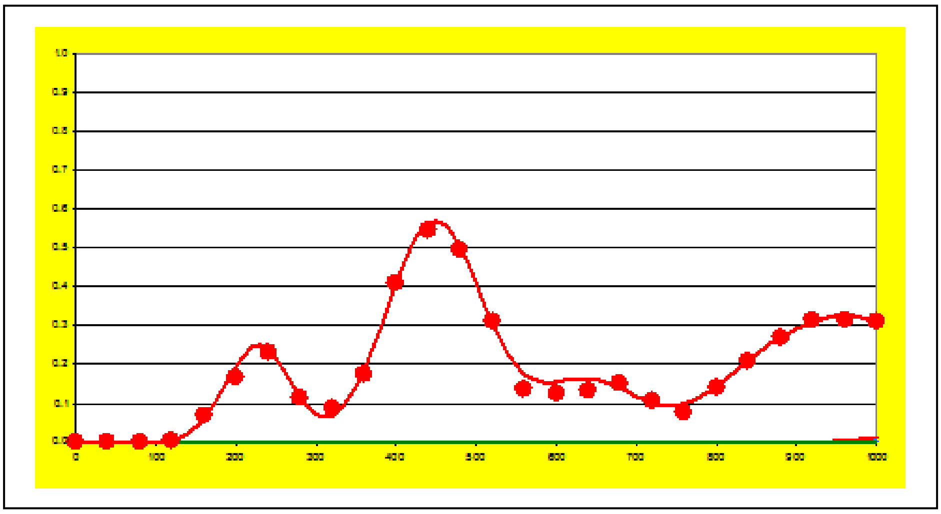


Figure 4: Maintainability Trajectory Calculated Analytically (solid line) and by Monte Carlo Simulation (dots) for a hypothetical Maintainable System

10. The Impact of Mirce Maintainability Equation on System Engineering and Management Process

Although science has to be truthful, rather then useful, Mirce Maintainability Equation presented in this paper provides a tool for maintainability engineers, managers, technicians and analysts in industry, government and academia to predict the motion of the future systems through maintainability states for each of feasible options, for a given configurations, in-service rules and conditions, in order to manage functionability events in the way that the functionability performance is delivered through the life of system, at least investment in resources and environmental impact. The capabilities of accurate predictions have been anticipated and hoped for during last 50 years among many professionals who were seeking a seat at the system engineering table, led by defence and aerospace industries.

11. Conclusion

In classical mechanics continuous uniform motion is a natural behaviour of the macro world that is fully defined and predictable by Newton’s equations. However, in Mirce-mechanics continuous and non-uniform change in the functionability states is a natural behaviour of maintainable systems during their in-service life, which is fully defined and predictable by mathematical principle of Mirce-mechanics [4].

The main objective of this paper, which was to delineate the boundaries between systems stays in support part and in maintenance part of the NFS and develop a mathematical equation for predicting the motion of maintainable systems through maintenance process. The task has been successfully completed by developing the expression for the Mirce Maintainability Function. It enables accurate predictions to be made, regarding the stay of a system in a maintenance part of NFS, for each maintenance policy and logistics support strategy identified. Part of the mathematical scheme of Mirce-mechanics presented, in this paper, is the scientific foundation of the Maintainability Engineering and Management predictions and analysis regarding the motion of functionability through the life of maintainable system, as an integrated part of the system engineering process, which did not exist thus far.

12. Acknowledgement

The results of decades of research in maintenance process of maintainable systems are dedicated to the memories of the great Chief Mechanic of Boeing New Airplanes, , Jack Hessburg (1934-2013). His genius continuously inspired me to dig deeper and deeper in the fascinating world of aircraft maintenance whose only task is to enable airplanes to “go on time and never crash”.

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Mirce-mechanics Analysis of Forward Visibility Loss of ATR 72 Caused by the Sea Salt Accretion on Front Windscreen

Dr J. Knezevic
The MIRCE Akademy, Exeter, UK

Abstract

Mirce-mechanics is a scientific theory of the motion of a system through functionability space in time, which enables evaluation of Mirce Equations. Hence, the main objective of this paper is to present the Mirce-mechanics based analysis of the scheduled passenger flight, that carried out a go-around from its first approach to Cork Airport (EICK) in stormy weather, due to a significant increase in indicated airspeed on short final. The aircraft then positioned under radar control for a second approach to the same runway, which brought it south of Cork airport, close to the coast and at times over the sea. During this time a negative functionability event took place, which was manifested as a thick layer of sea salt formed on the front windscreens, totally obscuring the Flight Crew's forward visibility. As it was not possible to acquire the necessary visual references for landing, another go-around was necessary. To try to return the aircraft into positive functionability state, the Flight Crew flew the aircraft to areas of shower activity and a small portion of the Commander's windscreen was cleared and enabled a successful landing in the third attempt.

1. Introduction

Aerospace Engineering is one of the major branches of engineering that is concerned with the application of the science and technology to research, design, development, construction, testing, of aircraft and spacecraft. Aerodynamics, which is the bed rock of aerospace engineering, is concerned with studies of the motion of air, particularly when it interacts with a solid object, such as an airplane wing. Formal aerodynamics study in the modern sense began in the eighteenth century, although observations of fundamental concepts such as aerodynamic drag have been recorded much earlier. Most of the early efforts in aerodynamics worked towards achieving heavier-than-air flight, which was first demonstrated by Wilbur and Orville Wright in 1903. Since then, the use of aerodynamics through mathematical analysis, empirical approximations, wind tunnel experimentation, and computer simulations has formed the scientific basis for ongoing developments in heavier-than-air flight and a number of other technologies.

While, aerodynamics is the scientific foundation of the functionality performance of aircraft, Mirce-mechanics: is a scientific theory of the behavior of systems in service that enables predictions of the functionability[4] performance. Its axioms, mathematical formulas, rules and methods enable predictions of a system's measurable functionability performance data, like reliability, punctuality and others to be made with probabilistic regularity. [1]

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

From the Mirce-mechanics point of view, at any instant of time a system can be in one of the following two functionability states [2]:

- Positive Functionability State (PFS) is the state in which a system is being able to deliver functionality (function, performance and attributes)
- Negative Functionability State (NFS) is the state in which a system in not being able to deliver functionality.

Consequently, the life of a maintainable system could be considered as motion of system through functionability states, which is governed by the occurrence of functionability events, which are classified as:

- Positive Functionability Events (PFE) which cause the change of transition from NFS to PFS
- Negative Functionability Events (NFE) which cause the transition from PFS to NFS

The main objective of Mirce-mechanics is the scientific understanding of the physical mechanisms that generate positive and negative functionability events, resulting from atomic, environmental or human actions. Hence, this paper addresses the mechanisms that caused the occurrence of NFE that manifested loss of forward Visibility of ATR 72, during the flight from Manchester (UK) to Cork (Ireland) on 2nd January 2014 together with mechanism that caused the occurrence negative and positive functionability events.

2. Mirce-mechanics Data Information

The flight considered in the paper was operated by and originated from Manchester airport in UK, on scheduled passenger service to Cork in Ireland (EICK), with 46 passengers and 4 crew members on board, on 2 January 2014

2.1 The aircraft

The aircraft that was serving this flight was Irish registered ATR 72-212A. It is a twin-engine turboprop short-haul regional airliner built by the French-Italian aircraft manufacturer ATR. It accommodates 50 passengers in a single-class configuration, and is operated by a two-pilot crew.

It is power by two turboprops engines of the type PW127F, manufactured by Pratt & Whitney Canada. It is relatively unusual three-shaft engine configuration where a centrifugal LP impeller, driven by a single stage LP turbine, supercharges a centrifugal HP impeller, driven by a single stage HP turbine. Power is delivered to the offset propeller reduction gearbox via a third shaft, connected to a 2-stage free (power) turbine. The engine first entered service in 1984.

The aircraft considered entered into service in 2007 with a serial number of 748.

According to the ATR 72 Flight Crew Operating Manual the rain removal from the front windscreens is provided by two wipers, each of which is driven by a two-speed electric motor. The maximum speed for operation of the wipers is 160 kts. There is no windscreen washer facility installed.

The front windscreens are each protected against ice formation by an electrically heated transparent film, incorporated between two plies of glass. The temperature is controlled by an electronic controller which keeps the outer windscreen temperature above 2°C. The inner surface remains above 21°C to prevent mist formation. Each front windscreen has an individual on/off push button for heating control.

2.2 The Flight Crew

The commander of this flight was 40 year old female with 5,036 flying hours, of which 4,750 were on this type of aircraft, with an ATPL5 pilot licence issued by the Irish Aviation Authority (IAA). [3]

The first officer was a male with less flying hours than the commander.

2.3 The Weather Conditions

Met Éireann, meaning "Meteorology of Ireland", is the national meteorological service in Ireland, which is a part of the Department of the Environment, Community and Local Government, provided the meteorological situation at the time. It was a deep depression of 947 hPa10 tracked close to Ireland’s west coast. An occluded front had cleared the area and was followed by a very strong, unstable, showery flow with embedded trough lines.

Surface winds at EICK were 220°, 25-30 kts with gusts of 45-50 kts. The winds at 2,000 ft were 230°, 60 kts. Visibility was 15 to 20 km. The surface temperature was 8°C and the dew point was 3°C. The mean sea level pressure was 977 hPa.

Significant Meteorological Information, SIGMET, is a weather advisory that contains meteorological information concerning the safety of all aircraft has been issued a number of Local Warnings for the relevant timeframe.

The Local Warning for EICK for the time period between 21.00 hrs on 2 January and 11.00 hrs on 3 January forecast southerly winds of maximum values between 40 and 45 kts becoming south south-westerly 25-30 kts, maximum 45-50 kts between 23.00 hrs and 01.00 hrs. There was also a wind-shear warning issued for EICK.

3. The First Functionability Event

The aircraft made an initial approach to the runway, RWY 25, at EICK at 22.29 hrs. The Flight Crew expected, from their weather briefing, a strong south-westerly winds. Based on the information provided by the Tower that the wind was from 230°, 29 knots (kts) gusting to 44 kts., the commander decided to go-around, solely to an increase in indicated airspeed on final approach. The Air Traffic Control, ATC, accepted the decision and at 22.34 hrs, issued instruction to the commander to maintain the runway heading and to climb to 3,000 feet. The Flight Crew responded by the confirmation that they intend to make a second approach to RWY 25. This was acknowledged by ATC, and instruction was issued to turn left onto a heading of 180°, which brought the aircraft onto an easterly track to the south of EICK, close to the coast and at times over the sea. [3]

4. The Second Functionability Event

At 22.43:14 hrs, ATC provided EI-REL with its final vector; turning left onto a heading of 280° to intercept the radial and cleared it for the second approach to RWY 25. A wind check passed by ATC at this time was 220°, with a mean speed of 28 kts and a maximum reaching up to 41 kts.

At 22.44:16 hrs, the crew confirmed that they were established on the inbound course to land. However, a few moments later, as the Flight Crew was ready to make the final approach, the Commander experienced *"problem with the windscreens."* [3] The Commander explained that it was impossible to see anything through the windscreens and that something had totally blurred her vision through the windscreens during the preparation for the second approach. She suspected that the aircraft may have flown through some substance since the first approach and she enquired from ATC whether they were aware of any major fires in the area *"because it seems to be like smoke on the front of the windscreen that's sealed and dried in. The wipers aren't taking it off." The* reply from ATV was negative. [3] Three minutes later, EI-REL advised ATC that they will aboard this landing attempt.

The next communication between the Flight Crew and the ATC was at 22.52 hrs, when the Tower was informed by EI-REL that they were going around. ATC instructed them to climb to 3,000 ft and requested information regarding Flight Crew intentions. EI-REL was then transferred back to the Cork Approach frequency.

ATC instructed EI-REL to climb to 4,000 ft and vectored them initially towards the north-west because an Airbus A321 was inbound from the east for an approach to RWY 17.

To deal with this negative functionability event that cause the delay in landing due to loss of visibility of the front windscreen the Flight Crew made contact by mobile phone with their engineering staff on the ground at the Cork Airport.

5. The Third Functionability Event

At 23.09 hrs, the Flight Crew asked about the wind and runway condition at Shannon (EINN), which was their alternative airport, as commander described the problem with following words *"I can't see out the windscreen." [3]*

At 23.15 hrs, the commander reported that looking at her weather radar it looked like that there was a weather cell ten miles straight ahead, She requested the permission to maintain the current heading (330°) in anticipation that *"possibly the rain in that cell might help clear the windscreen*."[3]. She continued that their intention is to fly to the edge of the cell and hope that the rain would wash the contamination off, as at that time they could see nothing.

In response the ATC informed EI-REL of a similar situation in Shannon a couple of weeks earlier in high winds which turned out to be a film of sea salt on the windscreen. The Commander informed ATC that they learned, the from the phone conversation with the engineering staff on the ground, that the same thing had happened to a company's other aircraft that evening but that obviously it wasn't as bad for them

Between 23.16 hrs and 23.26 hrs, ATC assisted EI-REL with all requested heading changes in the area of the shower activity while the aircraft maintained 4,000 ft. During this time, a *"3 inches wide and 1 inch high"*, [3] area at the base of the commander's windscreen cleared, through which was possible to see the runway. However, the First Officer had no visual reference to the runway. ATC also informed EI-REL that the crew of the A321 which had just landed believed that a film on the outside of their windscreen was sea salt.

At 23.27 hrs, ATC informed EI-REL that they could be seen from the Tower and that all of the runway lights will be put on to full brightness to help them to identify the airport. EI-REL reported that they could see the runways and requested a descent for an approach onto RWY 25. ATC provided vectors for a procedural VOR approach to RWY 25.

Finally, at 23.30 hrs, the Commander requested for the fire services to be put on standby. ATC responded that all emergency services are in the position. Following the approach briefing, the Flight Crew commenced an approach at 23.42 hrs. As they approached the runway, the aircraft entered a rain shower which further cleared the windscreen. The aircraft landed safely on RWY 25 at 23.54 hrs, some 90 minutes behind schedule.

6. Post Flight Serious Incident Investigation

In accordance with Annex 13 to the Convention on International Civil Aviation, Regulation (EU) No 996/2010 and the provisions of S.I. No. 460 of 2009, the Chief Inspector of Air Accidents on 3 January 2014 appointed Mr Thomas Moloney as the Investigator-in-Charge to carry out an Investigation into this Serious Incident and prepare a Report for ATR 72-212A, EI-REL [3]. The analysis presented below is mainly based on this Accident Report.

6.1 Functionability Analysis of the ATR-72 EI-REL

Irish Air Accident Investigation Unit for the Serious Incident learned from the Commander that while they were making the second approach “a considerable build-up of white contamination forming on the windscreen.” Initially, the Flight Crew had no idea what was causing the build-up but later they learned that it was a sea salt residue caused by the stormy weather. Both crew members confirmed that the salt contamination had created a thick opaque layer and that it was impossible to make out the runway as the residue had the effect of diffusing the lights into a complete blur. The Commander stated that:

- “It looked like a frosted glass windscreen.”
- “The windscreen wipers had no effect in clearing the residue since it was so dry, as the front windscreens were heated to prevent ice accretion, which further exacerbated the problem in that, as the salt built up, it dried and became more opaque”.

The Commander described how the weather radar was showing evidence of showers and cells on the periphery of the Cork control zone. Hence, the request for the clearance from ATC to fly towards them in an effort to clear the windscreen was made. It was confirmed that by flying towards the edge of the cells, a fraction of the contamination on the base of the windscreen became clear. However, the First Officer soon noticed that the salt residue was reforming on his side. The Commander stated that as there was not much moisture in the weather cells and as the salt residue was thick and dried out, they were unable to completely clear the windscreen but the visual reference to runway became possible on her side through a small gap at the base of the windscreen. Since at that point EI-REL had 1 hour 20 minutes fuel endurance remaining, the decision was made to attempt the third approach to RWY 25 at EICK while still having sufficient fuel to, if necessary, divert and try to land at EINN without reaching the final reserve fuel figure. The Commander was also conscious that the conditions at EINN were approaching maximum crosswinds across a wet runway and she was reluctant to attempt a landing in such conditions with an obscured windscreen.

In response to specific questions, the Commander told the Investigation that the aircraft was not in cloud but was flying through apparently clear air when the salt accretion began to become visible. There was no evidence of icing on the windscreen just before the salt deposits appeared. It is possible that the heated windscreen exacerbated the problem by drying the salt and enabling a thick layer to form. Also it was confirmed that even when the aircraft climbed to a higher altitude in the effort to fly into cloud cells to clear the windscreen, salt accretion continued. The Flight Crew attempted to clear the windscreen by using the wipers when they initially saw the contamination start to build up. At that point they were unaware of what it might be and thought that it could be moisture or condensation. They also used the wipers during the time that they flew towards the rain showers, but with only very limited success.

6.2 Functionability Analysis of the ATR-72 EI-REI

Another of the Operator's ATR 72 aircraft, EI-REI, was also affected by sea salt contamination in a similar timeframe to EI-REL. However, the effects were less severe and the aircraft landed on RWY 25 at 22.45 hrs from its first approach. This aircraft had been approaching EICK from a northerly direction and it did not fly over the sea at low level.

The Commander of the EI-REI stated that neither he nor the First Officer noticed any salt accretion on the windscreen until about two minutes before establishing on the VOR approach (VHF Omni Directional Radio Range) in VMC9 (Visual Meteorological Conditions). Before that, they had been vectored onto a right base for RWY 25. They had been in visual contact with the lights of Cork city and EICK from 15 to 20 miles away and they did not encounter any icing conditions.

However, the commander recalled that the aircraft had probably been heading south at a speed of 180 kts when they first noticed the salt accretion, which seemed to be a fast and invisible process. Although the aircraft was VMC, due to the level of turbulence and the type of approach (VOR) being carried out, the Flight Crew's focus was on their instruments rather than on the outside.. He felt that the salt accretion occurred during a few minutes, turning the windscreen condition from clear to a blur. The Flight Crew tried to clear the windscreen using both wipers, but to *"absolutely no effect"*. [3]

6.3. Functionability Analysis of the Airbus A321 Flight Crew

The investigation found that there was the third aircraft which reported windscreen contamination on the same evening. This was an Airbus A321 which landed on RWY 17 at 23.13 hrs. The Flight Crew of the A321 was aware of EI-REL's situation and, after parking, commented to ATC that they had a powdery dusty substance on their windscreens and that *"you could write your name on it"*. [3]

The Flight Crew stated that the substance did not affect their visibility during the final approach, but that it became noticeable in the terminal lighting when they parked the aircraft. Later, they informed the Tower that they thought the substance was sea salt. This aircraft had not flown over the sea at altitudes below approximately 8,000 ft during its approach.

6.4 Another Instance of Visibility Loss through Windscreen

Another case of sea salt accretion on an ATR 72 was experienced during stormy weather in January 2015. In this case, the aircraft was unable to land at Dublin from two approaches due to out-of-limits crosswinds. The Commander reported that on his second approach, there was a light layer of salt on both front windscreens following a downwind flown at 3,000 ft.

The resulting functionability action was that the flight was diverted to Belfast International Airport (EGAA). The Commander reported that "*with one mile to go to on finals, he was unable to see the runway because of the salt deposits*". [3] The problem was solved by raising his seat and moving his head to make out the runway through a small area near the top of the windscreen.

This event occurred during daylight, in severe turbulence and winds gusting above 50 kts.

6.5 Civil Aviation Authority Instigations

The Investigation made enquiries through the Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile (BEA), the civil aviation safety investigation authority of France, as to whether any instances of sea salt accretion on aircraft windscreens were known to them.

The BEA confirmed that no such occurrences were noted in their files and that furthermore, no similar events were contained in the databases of the aircraft manufacturers, Airbus and ATR.

7. Consequential Safety Actions

Following discussions with the Air Accident Investigation Unit regarding the functionability event analysed in this paper, the Operator issued a Flight Crew Instruction (FCI) on Sea Salt Aerosol Accretion. This FCI contains general information on the generation of sea salt contamination, similar to the information contained in the Report [3].

Also, Flight Crews are reminded that, in the event of experiencing contamination leading to degradation of visibility through the windscreen of an aircraft, it may be necessary to fly through precipitation prior to conducting a landing.

The Investigation [3] considers that, given the rarity of this type of event, no specific Safety Recommendations are warranted other than a general rising of awareness through the publication of this Report.

8. Analysis of Dangerous In-service Conditions Due to High Concentration of Sea Salt

The existing research literature [4-13] identified several major contributing factors which can potentially generate a dangerous operating environment due to the presence of a high concentration of sea salt aerosol in the atmosphere. Generally speaking, the following factors contribute to such an environment:

- A large difference between the sea surface temperature and the air temperature, particularly with warm water and cold air. Along with this, large horizontal temperature gradients within the ocean appear to contribute significantly.

- High surface wind speeds, approximately in excess of 30 m/s. Also, together with wind speed, large distance of fetch and long duration of continued high wind speeds are important. Although it is difficult to specify exact values, 500 nm and 48 hours would seem to reasonable figures.
- Relative humidity at or above 80%.
- Lack of precipitation, particularly in ambient air temperatures near 0°C.
- Height of the Marine boundary layer. However, the high salt environment will not extend above a well-defined boundary layer.

In is necessary to stress that:

- if several of these conditions prevail in a given environment, the likelihood of high sea salt aerosol concentration existence also increases.
- the combination of several of these parameters can create a synergy allowing the production of excessive salt aerosols at the surface and their subsequent transport to altitudes which would not normally be reached.
- precipitation will very effectively remove salt particles from the atmosphere, even in the presence of large vertical mixing velocities. Dangerous concentrations of sea salt aerosol are not anticipated above 5,000 ft, due to dilution and settling.

9. Conclusion

Since aircrafts perform the main function within stratosphere (lower 20 km of the Earth’s atmosphere) which shares enormous are with the oceans and seas it is inevitable that this complex interaction will generate negative functionability events that could have a significant impact on the safety of flights. Hence, it is necessary to establish a scientifically based relationship between these interactive elements of natural environment in respect to the behaviour of systems in service and their consequential functionability performance.

The paper presented used principles of Mirce-mechanics for the analysis of the system in service functionability phenomena, which in this paper was the loss of visibility in the front windscreen. This negative functionability event has been generated by the complex interactions between: sea salt, dry and heated windscreen during the final approach to landing, and the wind speed of 25-30 kts with gusts of 45-50 kts. However, the occurrence of this event has generated a need for the further research towards understanding the physical mechanism of sea salt accretion on front windscreen of aircrafts, as well as the necessity of addressing this functionability phenomenon during the aircraft design in general and considering installation of some sort of windscreen washing capabilities.

Finally, the occurrence of the positive functionability event, which in this case was the flight through the rain cell which cleaned the part of the windscreen and enabled safe landing was addressed. \it is necessary to stress that the occurrence of this event resulted from the “lateral” thinking of the commander of the EI-REL. This clearly illustrates the necessity of addressing in service behaviour of systems during the design stages of their development, uniquely promoted by Mirce-mechanics.

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Aircraft Ground Icing and De-icing Processes as Mechanisms of the Motion in Mirce-mechanics

Dr Jezdimir Knezevic
The MIRCE Akademy, Exeter, UK

Abstract

Mirce-mechanics is a scientific theory of the motion of in-service systems through Mirce Spacetime that enables prediction of the work done by them to be made by using Mirce Equations. Practical applications of Mirce-mechanics are possible only, when the physical mechanisms that generate the motion of systems through positive and negative states of Mirce Spacetime are understood. The mechanism of ice building on an aircraft on the ground is addressed in this paper, as a cause of occurrence of a negative in-service event. It is generated under certain environmental conditions when precipitation falling onto the aircraft freezes, mainly on upper surfaces of the wing and tail, endangering the flight safety. This type of negative events is followed by de-icing the aircraft at the airport, as a physical mechanism that causes the transition of an aircraft from the negative to the positive in-service state. Several de-icing methods are presented in this paper and their impact on aircraft and environment analysed from Mirce-mechanics point of view.

1. Introduction

Aerospace Engineering is one of the major branches of engineering that is concerned with the application of the science and technology to research, design, development, construction, testing, of aircraft and spacecraft. Aerodynamics, which is the bed rock of aerospace engineering, is concerned with studies of the motion of air, particularly when it interacts with a solid object, such as an airplane wing. Formal aerodynamics study in the modern sense began in the eighteenth century, although observations of fundamental concepts such as aerodynamic drag have been recorded much earlier. Most of the early efforts in aerodynamics worked towards achieving heavier-than-air flight, which was first demonstrated by Wilbur and Orville Wright in 1903. Since then, the use of aerodynamics through mathematical analysis, empirical approximations, wind tunnel experimentation, and computer simulations has formed the scientific basis for ongoing developments in heavier-than-air flight and a number of other technologies.

While, aerodynamics is the scientific foundation of the functionality performance of aircraft, Mirce-mechanics is a scientific theory for the motion of in-service systems through Mirce Spacetime. Its axioms, mathematical formulas, rules and methods enable predictions of the work done by the system on one hand and the work done on the system, to keep it going, on the other.

From the Mirce-mechanics point of view, at any instant of time a system can be in one of the following two states of the functionability space [2]:

- Positive State (PS) is the state in which a system is being able to deliver functionality (function, performance and attributes)

- Negative State (NS) is the state in which a system in not being able to deliver functionality.

Consequently, the in-service life of a maintainable system could be considered as motion of system through functionability states, which is governed by the occurrence of functionability events, which are classified as:

- Positive Events (PE) which cause the change of transition from NS to PS
- Negative Events (NE) which cause the transition from PS to NS

Humans' ability to travel by air in winter is heavily dependent on de-icing process , which started in 1920s when airplanes used to be de-iced with a rope, tied knots in it, dragged it over the wings to regain their flight worthiness. Today, it is routine process repeated hundreds of times a day during the winter months. For example, the United Airlines despatch team at the Chicago O'Hare airport in 2011 de-iced 12,000 airplanes and about 14,000 in the 2012. Hence, the total number of aircraft de-iced by all operators on all the world airports is measured in millions.

The deadly crash of Air Florida Flight 90 in Washington D.C. in January of 1982 was a harsh reminder of the importance of proper de-icing. Seventy-eight people died when the Boeing 737 lost altitude, struck a crowded bridge, and plunged into the icy Potomac River. The plane had been de-iced, but with the wrong chemical mix, together with delays brought on by heavy snow allowed new ice to coat the wings.

Consequently, the main objective of Mirce-mechanics is the scientific understanding of the physical mechanisms that generate positive and negative events, resulting from atomic processes, environmental impacts or human actions. In this paper a physical process of ice formation of aircraft surfaces and its removal will be addressed. Ice builds up on aircraft in two ways: in flight or on the ground. On the ground, precipitation falls onto the airplane and freezes on upper surfaces. On planes, ground icing forms on the upper surfaces of the wings and tail. The ground forming ice is managed by de-icing the plane with a fluid, typically propylene glycol, at the airport, imminently to the take off. Hence, this paper addresses the de-icing process as one of the physical mechanisms that caused the transition from the NS (inability of a system to perform the function due to undesirable formation of ice) to the PS of the Mirce Spacetime.

2. Aircraft Icing on the Ground as a Negative Mechanisms

Aircraft on the ground is exposed to the ground conditions, everywhere in the world. However, in some of these environmental conditions frozen contaminants could cause critical control surfaces to be rough and uneven, disrupting smooth air flow and greatly degrading the ability of the wing to generate lift, and increasing drag. This situation can cause a crash. Large pieces of ice separate from the moving aircraft can cause catastrophic failure by being ingested in engines or damaging propellers. Also, frozen contaminants can jam control surfaces, preventing them from moving properly. Consequently, due to potential severe hazards, de-icing of control surfaces on aircrafts affected is performed at airports where temperatures are likely to be around 0°C.

2.1 The Ice Formation

Fine particles of frost or ice, the size of a grain of table salt and distributed as sparsely as one per square centimetre over and airplane wing's upper surface, can destroy enough lift to prevent a plane from taking off.

Almost virtually imperceptible amounts of ice on an aircraft wing's upper surface during takeoff can result in significant performance degradation. Small, almost visually imperceptible amounts of ice distributed on an airplane's wing upper surface cause the same aerodynamic penalties as much larger (and more visible) ice accumulations.

2.2 Effects of Icing on Aircraft

The aerodynamic effectiveness of an airframe requires that it begins flight with critical surfaces free from contamination by frozen or semi-frozen moisture ('contaminant'), commonly known as the 'clean aircraft' concept.

Failure to remove contaminants from an aircraft and/or to protect it from acquiring further contamination before it becomes airborne may result in sudden loss of control at or shortly after take off. In the case of aircraft with rear mounted engines, any ice on the inner wings of an aircraft at take off may be shed and ingested into the engines causing a partial or total loss of thrust. Also, small patches of ice or frost can result in localized, asymmetrical stalls on the wing, which can result in roll control problems during lift off.

Intake duct deposits and engine blade deposits may detach and be ingested by the engine(s) during the subsequent application of high power settings for takeoff, with consequential adverse effects on engine operation, and possible flameout.

2.3 Airliner Crashed Due to Failure to De-Ice Plane

The crash of a Russian-operated regional airliner, in April 2013, that killed 31 people was caused by failure to de-ice the aircraft before flight, was the verdict of crash investigators. (Source: ttp://sputniknews.com/russia/20130716/182264029.html#ixzz3bXHP6haC). The French-built ATR72 turboprop operated by the UTair airline crashed just after take-off from the Siberian city of Tyumen's Roshchino Airport with 43 people on board. The immediate cause of the crash was "the flight captain's decision to fly without conducting a de-icing procedure," the Interstate Aviation Committee (MAK) said in its final report, adding ice was detected by the crew on the aircraft's surfaces as late as when it was taxiing for departure. Conditions at Roshchino in the hours before the crash were cold, with temperatures of around 0 Celsius (32 Fahrenheit), with freezing rain and snow.

According to the report, a mechanic went into the cockpit just before flight and told the pilots: "the plane is clean." The aircraft commander replied "OK, we won't wash it with de-icer fluid then, we'll take off as it is." After takeoff, the ATR72 climbed to an altitude of some 210 meters, but then banked 35 degrees to the right and then over to the left, reaching over 50 degrees of bank by the time it hit the ground. The report attributed the steep banking to "ice and snow deposits" on the aircraft's lifting surfaces, which affected the plane's aerodynamics.

It is necessary to stress that this example is just one of many that take place all over the world, year after year, in accordance to the well established weather pattern.

2.3 The Ice Detection

In many situations it is almost impossible to determine by observation whether a wing is wet or has a thin film of ice. A very thin film of ice or frost will degrade the aerodynamic performance of any airplane. Ice accumulation on the wing upper surface may be very difficult to detect from the cockpit, cabin, or front and back of the wing because it is clear/white.

Accident history shows that non-slatted, turbojet, transport-category airplanes have been involved in a disproportionate number of takeoff accidents where undetected upper wing ice contamination has been cited as the probable cause or sole contributing factor.

Majority of pilots understand that visible ice contamination on a wing can cause severe aerodynamic and control penalties, but it is apparent that many pilots do not recognize that minute amounts of ice adhering to a wing can result in similar penalties. (http://www.ntsb.gov/safety/safety-alerts/Documents/SA_006.pdf)

Despite evidence to the contrary, these beliefs may still exist because many pilots have seen their aircraft operate with large amounts of ice adhering to the leading edges and consider a thin layer of ice or frost on the wing upper surface to be more benign.

3 Aircraft Ground De-Icing Process as a Positive Mechanisms

De-icing is defined as removal of snow, ice or frost from aircraft surfaces, while anti-icing is considered to be the application of chemicals that not only de-ice, but also remain on a surface and continue to delay the reformation of ice for a certain period of time, or prevent adhesion of ice to make mechanical removal easier.

At many airports, de-icing is done away from the gate at an area called the deice pad, due to some of the following reasons:.

- Airlines don't want their planes sitting at the gate any longer than they have to. If another plane is waiting to come into that gate, de-icing a departing plane will only slow down that process.

- De-icing fluids deplete the oxygen from water, and airports don't want the fluids going into the storm water drains. So at the deice pad, the fluids drain into a special tank or reservoir.

- De-icing fluid is very slippery, so it poses a safety hazard for people walking or working in the area.

- Airport gates are often congested by other ground vehicles, so it's easier for the deice trucks to move around freely out at the deice pad.

Once a plane is pushed back from the gate, the pilots taxi the plane to the deice pad. A dedicated radio frequency is used so that the pilots can tell the deice crew exactly what they want done to the plane. Some airlines use their own employees to deice planes, and some hire contractors

Deice fluids are applied methodically, from the wing's leading edge to the trailing edge, beginning at the wingtip and working back toward the wing root (where the wing is joined to the fuselage). The same is done to the horizontal stabilizers. For the tail, they go from front to back, starting at the top of the tail and work their way down to the base. Anywhere from one to four deice trucks can be used to deice a plane.

As a part of de-icing process it is required for a pilot to temporarily disable the aircraft's ventilation system to prevent fluid fumes from entering the cabin. Although the fumes are considered nontoxic for inhalation, it is necessary to keep the odour out of the cabin regardless.

4. De-icing Methods

De-icing can be accomplished by mechanical methods (scraping, pushing); through the application of heat; by use of dry or liquid chemicals designed to lower the freezing point of water (various salts or brines, alcohols, glycols); or by a combination of these different techniques.

Anti-icing of aircraft is accomplished by applying a protective layer, using a viscous fluid called anti-ice fluid, over a surface to absorb the contaminate. All anti-ice fluids offer only limited protection, dependent upon frozen contaminant type and prevailing weather conditions. A fluid has failed when it no longer can absorb the contaminant and it essentially becomes a contaminant itself. Even water can be a contaminant in this sense, as it dilutes the anti-icing agent until it is no longer effective.

4.1 Mechanical and Non-chemical De-icing Method

Mechanical and other nonchemical methods used to deice aircraft include brooms, ropes, hot water, infrared heating, and forced air. Brooms and ropes are not the primary method of aircraft de-icing, especially wet-weather de-icing, because they are so time- and labour-intensive, but rather used in combination with chemical de-icing. Forced air/hot air systems are used to blow or melt snow and ice from aircraft surfaces. Infrared heating de-icing systems consist of an open hangar-type structure with infrared generators suspended from the ceiling. The infrared wavelengths are targeted to heat ice and snow, and minimize heating of aircraft components. This system reduces the volume of ADF fluid required, but cannot provide anti-icing protection. Aircraft may also be stored in a hangar to prevent snow or ice from accumulating if a storm event is predicted.

5. Chemical Method

All chemical de-icers share a common working mechanism: they chemically prevent water molecules from binding above a certain temperature that depends on the concentration. This temperature is below 0°C, the freezing point of pure water. Sometimes, there is an exothermic dissolution reaction that allows for an even stronger melting power. The following list contains the most-commonly used de-icing chemicals and their typical chemical formula.

Inorganic salts

- Sodium chloride, $NaCl$, (commonly known as table salt)
- Magnesium chloride, $MgCl_2$, reduces working temperature of salt

- Calcium chloride, $CaCl_2$, reduces working temperature of salt
- Potassium chloride, KCl

Organic compounds

- Calcium magnesium acetate, $CaMg_2(CH_3COO)_6$
- Potassium acetate, CH_3COOK
- Potassium formate, CHO_2K
- Sodium formate (HCOONa)
- Calcium formate, $Ca(HCOO_2$
- Urea, $CO(NH_2)_2$, a common fertilizer
- Agricultural By-Products (generally used as additives to sodium chloride)

Alcohols, diols and polyols (these are antifreeze agents and scarcely used on roads)

- Methanol (CH_4O)
- Ethylene glycol ($C_2H_6O_2$)
- Propylene glycol ($C_3H_8O_2$)
- Glycerol ($C_3H_8O_3$)

6. Types of De-icing Fluids

The Society of Automotive Engineers publishes standards (SAE AMS 1428 and AMS 1424) for four different types of aviation deicing fluids:

1. Type I fluids have a low viscosity, and are considered "unthickened". They provide only short term protection because they quickly flow off surfaces after use. They are typically sprayed on hot (130–180°F, 55-80°C) at high pressure to remove snow, ice, and frost. Usually they are dyed orange to aid in identification and application.
2. Type II fluids are pseudoplastic, which means they contain a polymeric thickening agent to prevent their immediate flow off aircraft surfaces. Typically the fluid film will remain in place until the aircraft attains almost 200 km/h, at which point the viscosity breaks down due to shear stress. The high speeds required for viscosity breakdown means that this type of fluid is useful only for larger aircraft. Type II fluids are generally light yellow in color.
3. Type III fluids can be thought of as a compromise between type I and type II fluids. They are intended for use on slower aircraft, with a rotation speed of less than 100 knots. Type III fluids are generally light yellow in color.
4. Type IV fluids meet the same AMS standards as type II fluids, but they provide a longer holdover time. They are typically dyed green to aid in the application of a consistent layer of fluid.

The International Organization for Standardization publishes equivalent standards (ISO 11074 and ISO 11078), defining the same four types.

Deicing fluids containing thickeners (types II, III, and IV) are also known as anti-icing fluids, because they are used primarily to prevent icing from re-occurring after an initial de-icing with a type I fluid.

7. De-icing Usage Statistics

The amount of fluid necessary to de-ice an aircraft depends on a wide variety of factors. Deicing a large commercial aircraft typically consumes between 2000 and 4000 litres of diluted fluid.

The total annual usage of deicing fluids in the U.S. is estimated to be approximately 25 million litres. According to [4], 77.1% is Type I (Propylene Glycol), 11.4% Type IV Propylene Glycol, 10.3% Type I Ethylene Glycol and 1.2% Type IV Ethylene Glycol.

The cost of fluid varies widely due to market conditions. The amount deicing service companies charge end users is generally in the range of US$8 to US$12 per diluted gallon which works out as US$2,1 to US$3,2 per litre, FY 2012

8. Measurement of Performance of De-icing Fluids

De-icing fluid performance is measured by holdover time, HOT, which is the length of time an aircraft can wait after being treated prior to takeoff. Holdover time is influenced by the ambient temperature, wind, precipitation, humidity, aircraft skin temperature, and other factors. For Type I fluids, the holdover time is only about five to 15 minutes, so the aircraft must take off immediately or else wait to be deiced again. Type IV fluids generally provide a holdover time between 30 and 80 minutes.

Deicing fluids work best when they are diluted with water. For example, undiluted deicing fluid (type I ethylene glycol), has a freezing point of −28 °C. Water, of course, freezes at 0 °C. However, a mixture of 70% deicing fluid and 30% water freezes below −55 °C. This phenomenon is known as the eutectic concentration, and it is related to the freezing point of the mixture, which is at the lower point than either of the component substances.

Depending on the manufacturer, deicing fluids may be sold in concentrated or pre-diluted formulations. Dilution, where necessary, must be done according to ambient weather condition and the manufacturer's instructions in order to minimize costs while maintaining safety.

The dilution of a particular sample of fluid (and hence its freezing point) can be easily confirmed by measuring its refractive index with a refractometer, and looking up the result in the de-icing fluid manufacturer's tables.
Manufacturers of aviation deicing fluids must certify that their products conform to the AMS 1424 and 1428 standards by using a standard Aerodynamic Acceptance Test.

9. Environmental impact of De-icing Materials

De-icing salts such as sodium chloride or calcium chloride leach into the soils, where the ions (especially the cations) may accumulate and eventually become toxic to the organisms and plants growing in these soils. The chemicals could also reach water bodies in concentrations that are toxic to the ecosystems. Organic compounds are biodegraded and may cause oxygen-depletion issues. Small creeks and ponds with long turnover time are especially vulnerable.

Propylene glycol used to de-ice aircraft can contaminate drinking water supplies and harm aquatic life. Some airports are now capturing and treating de-icing runoff before allowing it to enter waterways.

10. Infrared Heating De-icing method

Infrared heating is the transmission of energy by means of electromagnetic waves or rays. Infrared energy is invisible and travels at the speed of light in straight lines from the heat source (the emitter) to all surfaces and objects (the receivers) without significantly heating the space (air) through which it passes. This heating process is much faster than conventional heating mechanisms used by conventional de-icing (convection and conduction), where the de-icing fluid spray is cooled by ambient air.

Infrared, IR, heating systems have been used at a few U.S. airports for several years and have been demonstrated to effectively de-ice aircraft. Currently, in USA, infrared de-icing systems are used at two large hub airports, John F. Kennedy and Newark Liberty, and one non-hub airport, Rhinelander-Oneida County, Wisconsin.

Infrared-based aircraft de-icing systems offer two advantages over traditional glycol-based de-icing methods. From an environmental standpoint, they can greatly reduce the amount of glycol-based fluids used for aircraft de-icing, while from an operational standpoint, they are relatively inexpensive to operate, as they use natural gas or propane as fuel.

Any infrared de-icing facility design must take into account the physical characteristics of all aircraft that will use the system. Design factors include the maximum tail height, the shape of tails, maximum wingspans, and differences in the length and width of the fuselage. The site selected for an infrared de-icing system must comply with the same FAA regulations that apply to glycol-based aircraft de-icing facilities, including aircraft separation rules, air traffic control tower line-of-sight criteria, and requirements to not interfere with radar signals, navigational aides, and airport lighting. FAA issued a new Advisory Circular in 2005 specifically for infrared de-icing facilities. As with traditional aircraft de-icing facilities, an infrared de-icing facility must provide taxiways that allow aircraft to bypass the de-icing facility.

According to documents provided by Radiant using data from the JFK facility for the 2010-2011 winter season, average snow/ice removal time for a Boeing 737-size aircraft was approximately 17 minutes from the time the aircraft rolls into the hangar until it exits. Boeing 747-300-size aircraft averaged 19 minutes. This means that three to four 737s or two 747s can be de-iced per hour, versus approximately 45 to 90 minutes per aircraft with conventional glycol de-icing. [10]

11. Conclusion

The main objective of this paper was to address the ice formation of aircraft surfaces and its removal through de-icing process as a mechanism of the motion in Mirce-mechanics. Ice-building on aircraft can take place in two ways: in flight or on the ground. This paper focuses on the formation of ice on the ground, resulting from the falling precipitations that freeze on the upper surfaces of the wings and tail in certain environmental conditions. The operators manage this process by de-icing the plane with a fluid, typically propylene glycol, at the airport, imminently to the take off.

Consequently, this paper addressed the de-icing, methods, fluids, procedures, statistics and associated environmental impacts with objectives to understand them in order to manage them, starting from the design processes of the aircraft itself, through the design of de-icing facilities with detail analysis of the chemical composition of the de-icing fluid and their usage.

Aircraft de-icing process is on vital important for the safe and reliable operation of thousands of daily flights that affected by this natural phenomena which comes with seasonal periodicity and as such has monetary impact of doing it and possible catastrophic consequences of not doing it. It is believed that this paper will make a positive contribution to the further understanding of this natural phenomenon on one hand, and its effective management, from the point of view of despatch reliability and resources invested to achieve it, on the other.

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Mirce-mechanics Analysis of Functionability of NASA-contracted Commercial Re-supply Services

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

The main purpose of this paper is to apply Mirce-mechanics to the analysis of functionability of Space Exploration Technologies Corporation and Orbital Sciences Corporation, organizations that have been selected by NASA to participate in the Commercial Orbital Transportation Services, COTS. The reason for this is the fact that at the moment of writing this paper, both CRS Programmes are out of action due to catastrophic launch failures that took place on 28th June 2015 and 28th of October 2014, respectively. It is expected that analysis performed on the past missions, conducted by both corporations, based on the publicly available information, will get incites into their practices and experiences gained, as well as highlighting the areas of potential applications of the Mirce-mechanics based knowledge to increase in the probability of the successful continuations of NASA-contracted Commercial Resupply Services.

1. Introduction

According to Einstein **“***Everything that the human race has done and thought is concerned with the satisfaction of felt needs*”.

Human needs for transporting, cooling, heating, communicating, navigating, sheltering and many others are continuously satisfied through the work done by transportation, ventilation, communication, refrigeration and other industrial systems. Their design-in performance in terms of speed, capacity, frequency, power and similar physically measurable quantities can be accurately predicted during the design process and tested at the delivery, as they are functioning in accordance to well understood laws of natural sciences, such as: Newton’s laws of motion, Coulomb’s law of solid friction, Hook’s law of stress and strain, Maxwell’s law of electrodynamics, Boltzmann’s law of thermodynamics, to name a few, which are characterised by certainty, reversibility and independence of time, location and humans.

However, the main concerns of the owners and users of industrial systems are related to how much of their “felt needs” will be satisfied during the life time of a system and how much maintenance and support efforts are expected from them to keep the system going[5]. This, property of industrial systems is known as functionability**[6].** Regrettably, system producers/constructors do not provide answers to these questions on the delivery day. Instead, years later the statistics for various functionability measures become available. The reason for this is the fact that in-service behaviour of industrial systems is governed by the complex processes that are governed by the laws of science, human rules and environmental impacts, which are characterised by indeterminism, irreversibility, inseparability, and dependence on time, location and humans.

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

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

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

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

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

In summary, the body of knowledge comprising of axioms, mathematical equations and computational methods that enable prediction of functionability measures, based on the on the scientific understanding of the processes that generate them, constitutes Mirce-mechanics.

The main purpose of this paper is to apply Mirce-mechanics to the analysis of functionability of Space Exploration Technologies Corporation and Orbital Sciences Corporation, organizations that have been selected by NASA to participate in the Commercial Orbital Transportation Services, COTS. The reason for this is the fact that at the moment of writing this paper, both CRS Programmes are out of action due to catastrophic launch failures that took place on 28th June 2015 and 28th of October 2014, respectively. It is expected that analysis performed on the past missions, conducted by both corporations, based on the publicly available information, will get incites into their practices and experiences gained, as well as highlighting the areas of potential applications of the Mirce-mechanics based knowledge to increase in the probability[7] of the successful continuations of NASA-contracted Commercial Re-supply Services.

2. NASA-contracted Re-supply Services

In 1958 the United States government created the National Aeronautics and Space Administration (NASA) with a specific responsibility to develop the civilian space program as well as aeronautics and aerospace research. Since that time, NASA has lead large number of space exploration efforts, including the Apollo moon-landing missions, the Skylab space station, and later the Space Shuttle. In early 1990s NASA was directed to pursue commercial options for launching spaceflight missions, whenever such commercial offerings are available.

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[7] Mirce-mechanics Axiom 2: Probability of in-service failure in any interval of time is greater than zero.

The development of the Commercial Resupply Services, CRS, vehicles began in 2006 with the purpose of creating American commercially operated uncrewed cargo vehicles to service the International Space Station, ISS.[i] The development of these vehicles was under a fixed price milestone-based program, meaning that each company that received a funded award had a list of milestones with a dollar value attached to them that they didn't receive until after they had successful completed the milestone.

On 23rd December, 2008 NASA awarded Commercial Re-supply Services contracts to:

- Space Exploration Technologies Corporation, which is an American aerospace manufacturer and space transport services provider, with headquarters in Hawthorne, California, USA, which uses its Falcon 9 rocket and Dragon spacecraft. This, $1.6 billion contract was for 12 cargo transport missions to ISS with spacecraft SpaceX.

- Orbital Sciences Corporation, which is also American company, specialising in the design, manufacture and launch of small- and medium- class space and rocket systems for commercial, military and other government customers, based in Dulles, Virginia, USA, which uses its Antares rocket and Cygnus spacecraft.. This contract was worth $1.9 billion for 8 missions to ISS using Cygnus cargo spacecraft, covering deliveries to 2016.

As NASA has contracted all the missions, the primary payload, date and time of launch, and orbital parameters for each mission are determined by NASA.

3. Mirce-mechanics Analysis of Functionability of Orbital Sciences

Orbital Science Corporation plan for the commenced regular ISS cargo missions to ISS under the Commercial Resupply Services contract was to deliver approximately 20,000 kg, or 20 metric tons, of cargo to the space station over the course of eight missions by using the Antares launch vehicle and Cygnus spacecraft. Antares is a two-stage launch vehicle designed to deliver medium-class payloads weighing up to 6120 kg into space. Antares utilises refurbished Russian-built engines which were originally manufactured in the 1960s and 1970s for the Soviet space programme. Cygnus spacecraft is capable of delivering 2000 kg of pressurised cargo to the ISS. It was planned that an enhanced version to be flown in later CRS missions will be able to deliver 2700 kg of pressurised cargo. The first of the eight contracted Cygnus missions to the ISS was expected to be completed during 2013.

According to the planned sequence of in-service events, 10 minutes from the liftoff of the Antares the Cygnus space craft would separate, deploy its solar arrays and enter in its initial orbit. When it arrives to the orbiting laboratory four days later, after a series of checks, ground controllers command began to increase the altitude of Cygnus, until it matched that of the space station. At that point NASA was to make go/no-go decision for Cygnus to berth with the station. Cygnus would autonomously approach within 12 metres below the space station, where it would stay. Astronauts aboard the station would then command Cygnus to a "free drift" mode, when the space stations robotic arm would take hold of the spacecraft. At that moment the Ground commands would send command, from mission control in Houston, for the station's arm to rotate Cygnus around and install it on the bottom side of the station's Harmony module, enabling it to be bolted in place for its stay at the ISS.

In the preparation for an on-pad hot-fire test of the rocket scheduled for the early November 2012, Orbital Sciences rolled out its Antares rocket to the launch pad at the Mid-Atlantic Regional Spaceport in October 2012. The rocket successfully made its initial launch with a test payload on 21st April, 2013, from Wallops Flight Facility in Virginia. Orbital Sciences' first COTS demonstration mission was successfully carried out on the 29th September, 2013, a week behind schedule due to a software malfunction.

3.1 Orb-1

This was the first of eight contracted flights by Orbital Sciences under NASA's Commercial Re-supply Services program. The launch of Orb-1 was scheduled for November 2013, but a series of delays pushed the date to 20th December UTC.

The Antares launch vehicle left the Wallops Horizontal Integration Facility, HIF, on the morning of 17th December, and was later erected at Launch Pad 0A. However, later that day, due to the need for a series of spacewalks to fix a faulty coolant system on the ISS, NASA directed Orbital to stand down the Antares rocket. It was rolled back to the HIF where the time-sensitive cargo was removed. The launch date was rescheduled for no earlier than 13th January 2014.

However, after a scheduling conflict was resolved, at Wallops, the launched was moved forward to 7th of January. The launch was delayed one extra day due to cold temperatures at the launch site. Then on the 8th of January, NASA Wallops and Orbital Sciences announced that the launch attempt was scrubbed due to "an unusually high level of space radiation that exceeded by a considerable margin the constraints imposed on the mission to ensure the rocket's electronic systems are not impacted by a harsh radiation environment. Later, Orbital revised this, stating that a more extensive review of the radiation environment found it to be "within acceptable limits" of the Antares program, and that a launch would be attempted on 9th January.

In the fourth attempt, on the 9th of January the Orb-1 mission successfully started at 18:07:05 UTC from the Mid-Atlantic Regional Spaceport Launch Pad 0A. Cygnus was filled with 1261 kg of supplies for the ISS, crew provisions and spare parts, together with hardware to expand the research capability of the station. This included 12 experiments flying as part of the Student Spaceflight Experiments Program, selected from 1466 entrants and involving 7200 North American students. The Cygnus spacecraft arrived at the International Space Station early on 12th January, where it was successfully docked with the assistance of Canadarm2, as originally planned.

On 18th February 2014 at 10:25 UTC, Canadarm2 unberthed the Cygnus spacecraft from the nadir port of the Harmony module on. The spacecraft was then maneuvered to a position below the station, where it was released from the RMS at 11:41 UTC. It followed by a series of separation maneuvers that moved it away from the ISS. The spacecraft re-entered the atmosphere and burned up on 19th February 2014 over the southern Pacific Ocean, disposing of approximately 1470 kg of trash.

3.2 Orb-2

This was the second of eight scheduled flights by Orbital Sciences under the Commercial Resupply Services contract with NASA. It was the third flight of the Orbital Sciences' unmanned re-supply spacecraft Cygnus and the fourth launch of the company's Antares launch vehicle.

The mission was scheduled for the 1st May 2014. The Cygnus is expected to deliver 1650 kg of cargo to ISS and dispose of about 1470 kg of trash through destructive re-entry. However, the original launch date was delayed to no sooner than 6th May, which followed by the following sequence of estimated times, 17th June, 10th July and again to NET on 11th July, due to test stand failure of an AJ-26 engine. On the 12th the local weather conditions prevented the launch.

Finally, the second mission of the Orbital Science Corporation was launched from the Mid-Atlantic Regional Spaceport on 13th July, 2014.

During the Flight Days, 36 through 41 Cygnus was detached from the station and maneuvered a safe distance away. Engineering tests were performed for up to 15 days before a series of engine burns are conducted to slow the spacecraft for re-entry over the South Pacific Ocean, where it and the cargo inside were destroyed. Total weight of cargo was 1494 kg (Crew supplies, 764 kg; Hardware: 355 kg, Science and research, 327 kg, Computer supplies, 8.2 kg; Spacewalk tools: 39 kg).

3.3 Orb-3

Orbital Sciences CRS Flight 3 was the first attempted flight of the Antares 130, which uses a more powerful Castor 30XL second stage, and the last flight of the standard-sized Cygnus Pressurised Cargo Module.

Orb-3 carried a variety of NASA-determined payloads, some of which were finalised very close to the launch day. The cargo module from the rocket carried 2300 kg of supplies and experiments meant for the International Space Station. In addition, the Arkyd-3 satellite would have been transported to the ISS on this flight and 34 of the Planet Labs small “Dove” Earth-observation spacecrafts.

The mission was scheduled to launch on 27th October, 2014, at 22:45 UTC from the Mid-Atlantic Regional Spaceport at the Wallops Flight Facility in Wallops Island, Virginia, with rendezvous and berthing with the ISS early in the morning on 2nd November. This was the first night-time launch for both the Antares launcher and Cygnus spacecraft. The launch was scrubbed due to safety concerns of a sailboat entering the exclusion zone less than ten minutes before launch. A 24-hour delay was put in place.

The Antares rocket carrying the Orb-3 Cygnus was launched, from Launch Pad 0A on 28th October, 2014, at 6:22 p.m. (EDT). Fifteen seconds after liftoff a failure of propulsion occurred in the first stage and the vehicle began falling back to the launch pad. Before reaching the ground, the vehicle was destroyed by its flight termination system, which was engaged by a command from the Wallops Range Control Center. According to NASA’s emergency operations officials, there were no casualties and property damage was limited to the south end of Wallops Island.

The resulting explosion was felt in Pocomoke City, Maryland, 32 km away. The fire at the site was quickly contained and allowed to burn itself out overnight. Initial review of telemetry data found no abnormalities in the pre-launch, the launch sequence, and the flight, until the time of the failure. According to the NASA press release, there were no known issues prior to launch and that no personnel were injured or missing but that the entire payload was lost and there was significant damage to the launch pad and site fuel tanks.

3.3.1 Failure analysis

On 29th October, 2014, teams of investigators began examining debris at the crash site. With some preliminary investigation completed, Orbital Science Corporation cited the cause of the Orb-3 launch failure is likely to be a turbo pump malfunction in one of the AeroJet Rocketdyne AJ-26 engines (refurbished Russian NK-33 engine).
Repairs of the damage caused to Wallops Flight Facility, by the launch exploration, started in January 2015.

By the time on writing this paper there was not an official report regarding the cause of the failure of the Orb-3.

3.4 Orbital Science's CRS Plan

To meet its Commercial Re-supply Services obligations to NASA, Orbital is planning to launch at least one enhanced Cygnus cargo spacecraft via an Atlas V launch vehicle in 2015. Orbital has yet to officially announce which engine may replace the AJ-26, but evaluation of other engines such as the RD-181 and RD-193 were being conducted as an AJ-26 replacement prior to the incident. The re-designed Antares launch vehicle is expected to fly again sometime in 2016.

4. Mirce-mechanics Analysis of Functionability of SpaceX

Under the NASA COTS contract it is expected that SpaceX will make 12 deliveries of cargo to ISS, with each flight carrying up to 3300 kg of internal and external cargo to the space station and return up to 2500 kg of equipment to Earth.

The space agency paid SpaceX $396 million in installments as the company accomplished design, testing and flight milestones, including two test launches and demo missions of the Falcon 9 rocket and Dragon capsule.

4.1 SpaceX CRS-1

SpaceX CRS-1 was the third flight for Space Exploration Technologies Corporation's uncrewed Dragon cargo spacecraft, the fourth overall flight for the company's two-stage Falcon 9 launch vehicle, and the first SpaceX operational mission under their Commercial Resupply Services contract with NASA. The launch occurred in accordance to the plan on 8th October 2012 (UTC) and successfully placed the Dragon spacecraft into the proper orbit for arriving at the International Space Station with cargo re-supply several days later.

During the launch, one of the nine engines suffered a sudden loss of pressure about 80 seconds into the flight, which was followed by its immediate shutdown. The remaining eight engines continued to fire, while the flight control software adjusted the trajectory to insert Dragon into required orbit.

At launch the CRS-1 Dragon was carrying approximately 905 kg of cargo, 400 kg without packaging (120 kg of crew supplies and 180 kg of critical materials to support the 166 experiments on board the station and 66 new experiments) and 105 kg of hardware for the station as well as other miscellaneous items. It was also planned to launch a 150 kg prototype of the second-generation Orbcomm satellite, as a secondary payload from Falcon 9's second stage.

4.1.1 Falcon 9 Engine Anomaly

During the ascent, an engine anomaly occurred with one of the nine engines on the Falcon 9 first stage. SpaceX has emphasized for several years that the Falcon 9 first stage is designed for "engine out" capability, with the capability to shut down one or more malfunctioning engines and still make a successful ascent. In this event, the SpaceX CRS-1's first stage shut down engine no.1 and as a result continued the first-stage burn on the remaining eight engines longer than usual at a reduced thrust to insert the Dragon spacecraft into the proper orbit. SpaceX referred to the event as a "Rapid unscheduled disassembly" which, although unintended, was the first in-flight demonstration of Falcon 9's "engine out" design and "provides a clear demonstration of the engine out capability."

In response to the anomaly, NASA and SpaceX jointly formed the CRS-1 Post-Flight Investigation Board. Preliminary information from the post-flight review board indicates that the Engine no.1 fuel dome, above the nozzle, ruptured but did not explode. The burning fuel that exited before the engine was shut down caused the fairing rupture, as seen in the flight video recordings. Subsequent investigations revealed in a Congressional hearing pinpointed the issue as a result of an undetected material flaw in the engine chamber jacket, likely introduced during engine production. During flight, the data suggests this material flaw ultimately developed into a breach in the main combustion chamber. This breach released a jet of hot gas and fuel in the direction of the main fuel line, causing a secondary leak and ultimately a rapid drop in engine pressure. As a result, the flight computer commanded shutdown of engine 1 and Falcon 9 continued on its path to ensure Dragon’s entry into orbit for subsequent rendezvous and berthing with the ISS.

The primary payload contractor, NASA, requires a probability of 0, 99 that the stage of any secondary payload on a similar orbital inclination to the International Space Station will reach their orbital altitude goal above the station. Due to the one engine failure, the Falcon 9 used more propellant than intended, reducing the success probability estimate to approximately 0.95. Consequently, the second stage did not attempt a second burn, and Orbcomm-G2 was left in an unusable orbit and burned up in Earth's atmosphere within 4 days after the launch.

Video of the launch shows debris falling from the rocket as it speeds to orbit, though SpaceX indicates that the engine did not explode, as they continued to receive data from it.

4.1 SpaceX CRS-2

The second CRS mission from Space Exploration Technologies Corporation took place on 1st March, 2013. A minor technical issue on the Dragon spacecraft involving the RCS thruster pods occurred upon reaching the orbit, which was recoverable.

When launched the CRS-2 Dragon was filled with 6 77 kg of cargo, 575 kg without packaging (81 kg of crew supplies, 347 kg of scientific experiments and experiment hardware, 135 kg of hardware for the station) and other miscellaneous items. The two Heat Rejection Subsystem Grapple Fixtures (HRSGFs) had a combined weight of 221 kg and were transported to the ISS inside the unpressurised Dragon trunk as external cargo.

The vehicle was released from the station on March 26th, 2013, at 10:56 GMT, and splashed down in the Pacific Ocean at 16:34 GMT.

The Dragon returned 1370 kg of cargo, 1210 kg without packaging. Included is 95 kg of crew supplies, 660 kg of scientific experiments and experiment hardware, 401 kg of space station hardware 38 kg of spacesuit equipment and other miscellaneous items.

4.3 SpaceX CRS-3

There were several delays between the nominal December 2013 date that had been planned since early 2013, mostly due to limited berthing windows in the ISS Visiting Vehicle schedule, and delays to Programmes, Orbital's Cygnus and SpaceX's Dragon, resulted from the December 2013 cooling issue on the ISS which required several spacewalks to mitigate.

The launch planned for 12th March 2014 was rescheduled to 30th March and then for 2nd April 2014 due to a variety of reasons, including data buffering issues, some operational issues with the new Dragon design and some contamination of the impact shielding blanket. SpaceX ultimately decided to move forward and use the shielding blanket with the minor contamination problems, believing it would not impact the optical payloads being carried in the Dragon trunk

However, a further delay was announced on 26th March, which was related to a fire at one of the radar facilities on the Eastern Range. There is mandatory radar coverage for any launches from Cape Canaveral, and the fire forced a delay until that section of the launch trajectory could be covered, possibly by alternative means that would have telemetry communication capability to the Air Force facility responsible for launch safety.

By April 4th the Eastern Range radars were repaired and back online to support launch and the CRS-3 launch was slated for no earlier than 14th April with a backup date of 18th April, contingent upon a ULA Atlas V flight scheduled for 10th April.

On 11th April, the International Space Station suffered a failure of an external computer known as a Multiplexer/Demultiplexer (MDM), which required a spacewalk on 22nd April to replace it, in order to restore vital redundancy to the station. Despite the challenges, the CRS-3 mission, which could have been impacted by the MDM failure, was still on for Monday, 14th April, with ISS berthing scheduled to take place two days later on 16th April.

However, during the launch attempt on 14th April, a primary helium supply valve used in the stage separation system failed a pre-launch diagnostic test approximately one hour prior to the scheduled launch, so the SpaceX launch manager scrubbed the mission. In ground tests following the scrub, the redundant backup helium supply valve tested okay so the mission would likely have succeeded.

The launch was immediately rescheduled for no earlier than the backup date, 18th April. That date was confirmed two days later, following replacement of the defective valve, but it was noted that weather constraints may prevent the launch on 18th April from occurring. If the launch had been scrubbed on 18th April, the next launch window would have been, 19th April at 3:02 pm ET. However, on Friday, 18th April 2014 at 7:25:21 p.m. UTC, the vehicle was successfully launched.

During this flight the CRS-3 booster made history by being the first liquid-rocket-engine orbital booster that successfully performed the controlled ocean soft touchdown. The booster included landing legs for the first time which were extended for the simulated "landing", and the test utilised more powerful gaseous nitrogen control thrusters than had been used in the previous test to better control aerodynamic-induced rotation. The booster stage successfully approached the water surface with no spin and at zero vertical velocity, as designed. The SpaceX team was able to receive video from cameras placed on the first-stage booster during soft landing test, as well as vehicle telemetry recorded by aircraft, but swells of 4.6–6.1 m were reported in the anticipated recovery area. The first stage successfully hovered over the ocean surface, but heavy waves destroyed the stage before boats were able to retrieve it.

Two days after splashdown, the 1600 kilograms of down-mass cargo, from the mission was returned to the Port of Long Beach by a marine vessel. Time-sensitive cargos are unloaded in California and flown to NASA receiving locations. The remainder of the cargo was unloaded and transferred to NASA at the SpaceX McGregor test facility in Texas, where the Dragon capsule was fully decommissioned and defueled. Although water was found inside the Dragon capsule, the preliminary checks indicated that no scientific equipment had been damaged. The source of the water has not been confirmed and will be investigated during the decommissioning of the capsule.

4.4 SpaceX CRS-4,

SpaceX's fourth CRS mission was scheduled for launch on September 20th, 2014, but was delayed due to adverse weather conditions. The launch took place on 21st September, 2014 at 1:52 a.m. EDT from Cape Canaveral Air Force Station in Florida.

As contracted, the CRS-4 mission the payload consisted of 2216 kg of cargo (1627 kg of pressurised and 589 kg of unpressurised.

The CRS-4 mission, which lasted 31 days, 22 hours and 41 minutes, was successfully completed on the 25th October 2014.

4.5 SpaceX CRS-5,

By July 2014, NASA scheduled this for "no earlier than" December 2014, with docking to the station projected to occur two days after launch.

This mission, was scheduled for launch on December 9th, 2014, but was delayed over several dates in December due to manifest adjustments for items lost from the Cygnus CRS Orb-3 launch failure (described in 4.3), technical issues found from a static fire test, the U.S. holiday season and staff scheduling, as well as a beta angle period during late December where thermal and operational constraints would make a Dragon berthing prohibited.

On 6th January 2015, the launch attempt was placed on hold at 1 minute 21 seconds prior to scheduled lift-off after a member of the launch team noticed actuator drift on one of two thrust vector control systems of the Falcon 9 second stage engine. As this launch had an instantaneous launch window, meaning no delays are possible in the launch sequence, the flight was postponed to 9th January 2015. On 7th January, the flight was rescheduled for 10th January 2015.

The Falcon 9 rocket carrying the CRS-5 Dragon spacecraft successfully launched on 10th January 2015 at 9:47 UTC. Dragon reached the station on 12th January. It was grappled by the Space Station Remote Manipulator System at 10:54 UTC and berthed to the Harmony module at 13:56 UTC.

The Dragon spacecraft for CRS-5 carried 2317 kg of cargo to the ISS. Included in this was 490 kg of provisions and equipment for the crew, 717 kg of station hardware, 577 kg of science equipment and experiments, and the 494 kg Cloud Aerosol Transport System (CATS).

In this flight, SpaceX attempted an unprecedented operation, which was to return the nearly-empty first stage of the Falcon 9 through the atmosphere and land it on a 90x50-meter floating platform called the autonomous spaceport drone ship. In October 2014, SpaceX had revealed that the ship was being built for SpaceX in Louisiana, and by mid-December, the ship was docked in Jacksonville, Florida, ready to go to sea to support the test flight landing attempt.

SpaceX attempted a landing on the drone ship on 10th January. Many of the test objectives were achieved, including precision control of the rocket's descent to land on the platform at a specific point in the South Atlantic Ocean and a large amount of test data was obtained from the first use of grid fin control surfaces used for more precise re-entry positioning. The SpaceX webcast indicated that the boost-back burn and re-entry burns for the descending first stage occurred, and that the descending rocket then went "below the horizon," as expected, which prevented the live telemetry signal. Shortly after that, the information released by SpaceX stated that the rocket did get to the drone spaceport ship as planned, but it had “hard landing”, while ship itself is fine, although some of the support equipment on the deck will need to be replaced. Full details of what happened to the rocket are not yet publicly known (one of the possible problems was the grid fins running out of hydraulic fluid).

4.6 SpaceX CRS-6

As of July 2014, this mission was tentatively scheduled by NASA for February 2015, with expected berthing to the station occurring two days later. However, as a result of delays in the launch of the SpaceX CRS-5 mission, in late March 2015, the tentative launch of this mission was scheduled for 13th April 13, 2015.

Due to bad weather conditions 13th April launch was postponed. Finally, the sixth SpaceX mission was successfully launched on 14th April 2015, at 20:10:41 UTC from Cape Canaveral Air Force Station in Florida. It was the eighth flight for SpaceX's uncrewed Dragon cargo spacecraft and the sixth SpaceX operational mission contracted to NASA under a Commercial Re-supply Services contract. It was docked to the International Space Station from 17th April to 21st May 2015.

The Dragon spacecraft was filled with more than 2000 kg of supplies and payloads, including critical materials to directly support about 40 of the more than 250 science and research investigations carried out at the ISS.

Planetary Resources will transport Arkyd 3 to the ISS aboard Dragon on CRS-6, which was the attempt to validate and mature the technology of its Arkyd series of spacecraft, (the first Arkyd 3 satellite was destroyed on launch in the explosion of the Orbital Sciences Antares launch vehicle carrying it aboard the third Cygnus cargo resupply flight to the ISS, as was decsribed in 4.3).

SpaceX has the primary control over manifesting, scheduling and loading secondary payloads. However there are certain restrictions included in their contract with NASA that preclude specified hazards on the secondary payloads, and also require contract-specified probabilities of success and safety margins for any SpaceX reboosts of the secondary satellites once the Falcon 9 second stage has achieved its initial low-Earth orbit.

CRS-6 included science payloads for studying new ways to possibly counteract the microgravity-induced cell damage seen during spaceflight, the effects of microgravity on the most common cells in bones, gather new insight that could lead to treatments for osteoporosis and muscle wasting conditions, continued studies into astronaut vision changes and test a new material that could one day be used as a synthetic muscle for robotics explorers of the future. Also making the trip was a new espresso machine for space station crews!

After the separation of the second stage, SpaceX conducted a flight test and attempted to return the nearly-empty first stage of the Falcon 9 through the atmosphere and land it on a 90x50-meter floating platform called the autonomous spaceport drone ship. Although the unmanned rocket technically landed on the floating platform, as it came down with too much lateral velocity, it tipped over and was destroyed. According to SpaceX, as the bipropellant valve was stuck the control system could not react rapidly enough for a successful landing.

The sixth mission was successfully completed on 21st May 2015, at 16:42 UTC.

4.7 SpaceX CRS-7

In January 2015, the launch of the seventh SpaceX CRS mission was tentatively scheduled by NASA for no earlier than 13th June, 2015. This was adjusted to 22nd June, then moved forward to 19th June and adjusted again to 26th June, 2015. Subsequently, the launch had been rescheduled to 28th June, 2015 at 14:21:11 UTC, from Cape Canaveral LC-40.

A full listing of the cargo aboard the failed mission included the following items: 690 kilograms of Crew Supplies related cargo and 573 kg of the cargo required for the operation, 36 kg of Computer Resources, 462 kg of Vehicle Hardware, 167 kg of Hardware for Extra vehicular activities (including Russian Cargo, Russian Segment Torque Wrench) and International Docking Adapter # 1 weighing 526 kg.

As of July 2013, the first International Docking Adapter, IDA-1 was scheduled to be delivered to the International Space Station on this mission in order to be attached to one of the existing Pressurised Mating Adapters and convert the existing docking interface to the new NASA Docking System (NDS). The new adapter is intended to facilitate future docking of new U.S. human-transport spacecraft. Previous United States cargo missions since the retirement of the Space Shuttle have been berthed, rather than docked, while docking is considered the safer and preferred method for spacecraft carrying humans.

The spacecraft was planned to stay in orbit for five weeks before returning to Earth with approximately 640 kg of supplies and waste.

4.7.1 Planned Landing on Floating Platform

The launch was scheduled to be the third controlled-descent and landing test for the Falcon 9's first stage. It was planned that after the second stage separation, SpaceX planned to conduct a flight test and attempt to return the Falcon 9's nearly-empty first stage through the atmosphere and land it on a 90x50-meter floating platform barge. SpaceX calls the barge an autonomous spaceport drone ship (ASDS), and this particular mission's ASDS was named “Of Course I Still Love You”.

4.7.2 Launch Failure

The vehicle's second stage failed with a measured overpressure at T+02:19, well after max Q (at T+01:26) and before first stage engine shutdown (MECO, scheduled at T+02:45). The second stage developed a very large Liquid Oxygen Tank leak, releasing large clouds of vapour while the first stage continued to thrust stably on course for about 9 seconds, until it disintegrated at T+02:28.

It was the first Falcon 9 failure in the 19 launches of the rocket type. According to SpaceX, the launch vehicle experienced a problem shortly before first stage shutdown due to an overpressure event in the upper stage liquid oxygen tank.

It is not clear if the destruction of the first stage was due to the flight termination system, which would have been activated automatically by on-board sensors. The Eastern Range's range safety officer did transmit a remote destruct signal, but only as a formality, 70 seconds after the event when there was nothing left to be destroyed.

5. Current Status of NASA-contracted Commercial Re-supply Services

At the time that this paper was written (July 2015) NASA-contracted Commercial Resupply Services had no capabilities of supporting the ISS, due to catastrophic launch failures that took place on 28th June 2015 and 28th of October 2014, respectively. Consequently, NASA was without spares for the water filtration system of ISS.

The first opprtunity to improve the water filtration system of ISS will be in mid August 2015 when the planned launch of a Japanese ISS re-supply mission will take place. It is expected that Japan’s HTV will be loaded with water containers and other supplies that should help to ensure six-crewmember operations until late this year.

6. The Future of NASA-contracted Commercial Re-supply Services

On February 21st, 2014 NASA posted Request for Information, RFI, about a possible follow on options to the current Commercial Re-supply Services to the International Space Station.

The anticipated contract reqgarding the future flights will include:

- delivery of pressurised and unpressurised cargo,
- return and disposal of pressurised cargo,
- disposal of unpressurised cargo,
- ground support services for the end-to-end re-supply mission

and will include: delivery of approximately 14000 to 17000 kg per year, 55 to 70 m^3 of pressurised cargo in four or five transport trips delivery of 24–30 powered lockers per year, requiring continuous power of up to 120 Watts at 28 Volts,.
The draft Request for Proposal, RFP, was released in May 2014 with a final RFP in June 2014.

Five companies are known to have submitted proposals to NASA, namely: SpaceX, Orbital ATK, Boeing, Sierra Nevada, and Lockheed Martin. Although the contract awards were originally anticipated by NASA in April 2015, they moved back to a June target date, and in April, delayed again to a contract award target date of September 2015.

In 2015, NASA extended the contract by ordering another three re-supply flights from SpaceX and one from Orbital Sciences. It is expected that the second round of contracts, CRS2, will cover deliveries from 2017 until 2024 and are expected to be awarded in 2015.

7. Conclusions

The factual results of the analysis of NASA-contracted Commercial Re-supply Services presented in this paper are another confirmation of the uncertainty of the in-service behaviour of industrial systems. Hence, this is another confirmation of the validity of the Mirce-mechanics Axiom related to the probability of occurrence of in-service failures. Even further, it is also confirmed that causes of mission failures are not due to the failures of their consisting components only. Several launches have been postponed due to unsatisfactory environmental conditions during the attempted launches on one hand and high level of space radiation on the other.

Both catastrophic launches are still under investigations, which only confirm the complexity of the processes taking place in the launch process, and even more the complexity of the interactions between internal components of the launch system, as well as the interactions between the launch system and the surrounding natural environment.

Finally it is necessary to stress that all processes from the conceptions of both the launch systems, Space Exploration Technologies Corporation and Orbital Sciences Corporation, through their design, production, testing, launches, space flights, berthing with the ISS, return flight to the Earth and finally post failure analysis are performed by humans that despite all creative, scientific, motivational and similar positive qualities also have proven abilities to make errors on the execution of tasks required to be performed by them, to the level that the 3rd Axiom of Mirce-mechanics states *"The probability of a human error in the execution of any functionability action is greater than zero"*.

In summary this paper provides further confirmation that functionability and safety considerations of a large number of modern industrial systems, including NASA-contracted Commercial Re-supply Services, are complex properties whose full understanding requires scientific approach towards understanding intricate mechanisms that lead to the occurrence of in-service failures, starting from atomic structure that drives the behaviour of matter, up to the solar system that drives the energy conversions (a physical scale ranging from 10^{-10} to 10^{10} metre). Then and only then, can accurate and meaningful reliability and safety predictions become possible, enabling the ultimate goal of reducing the probability of the occurrence of in-service failures during the life of industrial systems like power networks, aviation, satellite services, pipelines, digital control sand many others, including NASA-contracted Commercial Re-supply Services of today and of the future.

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Aircraft Air-intake Icing on the Ground as a Mechanism of the Motion in Mirce-mechanics

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

Mirce-mechanics is a scientific theory of the motion of maintainable systems through Mirce Spacetime resulting from any actions whatsoever and the actions required to produce any motion accurately proposed and demonstrated. Hence, the main purpose of this paper is to address the air-intake icing as a mechanism of the motion in Mirce-mechanics that causes the transition from the positive to the negative in-service state of an aircraft. To address this mechanism the Loganair scheduled cargo flight for the Royal Mail, from Edinburgh-Turnhouse Airport, Scotland to Belfast International Airport, has be selected for the analysis. The flight took place on 27th February 2001, with 17.10 take off and ditching into water several minutes later, killing both crew members A few other examples, where this mechanism caused the transition to the negative state, with similar consequences, are also mentioned in the paper.

1. Introduction

> ***"****Everything that the human race has done and thought is concerned with the satisfaction of felt needs*". Albert Einstein

Human needs for transportation, ventilation, communication, refrigeration, information, computation and many other functions are continuously satisfied through human created and managed entities, commonly known as systems. Their design-in performance, in terms of speed, capacity, frequency, power and similar physically measurable quantities, can be accurately predicted during the design process and tested at the delivery, as they are functioning in accordance to well understood laws of natural sciences, such as: Newton's laws of motion, Maxwell's law of electrodynamics, Coulomb's law of solid friction, Hook's law of stress and strain Boltzmann's law of thermodynamics, to name a few, which are characterised by certainty, reversibility and independence of time, location and humans.

Experience teaches us that due to internal and external interactions, variety of mechanical, electrical, chemical, thermal, radiant and other physical events are generated, some of which cause the loss of the ability of systems to function. To maintain functionability[8]**,** actions like servicing, repairs, inspections, replacements and similar, are undertaken by humans. Thus, the motion of functionability through time, which is physically manifested by the sequential transitions of maintainable systems[9] through positive and negative functionability states, resulting from the complex interactions between atomic, environmental and human actions, is a key determinant of the in-service performance of systems. Unlike accurate quantitative information regarding the design-in functionality performance of systems that is available on the delivery day, the in-service performance is not. Instead, years later the statistics for

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

[9] In Mirce-mechanics a functionable system is defined as any collection of entities that enables the flow of functionability through time.

various functionability measures become available. The reason for this is the fact that they are characterised by uncertainty, discontinuity, irreversibility, inseparability, and dependence of time, location and humans, and as such non predictable by existing laws of science. [1]

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

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

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

In summary, the body of knowledge comprising of axioms, mathematical equations and methods that enable prediction of the motion of functionability through time to be made, for all possible combinations of design-in and in-service alternatives, based on the scientific understanding of the mechanisms that cause occurrences of observable positive and negative events through the life of in-service systems constitutes Mirce-mechanics.

The main purpose of this paper is to address air-intake icing as a physical process that could potentially cause the motion of an aircraft from positive to negative in-service states and thus have significant impact on the passengers and cargo.

The main example of this mechanism, analysed in this paper, is related to the Loganair Flight 670A on 27th February 2001 that lost all power on both engines soon after take off from Edinburgh. An attempt to ditch in the Firth or Forth in rough seas resulted in the break up and sinking of the aircraft and neither pilot survived. The loss of power was attributed to the release of previously accumulated frozen deposits into the engine core when the engine anti icing systems were selected ON, whilst climbing through 2200 feet. These frozen deposits were considered to have accumulated whilst the aircraft had been parked prior to flight without engine intake blanks fitted.

2. Aircraft Ground Air-intake Icing Phenomena

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

Within the aviation community the effects of airframe contamination and the potential consequences of failure to properly de-ice prior to takeoff are well documented and are generally well understood. However, the concepts and liabilities of jet engine contamination, inclusive of engine core and fan blade icing, have not had the same degree of exposure and are less well understood.

Blowing snow, precipitation, freezing fog, slush and other ground contaminants or airport snow removal operations can all result in the contamination of jet engine intakes and components. The area of the engine that will be affected is dependent upon the origin and type of contaminant, and whether or not the engines are running at the time of exposure. The potential for damage due to ice ingestion is significant but the more subtle effects of airflow disruption due to ice accretion on compressor and fan blades can also result in loss of thrust, engine damage or flameout.

The engine anti-ice system, as installed on most types, serves solely to prevent ice build up on the air intake opening of the engine nacelle. It does not prevent ice build up in the primary stages of the engine core (compressor) or on the fan blades. Jet engines are most susceptible to the build up of blade ice in conditions of freezing fog or freezing precipitation while the engine is at or near its minimum rotation speed (ground idle). Compressor and fan blades are aerofoils and, due to the affect that they have on the airflow across them, any ice accretion will normally be found on the back side of the blade. This makes the ice difficult to see during a preflight inspection and also inhibits its removal.

3. Loganair Flight 670A on 27th February 2001

For the purpose of this paper the Loganair scheduled cargo flight for the Royal Mail, from Edinburgh-Turnhouse Airport, Scotland to Belfast International Airport, has be selected for the analysis, as an illustration of the air-intake icing as a Mechanism of the Motion in Mirce-mechanics

3.1 The Aircraft

The aircraft considered was a Short 360-100, a turboprop airliner manufactured by Short Brothers Limited in 1987, constructor's serial number SH 3723 and registered G-BMNT. It is powered by two Pratt & Whitney Canada PT6A-67R engines.

For the Royal Mail flights the passenger seats had been removed for use as a freighter and its Certificate of Airworthiness was valid until 15 October 2001. The aircraft was loaded with 1,360 kg of fuel and carried 1,040 kg of cargo with a total weight at takeoff of 10,149 kg (maximum certified takeoff weight is 12,292 kg).

3.2 The Crew

The crew consisted of a 58 year old male holding a valid Airline Transport Pilot's license and with 13,569 hours' flying experience, as the pilot in command. [The co-pilot was a 29 year old male, also with a valid license and 438 total flight hours.

The report said that nothing is known of the crew’s activities at the aircraft.

"It is probable that by the time the accident crew arrived, any accumulation of snow or slush on the airframe had been blown away or melted," the report said. "In the absence of any other information it is assumed that the crew carried out normal pre-flight procedures and checks." [2]

3.3 Environmental Conditions

Weather reported at the Edinburgh Airport, just before the accident, was as follows:

- Air temperature of +2°C,
- dew point of -3°C,
- Visibility of more then 10km, broken clouds at 4500 ft and cover at 8000 ft.

3.4 The Takeoff

Loganair Royal Mail charter flight 670A to Belfast was given a clearance at 15:03. Two minutes later, the crew advised Air Traffic Controller that they aborting the flight due to a technical problem.

The crew then advised their company that a generator would not come on line. An avionics technician carried out diagnosis during which both engines were ground-run twice. No fault was found and the flight crew requested taxi clearance at 17:10.

3.5 The Accident

A normal takeoff took place at 17:10, whit the pilot flying. It was followed by a normal reduction in power at 1200 feet above mean sea level. At 2200 feet, while the pilot was changing the radio frequency, the co-pilot selected the anti-icing systems. However, only 3.9 seconds later the torque indicators for both engines rapidly fell to zero, causing a complete loss of propeller thrust. In response, the first officer radioed a Mayday call on the Air traffic control frequency; the pilot initiated a descent with a reduced airspeed of 110 kt while turning right towards the coast. Realising that they could not reach shore the crew prepared for ditching. At airspeed of 86 knots, with a 6.8 degree nose up, and 3.6 degree left wing down attitude the aircraft thatched the water.

At the final stop, the aircraft was 65 metres off shore in a 45 degree nose down attitude, with the forward half of the fuselage submerged in a water depth of approximately 6 metres. As the results of the impact with water the flight deck was almost completely destroyed, with a fuselage firmly embedded in the sand. The empennage had separated and was found floating 100 metres to the east of the main wreckage.

Both crew members were drowned, although both crew seats remained attached to the flight deck floor with no failure of the safety harnesses. The cockpit voice recorder (CVR) and flight data recorder (FDR) were both recovered intact. The aircraft was eventually salvaged, dismantled and transported to UK Air Accidents Investigation Branch (AAIB) headquarters at Farnborough for a detailed examination.

3.6 Actions that Caused Occurrence of Negative In-service Event

Upon investigation completion it was concluded that the snow accumulated overnight changed the engine intake air flow, causing both engines to flame out after both engines' anti-ice vanes were simultaneously opened as per the standard operating procedure.

The aircraft concerned was parked overnight, heading directly into moderate to strong surface winds for approximately 17 hours. As no protecting plugs were put inside the engine intakes by the flight crew, against established practical procedure for flights in adverse weather conditions, the wind drove a significant amount of snow into the intakes.

The reason for that was the fact that the intake plugs were not carried, as part of the aircraft's onboard equipment. Even further, they were not available at Edinburgh Airport. Finally, information concerning freezing weather conditions in the aircraft manufacturer's maintenance manual had not been including in the Loganair Operations Manual for Short 360, which meant not complied with.

The AAIB, in the final report, stated that the large volumes of snow or slush could have accumulated where it would not have been readily visible to the crew during a pre-flight inspection, as the engine intakes on this type of aircraft are about 2.8 m above the ground. [2]

4. Other Occurrences of Aircraft Ground Air-intake Icing Phenomena

A few examples of the aircraft ground air-intake icing occurrences are briefly describes here, as a further evidence of the nature of this phenomena and the manner of its manifestations.

- During the course of the investigation of the loss of G-BNMT, a report was received that there had been a previous occurrence, on an SD3-60 aircraft operated by a different company in the UK, of a double engine power anomaly as a result of accumulated ice or snow arising from pre-flight conditions. The power interruption occurred while the aircraft was on its take-off run. The event, that took place around 1992, had not been reported at the time through the established mandatory reporting system. However, both crew members and the station engineer concerned were located and spoken to, but the intervening period had resulted in considerable differences of recollection of the precise circumstances.

- The AAIB reported in the Bulletin 1/2002 on an accident which occurred on 20 March 2001 in which a DHC-8 aircraft experienced and undetected build up of slush in the engine intake and plenum areas. The aircraft was fitted with PW127 engines, a type with an intake system very different in concept from that on the PT6A-67, but which as similarly located and configured intakes in the engine nacelles. This accumulation had occurred while the aircraft was parked facing into wind in falling snow and resulted in both engines flaming out during the subsequent taxi for takeoff.

- On 13 January 1982, an Air Florida Boeing 737-200 took off in daylight from runway 36 at Washington National in moderate snow but then stalled before hitting a bridge and vehicles and continuing into the river below after just one minute of flight killing The aircraft was destroyed by impact forces and 69 of the 74 occupants and 4 people on the ground were killed and 4 more on the ground were injured. The accident was attributed entirely to a combination of the actions and inactions of the crew in relation to the prevailing adverse weather conditions and, crucially, to the failure to select engine anti ice on which led to over reading of actual engine thrust. [3]

- On 25 November 2004, a Mytravel Airways UK Airbus A320 departed the side of the runway at Harstad, Norway at a low speed after loss of directional control when thrust was applied for a night take off from surface-contaminated runway 35 in normal visibility and the aircraft departed the left side of the runway. The aircraft stopped short distance off the paved surface and the occupants were subsequently evacuated from the rear of the aircraft using normal aircraft steps before being taken back to the terminal by bus. Damage to the aircraft was minor and confined to the NLG. It was found that the crew had failed to follow an SOP designed to ensure that any accumulated fan ice was shed prior to take off and also failed to apply take off thrust as prescribed, thus delaying their appreciation of the uneven thrust produced. [5]

- On 20 March 2001, aircraft DHC-8-311, G-JEDD, with 2 Pratt & Whitney PW-123 turboprop engines landed at Bristol at 1314 hrs. At that time, the weather produced a surface wind from 080° at 25 gusting 36 kt, visibility 2,000 metres in light snow, scattered cloud base 500 feet, temperature 0°C. The aircraft parked normally on stand 5, heading east (into wind). After the passengers had deplaned, the crew went into the airport terminal, as the next planned departure was at 1510 hrs. The crew did not fit the engine intake blanking plugs during the turnaround. During the intervening period, the weather conditions worsened. The snow fall became heavier with a progressive deterioration in visibility and the strong, gusty easterly wind continued. During its time on the ground, the aircraft began to accumulate a covering of snow. When the crew returned to the aircraft in time to prepare for the next planned departure, the commander arranged for the aircraft to be de-iced using heated type II fluid. After this was carried out and the commander completed a pre-flight external inspection, which included a visual inspection from the ground of each engine intake lip and a tactile inspection of the rear of each intake through the open bypass doors. The commander assessed that there was no build up of snow or slush in these areas and considered that the engine intakes were clear of ice and snow. Once the runway had re-opened, the crew performed a normal engine start and the aircraft began to taxi out for departure at 1535 hrs. On reaching the holding point for Runway 09, ATC requested that the aircraft hold position in order to allow a stream of inbound aircraft to land. While waiting with the aircraft's tail into wind, the right engine suddenly stopped, for no apparent reason. The crew carried out the Engine Failure procedure from the aircraft's Quick Reference Handbook (QRH), without selecting Ignition to Manual (ON) for the left engine. About 2.25 minutes after that the left engine also flameout. The commander informed ATC and requested a bus to deplane the passengers and a tug and tow bar to move the aircraft to the parking ramp. While passengers were leaving the aircraft the left propeller was still wind milling quite fast close to the forward exit door. The aircraft was then towed to a parking stand. On arrival, the aircraft was quarantined and the engine intake blanks were fitted. [6]

These few examples, like thousands of other incidents, are recorded in different aviation data bases, form the statistics of the past performances. However, as statistics does not study causes of statistical behaviour and is mainly used by statisticians and government organisations, rather than by design, operation and maintenance engineers, many of the future accidents end up as the statistics. As indicated in the introduction of the paper one of the main objectives of Mirce-mechanics is the scientific understanding of the mechanisms that drive in-service processes like fatigue, operator errors, corrosion, creep, foreign object damage, a faulty weld, carburettor icing, shelf life, perished rubber, to name just, which cause occurrences of negative events.

5. Functionability Analysis of the Air0intake Icing Event

Mirce-mechanics is a a scientific theory of the motion of maintainable systems through Mirce Spacetime resulting from any actions whatsoever and the actions required to produce any motion accurately proposed and demonstrated. Hence, the main objective of this paper is to present an example of t the functionability analysis as a consistent part of the Mirce-mechanics through analysis of the actions that caused the accident of the flight 670A to Belfast. The data provided in the Air Accident Report 2/2003 [2] is the main source of information used to conduct the functionability analysis considered.

5.1 Sequence of Pre-flight Events

The aircraft considered landed at Edinburgh Airport from its previous flight at 0003 hrs on 27th February 2001. The weather conditions, recorded in the weather report, were as follows: surface wind 040 ^{0}/22 gusting 36kt, visibility 5,000 metres, light ice pellets, scattered cloud at 900 feet, broken cloud at 1,200 feet, temperature + 1 ^{0} C, dewpoint 0 ^{0}C and barometric pressure adjusted to the sea level was 992 mb.

The aircraft was taxied to and parked on Stand 31, with a heading of 035 ^{0} M. The inbound crew reported that there were no abnormalities observed or technical defects on the aircraft. As the Loganair does not use this airport as operating base, flight crews were responsible for normal aircraft turnaround procedures. Hence, they supervised the refuelling of the aircraft to a final load of 360 kg before leaving.

The aircraft was scheduled to depart Edinburgh at 0040 hrs with a different operating crew, which arrived at the aircraft at about 0030 hrs. Due to existing weather conditions the crew required de-icing before departure but they were advised that there would be a delay of several hours before equipment would be available. In the interim they returned to the crew room. At 0210 hrs the airport closed as a result of the severe weather. At 0600 hrs this second crew were advised that the airport was not likely to reopen for several hours and so they returned to the aircraft to ensure it was secure before going off duty. At this time they fitted propeller straps to each engine and also put on the pitot head covers. Engine air intake blanks were not available for the crew to fit to the aircraft. The aircraft had not been de-iced.

The overnight weather conditions comprised a sustained strong north easterly wind, with a maximum recorded speed of 43 kt. Light or moderate snow fall occurred until 0952 hrs. There was no further snowfall after this time and by 1500 hrs the weather conditions were: surface wind 030 ^{0} / 15km, visibility 10 km, scattered cloud at 4,000 feet, broken cloud at 7,000 feet, temperature + 2 ^{0} C, dewpoint –3 ^{0}C.

5.2 The Accident Flight

To commence a planned flight to Islay departing at 0910 hrs, the pilots that were aboard the aircraft on the accident flight reported for duty at Glasgow Airport at 0810 hrs on 27th February 2001. As a result of adverse weather conditions, that flight was cancelled and they were rescheduled to carry out the single sector flight delayed from 0040 hrs from Edinburgh to Belfast. Surface travel from Glasgow to Edinburgh was impossible due to adverse road conditions, so as soon as Edinburgh Airport re-opened at 11.30 hrs, the crew were positioned to Edinburgh as passengers on another company aircraft.

On their arrival at Edinburgh the crew went out to the aircraft. There was no record of their activities there, but at 1503 hrs they requested clearance to start engines. Start clearance was obtained and then, at 1512 hrs, the crew advised Air Traffic Control, ATC, they were shutting down due to a technical problem. During this period the right engine had been observed to start and stop several times.

The crew returned to the terminal and contacted their company at Glasgow to ask for engineering assistance. They indicated that the right engine driven generator would not come on line. A company avionics/instrument engineer was in transit through Edinburgh Airport. He was contacted by the Line Maintenance Controller at Glasgow and asked to assist the crew. He carried out trouble shooting with advice from the Maintenance Controller. This action involved transposing the connections to the Generator Control Protection Units and required the crew to start and run both engines for approximately 15 minutes. The connections were then returned to their original positions. Thereafter, the crew carried out a second engine run of similar duration, again at the engineer’s request. The original fault could not be reproduced. A ground power unit was not available, so the engine starts were carried out using aircraft battery power.

The commander then requested that the engineer check the engine oil contents. He also asked him to confirm that the upper surfaces of the aircraft were free from ice and snow. The engineer noted that the oil levels were such that replenishment was not required and the only airframe contamination was a small slush deposit on the windscreen. This was cleared by the engineer. Both engines were then restarted after which the aircraft remained on stand with the engines running for about another 20 minutes.

At 1710 hrs the first officer requested taxi clearance. After a short delay the aircraft powered back off stand and taxied to depart from Runway 06. While taxiing, as part of the first flight of the day engine checks, the crew carried out an Auto feather test, during the automatic operation of the engine anti-icing vanes to fully deploy and return was also observed. The commander briefed the first officer that after takeoff they would recycle the landing gear once to ensure that it was free of snow and slush.
The aircraft was cleared for a flight to Talla (TLA). The commander was the designated handling pilot. He carried out a normal takeoff which was followed by the landing gear being cycled up and down once, before its final retraction. A reduction to climb power was made at 1,200 feet above mean sea level, amsl. The commander then called for the after take-off checks to be completed. When the ‘Stall Warning Heaters’ item was reached, he requested that the first officer put on all the anti-icing systems. At this time the aircraft was handed over from Edinburgh Tower to Scottish ATCC, which was acknowledged by the first officer. With the aircraft at 2,200 feet amsl, the first officer then selected the anti-icing systems ‘ON’ while the commander selected the new radio frequency. Four seconds after the selection of each anti-icing vane switch, the torque on the corresponding engine reduced rapidly to zero. The commander quickly observed that the aircraft had suffered a double engine failure and advised the first officer who immediately broadcasted a MAYDAY call. In response the ATC passed the crew position and heading information.

The commander continued to fly the aircraft, initiating a descent while allowing the airspeed to reduce to 110 kt and turning the aircraft to the right towards the coastline. The rate of descent stabilised at 2,800 feet per minute and he realised that the aircraft would have to be ditched in the water. The first officer attempted to make a further call to ATC advising that the aircraft was ditching, but this was not received. As the aircraft descended close to the water surface, the commander gradually increased the pitch attitude of the aircraft and correspondingly reduced the speed.

The aircraft impacted the water in a 6.8^0 nose up attitude at airspeed of 86 kt on a heading of 109^0M. It came to rest on the sea bottom in a nose down attitude with the forward section of the fuselage submerged, 65 metres offshore, in a water depth of about six metres.

5.3 Operating Procedures

Aircraft operating procedures for flight crew were laid out in the Operations Manual. Emergency and Abnormal checklist Documents were derived from information contained in the Short Brothers Ltd, SD3-60 Aircraft Flight Manual (AFM), and approved by the UK Civil Aviation Authority (CAA).

The company's operations manual required ice-protection systems for the airframe, engines, propellers, windshield, pitot-static system and stall-warning system to be engaged before the aircraft enters visible moisture at an outside air temperature at or below 6 degrees C.

5.4 Ground Handling Procedures

In the Operations Manual Part 1, clearly specifies, that after flight, captain is responsible for safe guarding the aircraft if it is to be left unattended for any length of time, such during a split duty or an overnight stop. It specifies that:

" The aircraft is to be secured in such a manner that it is protected from adverse weather Conditions, actual or forecast, and is to be parked or hangared in a secure place or area. Control locks and, where applicable, propeller restraint straps and pogo sticks are to be used whenever aircraft are parked. Should an aircraft be left for any length of time then engine blanks, pitot covers and chocks must be in position.'

According [2] the Operations Manual Part 9 (Flying – Shorts SD3-60) in particular specifies that, even for short term parking, 'propeller ties should be fitted', in order to prevent undesired rotation of the propellers on the ground.

For the engine air intakes, that are located some 2.8 metres above the ground, the manufacturer suppliedair intake blanks as original equipment, which were designed to be fitted in the engine intakes to prevent debris, dust or snow from entering the engine intake area. Although supplied originally by the manufacturer with the new aircraft, these intake blanks were not routinely carried on the operator's SD3-60 aircraft.

The Maintenance Manual and the Operations Manual both contained a requirement for intake blanks to be fitted prior to the aircraft being de-iced. The Operations Manual also specified that, when ground de-icing of aircraft was to be carried out, then this should be under the supervision of a company engineer.

It was the operator's standard practice to keep intake blanks only at its main operating bases, namely Glasgow, Kirkwall and Inverness, where they were invariably fitted only by engineers to the night-stopping aircraft. Hence, no engineering personnel and no engine intake blanks were provided overnight at Edinburgh to support this operation. No intake blanks were therefore readily available to the crew, so they were unable to meet the stated responsibilities with regard to the safeguarding of the aircraft.

Even further, the crew would have needed a stepladder to visually inspect the engine intakes. Steps were not available at the aircraft, and a visual inspection inside the intakes was not specifically part of the pre-flight procedure. However, if the air intakes had been closely examined, it is possible that, some deposits of snow may have been visible within the intake cowl area.

5. Results of the Functionability Analysis of the Air0intake Icing Event

Based on the information presented in [2] and the analysis performed above it is possible to draw the following conclusions:

- The airline did not have an established practical procedure for flight crews to fit engine intake blanks in adverse weather conditions. This meant that the advice contained in the aircraft manufacturer’s Maintenance Manual ‘Freezing weather – precautions’ was not compiled with. Furthermore intake blanks were not provided on the aircraft nor were any readily available at Edinburgh Airport. However, even if they could have be found at the airport it would not be possible to install them without a ladders of a significant height.

- Resulting from the aircraft overnight parking position that exposed it directly into strong surface winds, during the conditions of light to moderate snowfalls, almost certainly a significant amount of snow entered into the engine intakes.

- The flow characteristics of the engine intake system most probably allowed large volumes of snow, ice or slush to accumulate in areas where it would not have been readily visible to the crew during a normal pre-flight inspection without making use of ladders, which were not readily available.

- The deposits of snow, ice or slush almost certainly migrated from the plenum chambers down to the region of the intake anti-ice vanes, at some stage (probably after engine ground running began).

- According to investigators [2] the conditions in the intakes prior to takeoff are considered to have caused re-freezing of the contaminant, allowing a significant proportion to remain in a state which precluded its ingestion into the engines during taxi, takeoff and initial climb.

- Movement of the intake anti-icing vanes, acting in conjunction with the presence of snow, ice or slush in the intake systems, altered the engine intake air flow conditions and resulted in the near simultaneous flameout of both engines.

- The standard operating procedure, approved by the operator, of selecting both intake anti-ice vane switches simultaneously enabled a simultaneous double engine flameout.

6. Conclusions

Mirce-mechanics analysis of the factual results available [2] regarding the Loganair Flight 670A on 27th February 2001 that lost all power on both engines soon after take off from Edinburgh and ditched into water several minutes later was presented in this paper. The action that caused this fatal event was the release of previously accumulated frozen deposits that were considered to have been accumulated whilst the aircraft had been parked overnight without engine intake blanks fitted.

Hence, this is another confirmation of the validity of the Mirce-mechanics Axiom which states that "*The probability of a human error in the execution of any functionability action is greater than zero*" [7]. Even further, it is also confirmed that causes of in-service failures are not always due to the malfunctioning of internal components of a system, but also from environmental impacts and humans actions.

In summary this paper provides further confirmation that in-service reliability and safety considerations of a large number of modern maintainable systems are complex properties whose full understanding requires scientific approach towards understanding intricate mechanisms that lead to the occurrence of in-service failures, starting from atomic structure that drives the behaviour of matter, up to the solar system that drives the energy conversions (a physical scale ranging from 10^{-10} to 10^{10} metre). Then and only then, can accurate and meaningful reliability and safety predictions become possible, enabling the ultimate goal of reducing the probability of the occurrence of functionability events (in-service failures) during the life of maintainable systems.

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Aerotoxic Syndrome as a Mirce-mechanics Phenomenon

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

Abstract

Mirce-mechanics is a scientific theory of the motion off maintainable systems through Mirce Spacetime, resulting from any failure causes whatsoever and the actions required to produce any motion accurately proposed and demonstrated. Hence, the main purpose of this paper is to address the impact of toxic aircraft materials that cause in-service effects such as blurred vision, disorientation, memory loss, lack of coordination, nausea and similar to flight crew and frequent flyers. Aerotoxic Syndrome is the term given to the adverse health effects resulting from the exposure to jet oil mist during commercial flights. There are some indications that methods of Mirce-mechanics could be used to make flying as safe as possible, while ensuring wellbeing for crew members and frequent flyers.

1. Introduction

While investigating the death of a British Airways pilot, Richard Westgate, the senior coroner in Dorset, England, Stanhope Payne, has raised concerns about aerotoxic syndrome. Mr. Westgate, a senior first officer, died in 2012 after claiming he had been poisoned by toxic cabin fumes. The coroner says that examinations of Westgate's body "disclosed symptoms consistent with exposure to organophosphate compounds in aircraft cabin air."Payne has suggested that those who spend the most time on board commercial aircraft, cabin crew and frequent travelers, could face "consequential damage to their health" because of these toxins.

Aerotoxic Syndrome is the term given to the illness caused by exposure to contaminated air in jet aircraft. The term was introduced on 20 October 1999 by Dr Harry Hoffman, Professor Chris Winder and Jean Christophe Balouet, in their report, Aerotoxic Syndrome: Adverse health effects following exposure to jet oil mist during commercial flights.

Aerotoxic syndrome is a somewhat controversial condition that could be triggered by the air compression systems in commercial planes. Some of the air that is compressed and recirculated throughout the cabins originates in jet engines; when excess oil molecules enter that air supply, it can result in what is called a "fume event" Thus, the main objective of this paper is to address the aerotoxic phenomena from Mirce-mechanics point of view, which means as one of many actions that could cause the change of the state of maintainable systems.

2. Cabin Pressurisation

Naturally, atmospheric pressure around the earth reduces with altitude. Consequently, humans can tolerate a reduction in oxygen partial pressure up to around 10,000ft. Beyond that oxygen partial pressure reduces rapidly and impairs brain function. To provide safe and pleasant flights, the maximum certified cabin altitude in normal operation is 8,000ft.

During flight, air is derived from the compression stage of the jet engine. This bleed air is conditioned and filtered, with an exchange of 10-15 times per hour with outside air and 20-30 times per hour including outside and filtered recirculated air.

3. Human Toxicology

In order for a toxic effect to occur chemicals foreign to the human body must be absorbed from the surrounding environment and transported to the relevant site in the body. Routes of entry include ingestion, skin absorption and inhalation with sufficient concentration for the chemical to cross the many cell membranes. In the case of inhalation, the absorption of the chemical will depend on the percentage partial pressure it exerts within the total pressure in the lung alveoli as well as its solubility. The human senses, particularly smell, are generally effective in detecting potentially hazardous substances at a level well below that which causes harm (the major exception being carbon monoxide). For most volatile organic compounds, the normal detection level is around 1,000 times less than the level which is likely to harm health.

For organophosphates, exposure to sufficient doses of the ortho isomer may cause adverse effects on the nervous system, including impairment of neuromuscular and peripheral nerve synapse function, but not brain cognitive function. The majority of cases recorded in the medical literature since 1943 have been associated with swallowing contaminated food or drink, and reports of occupational intoxication are rare with no cases due to inhalation.

There are legal exposure limits for hazardous substances at work, the Indicative Occupational Exposure Limit Values (IOELVs); for the ortho isomers ToCP, the workplace limit is 0.1mg/m3 for 8 hours with an emergency short term limit of 0.3mg/m3 for 15 minutes. From knowledge of aviation respiratory physiology, it can be shown that these values remain valid up to a cabin altitude of 8,000ft [3].

4. Physiology of Breathing

The total pressure in the lung alveolus is the sum of the partial pressures of all the gases in the mixture, and the transfer of any gas across the alveolar membrane depends on the properties of the membrane and the partial pressure exerted by that gas within the mixture.

Oxygen and carbon dioxide are exchanged in the alveoli; the partial pressure of oxygen is higher in the air than in the blood so it combines with haemoglobin to be carried to the tissues, whereas carbon dioxide is at a higher partial pressure in the blood so is given up to the alveolar air. It is important to stress that it is partial pressure of the concentration that drives the exchange. There is water vapour in the alveoli as well as oxygen, carbon dioxide and nitrogen, and while the partial pressures of the atmospheric gases fall with increasing altitude, the water vapour pressure remains constant as a result of metabolism. As alveolar absorption is governed by Dalton’s Law of partial pressures, as well as Fick’s Law, and the partial pressure of bleed air contaminants is a very small proportion of the total alveolar gas pressure, it is reducing rapidly.

5. Toxic Aircraft Materials

Aircraft materials such as jet-fuel, de-icing fluids, engine oil, hydraulic fluids, and so on, contain a range of ingredients, some of which can be toxic. Although these chemicals are usually retained in engines and equipment into which they have been added, they can sometimes find their way into cabin air where crew and passengers are located, through incidents such as engine oil leaks, seal failures and fluid ingestion by APU/engines. Further, operational activities, such as APU “pack” burnouts, can give rise to significant contamination.

Dozens of in-cabin leak/smoke events are documented annually often correlated to aircraft fluid leak events.

Fume events are much more frequent, correlated to less important aircraft fluid leaks (hundreds per year), or to other independent sources. In total, aircraft fluid leak/fume/smoke events are estimated to impact over 300 flights per year worldwide, resulting in exposures to an estimated 40,000 or more crew and passengers. Some models of airplanes appear to be particularly prone to leaks.

The range of bleed air contaminants and their concentrations, which may be found during in-cabin contamination events during flight, can be extensive. Significant contaminants include: carbon monoxide, aldehydes; aromatic hydrocarbons; aliphatic hydrocarbons; chlorinated, fluorinated, methylated, phosphate, nitrogen compounds; esters; and oxides. One additional problem is the lower oxygen concentration operating in the cabins of planes flying at altitude.

Inhalation is an important route of exposure, with exposure to uncovered skin being a second, less significant route (for example, following exposure to oil mists) and ingestion improbable.

In terms of toxicity, a growing number of crew are developing symptoms following both short term and long term repeated exposures. Neurotoxicity is a major flight safety concern, especially where exposures are intense.

6. History of the Problem

The first well-documented case was of a aerotoxicity was recorded in 1977 when the C-130 Hercules navigator became incapacitated after breathing contaminated cabin air in. However, the neuro-toxic properties of organophosphates have been known about since before the Second World War. The toxicity of heated jet oil was known from 1954.

UK Committee on Toxicity of Chemicals in Food, in 2007 report, produced by the in Consumer Products and the Environment, stated that fume events occur on average in 1 flight out of 100. However, on some aircraft types crews report that they experience fumes to some degree on every flight. However, as the definition of “fume event” is not agreed upon, it makes it impossible to get the real picture of the problem.

7. Causes of Cabin Air Contamination

In order to have a comfortable environment and sufficient air pressure to breathe at the altitudes at which jet airliners fly, a supply of warm compressed air is required.
This is nowadays supplied direct from the jet engines and is known as ‘bleed air‘, with the sole exception of the new Boeing 787. It is mixed inside the aircraft with recirculated cabin air at a ratio of 50/50. Although some of the air is subsequently recirculated, all of the air originates from the jet engines.

Bleed air comes from the compressor section of the jet engine, which has to be lubricated. Jet engines mostly have “wet seals” to keep the oil and air apart, which cannot be 100% effective. Furthermore, these seals, like any mechanical component, slowly wear out and their effectiveness gradually declines. This wear can occur more rapidly when the engine is working hard, such as climbing under full throttle. They may also fail suddenly and will then let a significant amount of oil into the very hot compressed bleed air, resulting in fumes and/or smoke entering the cabin. This is known as a “fume event”. There are no filters in the bleed air supply to stop this happening.

It is necessary to stress that the oil used to lubricate jet engines is not based on petroleum hydrocarbons, as are lubricants for internal combustion engines used in motor cars, outboard motors, tractors etc. As jet engines operate at much higher temperatures they use special synthetic chemicals as oil. They also contain organophosphate additives as antiwear agents and other aromatic hydrocarbons as antioxidants. Some of the oil gets partially decomposed, i.e. chemically altered due to the high temperatures in the engine. Thus, the contamination is composed of the “oil”, the additives, and the decomposition products. The last two of these three generates the harmful toxicity.

Materials used in the operation of aircraft may contain hazardous ingredients, some with significant toxicities, and need care in handling and use. Some maintenance or operational activities, such as leaks or poorly controlled maintenance procedures, can, through contamination of aircraft cabin air, produce unwanted exposures to personnel and passengers.

8. Detection of Aerotoxic

Slight leakage of oil into the cabin may be detected by smell. Descriptions such as ‘sweaty socks’, ‘wet dog’, ‘vomit’, ‘sweet oily smell’ have been used to describe it. Background levels of contamination may not be detectable by smell. If a “fume event” occurs bluish haze or smoke in the cabin may be visible. Only visible smoke is officially reported in the flight log, leading to under-reporting of the actual frequency. There are no chemical sensors in modern jet aircraft. The noses of the aircrew are the only detectors at the moment.

The degree of contamination depends on jet engine type and how recently it was serviced, among other factors. There are few reliable measurements but based on what has been documented it is possible to estimate that about a quarter of flights suffer slight but significant contamination. It is important to remember that this contamination might be continuous throughout a flight; hence the total exposure might end up as much as after a brief fume event.

Swab-testing confirms that fume events also deposit substantial residues on all the interior surfaces of the cabin, including the skin of those aboard.

The amount of leakage may increase due to faulty maintenance (including during the interval immediately preceding a scheduled maintenance intervention). If there is actual failure of a component of the seal, leakage may be considerable.

In any case, leakage tends to be greater when the engine is cold and when the engine is working hard. Furthermore, some oil is pyrolysed in the engine, and the complex mixture of pyrolysis products may also be present in the bleed air. Tricresyl phosphates are potent neurotoxins.

9. Aerotoxic Symptoms

Symptoms have been collected from ten cases of pilots, first officers, pursers and flight attendants, flying in five airlines, three models of airplane and in four countries. The only common feature is that at some stage, they were involved in an incident where a leak of oil mist to the flight deck or passenger cabin occurred.

Symptoms were reported from single exposures to elevated exposures and from long term low level exposures to low level oil leaks or residual problems from previous contamination. Combined exposures (that is, short term intense exposures combined with low level long term exposures) were also prevalent.

Symptoms from single or short term exposures are shown in Table 1 below and include: blurred or tunnel vision, disorientation, memory impairment, shaking and tremors, nausea/vomiting, parasthesias, loss of balance and vertigo, seizures, loss of consciousness, headache, light-headedness, dizziness, confusion and feeling intoxicated, breathing difficulties (shortness of breath, tightness in chest, respiratory failure), increased heart rate and palpitations, nystagmus, irritation (eyes, nose and upper airways).

Consequently, due to all of the above listed physical and psychological manifestations, the phenomenon described through the term ‘syndrome’ is used. Many general medical practitioners are unaware of Aerotoxic Syndrome and may diagnose sufferers with illnesses such as psychological or psychosomatic disorders.

Although some of these disorders may form part of Aerotoxic Syndrome, such part-diagnoses on their own miss the root cause of the problem, which is exposure to toxic oil components in a confined space. Furthermore, any misdiagnosis is likely to lead to inappropriate treatments, which may make the condition even worse.

Aviation medicine specialists are aware of the problem but Aerotoxic Syndrome does not seem to have gained official acceptance among the majority of them. Hence, despite (or because of) their expert knowledge they are likely to seek other explanations and there are plenty of neurological symptoms associated with aviation that have nothing to do with inhaling oil.

As the toxins attack the central nervous system, including the brain, it’s not easy to predict how different exposures may affect different people, due to the genetic variability of individuals. Hence, one person’s body may have less success than another’s at detoxifying contaminants and so be affected after just one flight, whilst others may be unaffected after years of exposure. Depending on detoxifying efficiency, the adverse health effects may be cumulative. Therefore, anyone frequently flying (which means once or more a week) is repeatedly exposed and is therefore especially at risk.

10. Mirce-mechanics Impact of Aerotoxic Syndrome

Aerotoxic syndrome presents significant issues regarding the health of pilots, cabin crew and passengers, but most notably with regard to safety if pilots are incapacitated and cabin crew cannot supervise cabin evacuations during emergencies. Health effects include short-term irritant, skin, gastrointestinal, respiratory and nervous system effects, and long term central nervous and immunological effects. Some of these effects are transient, others appear more permanent. The exacerbation of pre-existing health problems by toxic exposures is also highly probable. Thus, the aerotoxic syndrome has potential to generate a failure of commercial aviation flights and such has impact of functionability performance of maintainable systems.

In the past, safety systems have focused on the prevention and alleviation of accidents. Having achieved a largely accident-free state, attention can now turn to ensuring wellbeing to flight crew and frequent flyers passengers. Thus, some of the existing Mirce-mechanics method could be applied to reduce the probability of inhaling aerotoxic. Hence, some of the following options are available to the designers and operators of aircrafts [1]:

1. Eliminate toxic components from jet oil. Although this was tried, it is proving remarkably difficult to achieve the same high-temperature antiwear properties. Recent progress in understanding the molecular mechanisms of antiwear action gives grounds for some optimism

2. Incorporate filters or adsorbents in the air line between the bleed off the engine and the entry into the cabin. One problem with this approach seems to be that the existing spectrum of technologies are designed either to eliminate dust using through micro-porous membranes, or to eliminate small molecules via adsorption on the surface of a substance with a high specific surface area and broad nonspecific affinity. Another problem is that both filters and adsorbents become saturated and, therefore, need regular replacement

3. Eliminate bleed air by compressing the air using a separate compressor, as it was achieved on early jet airliners such as the Vickers VC10. However, the same approach is used during the design of the latest Boeing 787 “Dreamliner”. There may be additional reasons for doing this, such as the need to eliminate flows of hot air through a structure incorporating many novel composite materials.

4. Screen aircrew and passengers for susceptibility to organophosphate poisoning. It would appear that susceptibility is genetically determined; it depends on the available and potentially available variety and quantity of cytochrome P450 enzymes in the liver. There are possibly different degrees of susceptibility, according to which the occupational risk, or risk from frequent flying, may be too great or even a single flight might constitute an unacceptably high risk of health damage.

5. Retrofit sensors for continuously monitoring chemical contamination of the cabin atmosphere. There is already a considerable literature on measuring aerotoxic contamination, and even a personal sensor has been proposed. Given the general needs for non-interference with aircraft control systems and miniaturization, integrated optical nano-sensors would appear to be called for. Sensors should be provided in the bleed air ducts and at various points in the cockpit and passenger compartments. The sensors would firstly provide an objective physicochemical indication of the presence of contamination, and secondly they would provide information to guide the captain in deciding what action to take

6. Educate aircrew more comprehensively about the issue, especially so that they recognise the symptoms of incipient oil seal problems and can promptly take appropriate action like:

donning oxygen masks, landing at the next available aerodrome, ordering passengers to don activated carbon masks and so forth.

7. Issue activated carbon masks, preferably with filtration or adsorption capability, to all passengers, to be donned should a "fume event".

8. Facilitate prompt reporting of any suspected oil leakage into the cabin so that appropriate engine maintenance can be carried out without delay. In addition, the development of biomarkers for intoxication, which will assist prompt diagnosis and the application of appropriate therapy to passengers and aircrew having experienced a fume event.

11. Conclusions

Direct exposure to hydraulics and lubricants are known to be toxic, causing effects such as blurred vision, disorientation, memory loss, lack of coordination, nausea that if they occurred in flight crew, are direct threats to flight safety. Further, there is factual evidence that flight deck, cabin crew and passengers can be directly exposed to trace chemicals on aircraft in sufficient concentrations to cause acute, immediate to long term symptoms.

These exposures can produce symptoms of toxicity. Symptoms associated to the aerotoxic syndrome clearly include neurotoxicity as neuropsychological effects, as well as other symptoms typically correlated to chemical intoxication. Links between neurotoxic effects and certain contaminants known to be neurotoxic (such as the phosphate esters) are suspected.

Aerotoxic syndrome presents significant issues with regard to the health of pilots, cabin crew and passengers, but most notably with regard to air safety if pilots are incapacitated and cabin crew cannot supervise cabin evacuations during emergencies. Health effects include short term irritant, skin, gastrointestinal, respiratory and nervous system effects, and long term central nervous and immunological effects. Some of these effects are transient, others appear more permanent. The exacerbation of pre-existing health problems by toxic exposures is also highly probable.

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Simultaneous Multiaxis Shaking

Wayne Tustin, Equipment Reliability Institute,
1520 Santa Rosa Avenue, Santa Barbara, California 93109 USA

"Testing leads to failure, and failure leads to understanding." - Burt Rutan

Over about 60 years, first in Connecticut with an electrodynamic shaker (MB) manufacturer, then travelling the world from a California base as Tustin Institute of Technology, then as Tustin Technical Institute and currently as Equipment Reliability Institute, I've had the pleasure of introducing new instrumentation and test engineers and technicians to the basics of mechanical vibration.

Many of those test engineers and technicians progressed to conducting vibration tests, using mechanical, servo-hydraulic and electro-dynamic shakers. Their supervisors hoped that those tests simulated (and slightly exceeded) "real world" seismic, vehicular and/or flight vibrations. If their hardware survived the specified vibration test, it was hoped, their hardware would survive "real world" in-service vibrations.

But how could that be? The *vast* majority of shakers vibrates nominally in one-axis-at-a-time. Even though, when we measure "real world" vibrations, usually using numerous accelerometers, we find simultaneous-all-axes vibrations. So that several (at least three) shakers must *simultaneously* shake our hardware. Multiple-shaker systems, recently become available, are finding more of our existing hardware weaknesses.

Simultaneous multiaxis shaking. When will your lab commence?

About the Author:
Wayne Tustin was introduced to vibration and shock testing at Boeing Company in Seattle 1948-53, then sales, field service & technical training (vibration and shock test training) at MB Electronics (later reorganized as MB Dynamics) at New Haven, CT (shaker manufacturer) 1954-61, very briefly at Raytheon/Santa Barbara, CA 1961-62, then started the Tustin Institute of Technology/Santa Barbara, CA 1962-90, retired 90-95. Founded Equipment Reliability Institute/Santa Barbara, CA (ERI) 1995-present. Currently teaching ERI short courses and distance learning regarding vibration & shock measurement and laboratory testing, some consulting. Practical up-to-date instruction, nothing similar available at universities. Hardcover text "Random Vibration & Shock Testing" ISBN 0-9741466-0-9 nearly gone. Writes magazine articles. Contributes to ERI's Reliability Newsletter. See http://goo.gl/xNWC49 re series of 33 iBooks for iPads (#1 is free).

Specialties: Introduce engineers, technicians to vibration and shock testing, measurement, analysis & calibration via on site/company short courses listed at http://www.equipment-reliability.com, under Training/Onsite Courses. Also through "open-to-public" courses (under Training/Open Courses). Distance learning via CD + e-mail lesson correction (under Training/Distance Learning). Phone, gotomyPC & e-mail consultation. Visit the website to see my 2005 hardcover text on Random Vibration and Shock Testing.

Troubleshooting as a Mechanism of Motion in Mirce-mechanics

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

Abstract

The purpose of a paper is to address the troubleshooting, an activity performed by maintainers to identify failed component or module, as a mechanism of the motion of a maintainable system through the Mirce spacetime. For effective maintenance troubleshooting, as one of the main drivers of the "speed" of moving through negative functionability state, is essential element of any corrective maintenance task. To successfully perform troubleshooting tasks maintainers must possess both the knowledge and skills to find and fix problems efficiently. Many years of research, on-the-job observations, and common experience have demonstrated that it is much easier to teach and learn manual skills than troubleshooting skills. The paper clearly demonstrates that troubleshooting is a complex subject as it is driven by both sides of equation, namely system designers that conceive troubleshooting processes and maintenance managers that manage them during the life of a maintainable system.

1. Introduction

The human constituents of a maintenance process, either as a decision maker or as a task executor, bear the ultimate responsibility for recognising, interpreting, compensating for, and correcting or mitigating the consequences of deficiencies and faults of a maintenance process. [1] Full understanding of these phenomena's is only possible by understanding physical mechanisms that lead to the successful execution of maintenance tasks.

In general, troubleshooting is the identification of diagnosis of "trouble" in the operation of a system caused by any failure whatsoever. The problem is initially described as symptoms of malfunction, and troubleshooting is the process of determining and remedying the causes of these symptoms. Determining the most likely cause is a process of elimination – eliminating potential causes of a problem.

Every maintainer is responsible for performing the full range of maintenance tasks. However, not all tasks count equally in determining whether or not a maintainer is doing a good job, from the operational point of view. The basis for judging the efficiency and effectiveness of a maintainer is the ability to find and fix problems efficiently. Troubleshooting is the very first step in that direction. Hence, in today's competitive air carrier business environment, maintenance organisations are judged on their ability to keep aircraft safely in the air, not how good they are in the hangar.

Maintainers must possess both the knowledge and skills to find and fix problems efficiently. These requirements are essentially no different than those for medical doctors and any other profession or craft that involves both diagnostic and manual skills. As one might expect, the most valued maintenance abilities are also the most difficult to acquire and practice. Many years of research, on-the-job observations, and common experience have demonstrated that it is much easier to teach and learn manual skills than troubleshooting skills. [2]

Troubleshooting is a complex subject as it is driven by both sides of the equation, namely system designers that conceive troubleshooting processes and maintenance managers that manage them during the life of a maintainable system.

Consequently, in this paper the troubleshooting as a mechanism of the motion of a system through negative functionability state, is addressed together with some fundamental human factors concepts related to this extremely important element of a maintenance process, as both are driving forces for the in-service reliability, cost and effectiveness.

2. Mirce-mechanics Overview

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

Experience teaches us that due to complex internal interactions within the system, external impacts from environment and human actions, variety of mechanical, electrical, chemical, thermal, radiant and other types of energy are generated, some of which cause the failure of systems to deliver a function. To maintain f**unctionability**[11] actions like servicing, repairs, inspections, replacements and similar, are undertaken by humans, which make them maintainable systems. Thus, the life of a system could be considered as a motion through positive and negative functionability states through time, which is physically, manifested by occurrences of corresponding functionability events. Unlike accurate quantitative information regarding the design-in performance of systems that is available on the delivery day, the in-service performance is not. Instead, years later the statistics for various functionability measures become available. The reason for this is the fact that they are characterised by uncertainty, discontinuity, irreversibility, inseparability, and dependence of time, location and humans, and as such non predictable by existing laws of science.

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

- Determine the trajectory of the motion of a system through functionability states through time, which is uniquely defined by the sequence of occurrences of positive and negative events, together with the statistics of the work done by the systems and on the system[12]

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

[12] Boeing 747, registration number N747PA, been air born 80,000 flying hours, transported 4,000,000 passengers, burned 271,000,000 gallons of fuel while receiving 806,000 maintenance man-hours and

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

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

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

3. Corrective Maintenance task as a Negative Functionability Event

The second axiom of Mirce-mechanics states: *“the probability of failure of a system to deliver a measurable function at any interval of time is greater than zero”*. Hence, at random points in time when the system is operating, failures are likely to occur and will be detected by the operator through visual, audio, and/or physical means. The operator proceeds to notify the appropriate maintenance organisation that a problem exists.

The maintainer(s) assigned to deal with the problem must analyse the situation and verify that the system is indeed faulty. In some instances, the fault will be obvious, particularly in dealing with mechanical or hydraulic systems when a structural failure has occurred or a fluid leak takes place. On other occasions, the maintainer must operate the system and attempt to repeat the condition leading to failure occurrence. This is often the case for electronic equipment when the failure is not always obvious.

Generally speaking, during the life of any maintainable system, corrective maintenance commences with the identification of a failure symptom such as the system does not work, the hydraulic system leaks, the engine does not respond in terms of power output, no voltage indication on the front panel meter, and so on. Based on a symptom of this nature, the maintainer proceeds to troubleshoot and accomplish the necessary maintenance tasks.

4. Troubleshooting Activities

Troubleshooting may be extremely simple or quite complex. For example, if a hydraulic leak is detected, the source of the leak is often quite easily traced. On the other hand, the failure of a small component in radar or computer equipment is not readily identified. In this instance, the maintainer must accomplish a series of steps in a logical manner, which will lead him or her directly to the faulty item. However, at times, these steps are not adequately defined and the maintainer is forced into a trial-and-error approach to maintenance. A good example is

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consuming: 2,100 tyres, 350 brake systems, 125 engines, among other parts, during the 22 years of in-service life, at Pan Am airlines.

when the maintainer starts replacing parts on a mass basis (without analysing cause-and-effect relationships) hoping that the problem will disappear in the process. This of course, affects maintenance downtime and spare/repair part needs, as the maintainer may replace many parts when only one of them is actually faulty.

To preclude the possibility of wasting time and resources when the system is deployed in the field, the system design must provide the necessary characteristics to enable the maintainer to proceed in an accurate and timely manner in identifying the cause of failure. Such characteristics may constitute a combination of go/no-go lights, test points, meters, and other readout devices providing the necessary information, which allows the maintainer to go from step to step with a high degree of confidence that he or she is progressing in the right direction. This objective is one of the goals of the maintainability engineers during the design process. This facet of the analysis is best accomplished through the development of logic troubleshooting flow diagrams, including go/no-go solutions on a step-by-step basis, and supported by diagnostic software where applicable.

The analyst should review failure mode and effect analysis data to determine cause and affect relationships, and then proceed to list all of the major symptoms which the system is likely to experience. [1]For each symptom, various troubleshooting approaches are analysed in terms of maintenance time and logistics resources, and the best approach is selected. The analysis process is accomplished through the generation of logic troubleshooting flow diagrams in conjunction with the completion of maintenance task analysis sheets and for the troubleshooting requirement.

4.1 Troubleshooting Practises

Since its establishment, staff, students and fellows of the MIRCE akademy has analysed tens of thousands of maintenance task, including the troubleshooting activities. Some of the most common practises are presented below.

4.1.1 Consistent Fault Set

Consistent Fault Set, CFS, *is* one of the names given to the group of all possible failures that can reasonably explain a given set of trouble symptoms. The name comes from the fact that the group contains faults "consistent" with the symptoms. For example, when a car engine does not start, the **CFS** could contain an ignition failure, or fuel problem, but would not contain a failed seat back adjustment control.

4.1.2 Decision Tree

One type of maintenance job performance aid is called a "decision tree". A decision tree is a printed or computerised chart that directs the maintainer along a logical testing and diagnosis path for a particular system or product. After each test or observation, the decision tree branches to another test, or conclusion, based on the test results. An easy characterisation of a decision tree is a series of "if-then" statements, like “If the voltage is below 'x,' then do this."

4.1.3 Easter Egging

One method of troubleshooting is to replace various modules and components until the symptoms of trouble disappear. This method is known as "Easter Egging" because a maintainer never really knows where he or she will find the failed part. Easter Egging is an extremely inefficient, expensive way to find a problem.

4.1.4 Einstellung

Einstellung, also known as Psychic Blindness, describes a phenomenon discovered in the early 1940's and since shown to exist in different domains. It has been found that when people have spent time solving one particular type of troubleshooting problem, it is virtually impossible for them immediately to diagnose a different type of problem. Interestingly, this phenomenon holds even when people are told that they will see a new and different type of malfunction.

4.1.5 Test-Induced Failure

When a maintainer performs a functional test on a system or component, there is some probability that the test will cause a failure. Thus, a maintainer must balance the need for functional testing against the likelihood of a test-induced failure.

Even further, test-induced failures are safety risks only when they remain undetected. That is, a maintainer can test a subsystem, find it functioning properly and turn it off. If there is a test-induced failure, the component will be left in a failed state and will not work the next time it is needed.

4.1.6 Tunnel Vision

Tunnel vision describes viewing a situation as though through a tunnel, which means seeing in only one direction and being blocked from seeing information coming from other directions. In the maintenance domain, tunnel vision is a well-known occupational hazard.

Once a trouble-shooter thinks he or she knows what is causing a problem, information that might disprove the hypothesis tends to be given less weight than information confirming it. *“You cannot teach a person who knows that he knows.”*

One of the most common causes of tunnel vision in aviation maintenance is maintainers' use of problem reporting information that goes beyond describing symptoms to suggest a cause.

4.2 Expert System

Expert systems are diagnostic decision-making aids used in a number of different domains, including medicine, geological exploration, and maintenance. Expert systems are usually computer-based. They are generally developed by embedding a set of rules acquired from human experts. For example, if an expert system for diagnosing problems in aircraft braking systems is to be developed, the first step would be to determine how human experts do such diagnosis and then put these "rules" into our expert system.

Expert systems in aviation maintenance are commonly embedded in computer-based training systems or diagnostic equipment.

4.3 Heuristics Algorithms

Heuristics, commonly known as rules-of-thumb, troubleshooting algorithms are another method that could improve the efficiency of troubleshooting. Rules-of-thumb represent the distilled wisdom of maintainers who over a long period of time became experts in the troubleshooting process for specific type of systems, modules or components.

Rules-of-thumb vary, depending on the specific component or system. An example of them is a “wisdom” confined in the following statement: "If the symptoms include a low pressure indication, then always check the pressure sender unit first." Embedded expert systems depend on a rule base developed by consulting expert trouble-shooters.
Algorithms are usually unwritten procedures telling trouble-shooters generally how to proceed. Some research studies show that troubleshooting performance improves when maintainers are reminded, in general terms, what they should do first, second, etc. For example, a general algorithm might require a maintainer to gather information related to failure symptoms, to generate as many hypotheses consistent with the symptoms as possible, to prioritise the hypothesis set, etc. Such general algorithms seem to have the effect of dissuading maintainers from deciding on a specific failure being the cause of the symptom before they have enough information.

5. Troubleshooting constraints

Like all other processes, which convert inputs into output, by using certain resources, troubleshooting process is also impacted by certain constrains, some of which are briefly presented below.

5.1 Environment

Most troubleshooting tasks are conducted in work settings that include noise, heat or cold (or both), limiting lighting, cramped physical spaces, work during nighttime hours and so forth. These environmental factors have all been found to affect troubleshooting performance, albeit sometimes unpredictably.

Also, it is worth pointing out to “the obvious” impact factors, like:

- The work in very hot or very cold environments causes maintainers to lose their ability to concentrate and to perform logical operations such as inductive reasoning.

- The impact of noise affects novice and expert trouble shooters differently. A study of the effects of noise on troubleshooting performance found that high noise levels degraded experts' performance, but “enhanced novices'. Possibly, the high noise levels caused novices to stay alert and pay more attention to problems, whereas the noise simply distracted experts.

5.2 Time Pressure

Many troubleshooting tasks are performed under time pressure. Obvious examples are departure gates at airports, maintenance boxes in pit lane during car races, military operational theatres, and similar.

Research performed has shown that the time pressure degrades both novices' and experts' troubleshooting performance. This degrading effect is present even for troubleshooting tasks performed in laboratory settings with abstract "systems."

According to Hessburg part of chief mechanic job, at Boeing Company, is education. It is his task to make people aware of the environment in which mechanics operate. “It’s not that designers are stupid, but they’re inexperienced on this side of business. For example, they have to learn that there are different types of maintenance. Anyone can maintain an airplane component or system on the bench. However, the gate environment is very much result and schedule driven. That’s different type of maintenance” Knezevic (1998).

5.3 Experience

Experience is an area of individual difference research where findings support the common-sense view that more experience leads to better troubleshooting performance. As with other skills acquired over time, experience enhances one's ability to learn from new troubleshooting experiences. Much research in this area has been conducted in the aviation maintenance domain; this fact alone should make the research results directly applicable to the guidance we provide.

However, it is necessary to point out that while experience enhances troubleshooting performance, its advantages do not hold under all conditions. When certain job aids or specific troubleshooting procedures are employed, performance differences between experienced and novice trouble-shooters tend to disappear.

5.4 Individual Differences

People differ both physically and psychologically. In the troubleshooting domain, a number of individual differences have been studied. These include cognitive style, general ability, aptitude and similar.

Cognitive style is a general term used to classify people into categories related to a particular psychological variable. For example, common "scales" used in cognitive style research include "reflective-impulsive," "field dependent-field independent," "passive-aggressive," etc. If it could be shown that people with particular cognitive styles make better troubleshooters, this could be applied profitably to the personnel selection process.

While cognitive style has been shown to affect troubleshooting performance, the link between troubleshooting performance and general ability and aptitude is rather tenuous. Levels of ability and aptitude are generally inferred from scores on qualification tests design to measure specific characteristics of individuals. These measures have a fairly strong relationship with the time required to complete instructional modules and to the ability to use certain job aids. However, troubleshooting skills tend to be acquired over long periods. As individuals have an opportunity to work on actual systems, small performance differences related to initial abilities and aptitudes tend to disappear.

6. Reducing Troubleshooting Errors

Troubleshooting errors are the bane of most maintenance organisations. In fact, troubleshooting is notoriously error-prone. The fundamental complexity of many technologically modern systems contributes to the number and type of errors observed in actual troubleshooting tasks. There are also human traits that contribute to relatively poor troubleshooting performance.

Various strategies can be used to reduce troubleshooting errors. From both organisational and human factors perspectives, each technique has its advantages and disadvantages. The following techniques appear to hold the most promise for error-reduction:

· Teaching the theory of operation for systems and components, without also teaching how to use that knowledge to troubleshoot.
· Observing examples of specific troubleshooting experiences.
· Teaching non-specific troubleshooting techniques.
· Classroom instruction, in general.
· Non-interactive computer-based instruction.
· Teaching from technical manuals.

Although many issues and problems are associated with troubleshooting the following three troubleshooting issues that seem to pervade majority of maintenance organisations.

6. 1 Proceduralisation of Troubleshooting

Proceduralisation can improve troubleshooting performance. When troubleshooting is properly proceduralised, performance differences between expert and novice trouble-shooters can be virtually eliminated. However, as with any other endeavour, there are good and bad procedures. More accurately, there are procedures improving performance and procedures with either little effect or that actually degrade performance.

Proceduralisation must be preceded by a thorough analysis of relevant troubleshooting tasks to determine what each troubleshooting step tries to accomplish, what information is required and produced, and what tests or tools should be used. As with certain aspects of automation, it is possible to proceduralise to the extent that human maintainers are left with an essentially mechanical role. It is necessary to stress that:

- Troubleshooting procedures exist in an overall organisational and work environment.
- Good procedures are worthless if they are used improperly or ignored.

Although maintenance procedures serve various purposes, reduction of errors is certainly an implicit goal of all such procedures and as such they should be:

· **Specific** - Procedures should be written for a specific component, system, or piece of test equipment.
· **Clear** - The terminology should be consistent with the language commonly used by the people who will complete the procedure.
· **Explicit** - Tell users what they are supposed to do. Do not depend on maintainers to read between the lines.
· **Detailed** - Include all required steps in the procedure. Don't assume that maintainers will know the entire sub steps required to achieve a specific system state.

- **Accessible** - Procedures must be stored in a place and manner so they are easy to obtain.
- **Usable** - Procedures must exist in a format and on media that make them easy to use while maintainers perform the tasks they describe.

6.2 Training

Maintenance researchers and practitioners have long recognised that one of the most difficult aspects of troubleshooting is teaching and learning it. The questions researchers have attempted to answer, with variable success, include the following:

- What content should be taught?
- How should it be taught?
- What part should on-the-job experience play in training?
- Are simulators appropriate for troubleshooting training?
- Should troubleshooting training be equipment-specific or general?
- Do troubleshooting skills deteriorate with time?
- Is refresher training required?

6.2 Incorrectly Identified Failures

Large proportion of failures causing Line Replaceable Units, **LRU**s to be pulled during line maintenance turn out to be Can Not duplicate, **CND**, or sometimes called non-reproducible. However, it would be wrong to conclude that all CNDs are caused by line maintainers' improper troubleshooting. Built-in test algorithms in LRUs often leave line maintainers with no choice but to replace the module. In other instances, incorrect troubleshooting is caused by a number of conditions that have nothing to do with maintainers' ability to test and diagnose. For example, failures are sometimes reported by flight crew members or other third parties. The initial reports often incorrectly attribute cause.

Regardless of the cause, incorrect troubleshooting is a common and repeating problem across majority maintenance organisations, which is manifested in increasing repair time and making the maintenance process inefficient.

6.3 Simulation-Oriented Computer-Based Instruction

Simulation-Oriented Computer-Based Instruction, **SOCBI**, is one of the most diligently studied training methods that combine many elements for success in troubleshooting training. Work in SOCBI began in the aviation maintenance domain in the late 1970's. SOCBI provides students with a two-dimensional, interactive depiction of the particular system or component that they are learning to troubleshoot.
If the component is small enough, an SOCBI module can actually show a picture of its controls and displays,

Students use the working controls and displays to practice diagnosing a number of faults built into the simulation, which are usually randomly occurring. **SOCBI** modules also contain diagrammatic, i.e., logical, representations of the system being taught. These functional/logical diagrams teach students how a system is functionally connected and allow them to use logical troubleshooting algorithms such as half-splits.

Effective **SOCBI** allows students to acquire diagnostic information from the same sources available in the work environment. Students must be able to observe indications, such as lights and gauges; to perform specific tests on the system; to receive verbal reports from flight crew members, etc.

A number of **SOCBI** systems have been compared with more traditional training methods such as classroom instruction and demonstrations of actual equipment. In these studies, SOCBI produces troubleshooting performance as good as, or better than, that produced by less-efficient techniques

6.4 Practice

That "practice makes perfect" has been proven for troubleshooting tasks. The major factor distinguishing expert troubleshooters from novices is experience, i.e., practice.

Troubleshooting is a complex skill with cognitive and manual elements. As is true of all such skills, troubleshooting proficiency cannot be attained simply by reading books or by listening to someone explain what to do. Providing opportunities for meaningful practice is a valid, relatively inexpensive method to reduce troubleshooting errors.

Regardless of which training method, or combination of methods, one uses to teach troubleshooting skills, students must be given an opportunity for practice. To be meaningful, troubleshooting practice should:

· Pertain to the equipment that will actually be maintained on the job
· Be done using mock-ups that provide the same types of information as the real system
· Allow students to gather information from the same sources as in the actual work environment
· Provide feedback regarding the outcome of various tests and other actions
· Allow students to know how long their actions would take in the actual work environment

However, troubleshooting practice does not have to be on real equipment; in fact, real equipment is often an inefficient practice medium with the following drawbacks:

- It is difficult to know the precise nature of failures embedded in real equipment
- Experts often disagree as to the appropriate troubleshooting path(s) for failures in real equipment
- Using real equipment as practice aids prevents the equipment from being used to support operations
- Errors made while troubleshooting real equipment can have safety implications
- For failures to be intentionally embedded in real equipment, someone has to embed the failures, check the equipment when practice troubleshooting is complete, and ensure that only controlled failures are present.

6.5 Context-specific knowledge

Many maintenance skills are generalisable from one domain to another. For example, skill in the use of tools for repairing automobile engines is directly applicable to using tools to repair turbine engines. However, troubleshooting skills tend to be context-specific. The ability to identify problems with a television set does not directly transfer to troubleshooting avionics modules. When teaching troubleshooting knowledge, it is important to provide specific information, which should be:

- **Simple** - Students will not be able to remember long, involved troubleshooting procedures. Break these procedures into simple, serial steps. If there is no easy way to decompose a troubleshooting process, then supply a written procedure.
- **Specific** - Relate troubleshooting steps to the component(s) on which students will be working. For example, don't tell students how to perform a general half-split test. Tell them how to do a half-split on the antiskid controller.
- **Explicit** - Tell students how you expect them to use the information you are providing. Don't rely on them to guess how it should be used.
- **Heuristic** - There are almost always rules-of-thumb for troubleshooting specific components or subsystems. Describe them for the students.

7. Conclusions

The purpose of a paper is to address the troubleshooting, an activity performed by maintainers to identify a failed component or module, as a mechanism of the motion of a maintainable system through the Mirce spacetime. For effective maintenance troubleshooting, as one of the main drivers of the “speed” of moving through negative functionability state, is essential element of any corrective maintenance task. To successfully perform troubleshooting tasks maintainers must possess both the knowledge and skills to find and fix problems efficiently

Troubleshooting is a form of problem solving, applied to the motion of maintainable systems through Mirce Spacetime. It is a logical, systematic search for the source of a problem in order to solve it, and so the product or process can be made operational again. Troubleshooting is needed to the symptoms. Determining the most likely cause is a process of elimination – eliminating potential causes of a problem. Finally, troubleshooting requires confirmation that the solution applied has return a system into positive functionability state.

In general, troubleshooting is the identification of “trouble" in the system caused by a failure of some kind. The problem is initially described as symptoms of malfunction, and troubleshooting is the process of determining and remedying the causes of these symptoms.

Many years of research, on-the-job observations, and common experience have demonstrated that it is much easier to teach and learn manual skills than troubleshooting skills. The paper clearly demonstrates that troubleshooting is a complex subject as it is driven by both sides of the equation, namely system designers that conceive troubleshooting processes and maintenance managers that manage them during the life of a maintainable system.

As it is true of all skills, troubleshooting proficiency cannot be attained simply by reading books or by listening to someone explain what to do or watching a video.

8. Acknowledgment

This paper is dedicated to the memory of Jack Hessburg (1934-2013), whose unique experience in aviation made him the “king” of troubleshooting, on both sides of the equation. As an in-service engineer with a degree in Aircraft Maintenance Engineering he learned his troubleshooting skill in day-to-day operations of airlines, worldwide. As Chief Mechanic on the development of the Boeing 777, with a degree in Mechanical Engineering, he was responsible for the design of troubleshooting process that is “friendly” to the gate mechanic, whose responsibility it is that “airplanes go on time and never crash.” [2]

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Book Review

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Review by Dr J. Knezevic, MIRCE Akademy, Woodbury Park, Exeter, UK.

Behaviour of swarm of bees, birds, fish and other animals is frequently used to illustrate the behaviour of complex systems. Unique property of this behaviour is an emerging performance and power of the swarm resulting from the strong interactions of a large number of contributing elements. This book is the best example of that type of behaviour. It is consists of 19 chapters, each of which standing alone is inadequate to represents the beauty, power and necessity of understanding and managing complex systems. However, all together .nicely interwoven, represent a beautiful book that tells the unique story created by two talented researches and entrepreneurs.

The book is a product of the new way of looking and understanding the behaviour of the systems around humans that, up to now, have been characterised as either deterministic or probabilistic. Authors, in the opening chapter, clearly delineated the existence of the large number of systems in domains of banking, natural environment, politics, technology, communication, transportation, engineering and others that shape our lives, in the manner where the future is neither uniquely and precisely determined, nor is "totally unpredictable", which is defined as the random behaviour. This realisation ignited a curiosity spark that guided both authors towards research focused on the understanding of this complex behaviour of surrounding systems. The research performed culminated in the creation of the new body of knowledge, necessary to assist humans in day to day living in and being subjective to the emerging behaviour of these systems. Seven criteria of complexity, identified by the authors, clearly defined unique behaviour of complex systems that led them to the conclusion that their emerging behaviour cannot be controlled, but it could be managed "*by coping with external complexity and tuning internal complexity*".

Methods for managing complexity, according to the authors, should be focused on the creation of the adaptive properties of complex systems. The process of "engineering" adaptability of complex systems has been clearly presented in this book, through seven interrelated and integrated steps. This uniquely led to the creation of multi-agent technology, which is a software technology dedicated to the creation of the virtual world in computers where agents communicate, collaborate and create information that is used in the real world for decision-making under constrains like budget, weight, time, volume, distance or combination of them.

Finally, the large number of real commercial applications, developed and applied by the authors and their team of programmers, which used methods and "tools" presented in the book, clearly demonstrate their befits to the daily lives of humans. The examples presented are related to the process of managing complexity of manufacturing systems, space station operation, aircraft wing design, London taxies scheduling, high-speed railway planning, adaptive management of service teams, to mention a few, all of which have delivered the monetary savings, increased safety and reliability of operations, better utilisations of resources available, higher customers satisfaction of other measure of the key performance of complex systems considered.

At the end of the book, authors clearly have presented their view of the future that is continuous increase in complexity of systems, which could be managed only by extensive, internet based, connectivity of “things” within the complex systems, which will start communicating and managing the system complexity without involving humans. Hence, in the view of authors, cars, trucks, railways carriages, airplanes, plants, shops, warehouses, spare parts, assemblies pallets and “million” other things will drive complex systems of the future through exchange of information in real time, all the time, leading to autonomous decision-making.

In summary, this book represents the new view of the systems that drive business world whose complexity has exceeded the capability of humans, however experienced and motivated, to manage it in the manner that improve business outputs regarding any criteria that is consider important. It is original, it is refreshing, it is brave and it will benefit all those who are able to change their minds, based on the current, well established and hardly ever challenged, believe that future is predictable and controllable.

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