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2014 Annals of MIRCE Science

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

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

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Mirce-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 **functionability**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 Academy at Woodbury Park. Staff, Fellows, Members and students of the Academy 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.

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 functionality trajectory of the future transportation, communication, navigation and many other maintainable systems to be made.

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Mathematical Principles of Mirce-mechanics

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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 functionality 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 is the bedrock for the prediction of the functionality performance of maintainable 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 functionality.

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:	$\nabla \times E = \frac{\rho}{\epsilon_0}$	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):	$\nabla \times B = \mu_0 J + \mu_0 \epsilon_0 \frac{\partial E}{\partial t}$	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:

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

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 formulated it in 1925 in the following expression:

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

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 Maintainable 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 design-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 maintainable system.

4. The Concept of Functionability

Thus, the ability of being functional through time, known as **functionability**, is an essential in-service property of maintainable 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 cause the transition from NFS to PFS
- Negative Functionability Events, NFE, which cause the transition from PFS to NFS

Consequently, the life of a maintainable 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 functionality questions the author established the MIRCE Akademy in 1999. Staff, Fellows, Members and students of the Akademy study in-service behaviour of maintainable systems to:

- Physically observe the emerging trajectory of the motion of functionality through the life of maintainable systems and to measure emerging in-service performance
- Scientifically understand mechanisms that cause the motion of a functionality through the life of maintainable 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 functionality states in respect to time constitutes Mirce-mechanics.

The ability to simultaneously predict the design-in functionality performance and in-service functionality 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 maintainable 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 functionality through the life of maintainable 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 functionality state of a system through time. Hence, a life of any maintainable system could be viewed as a sequence of occurrences of positive and negative functionality events that “move” systems through functionality 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:

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

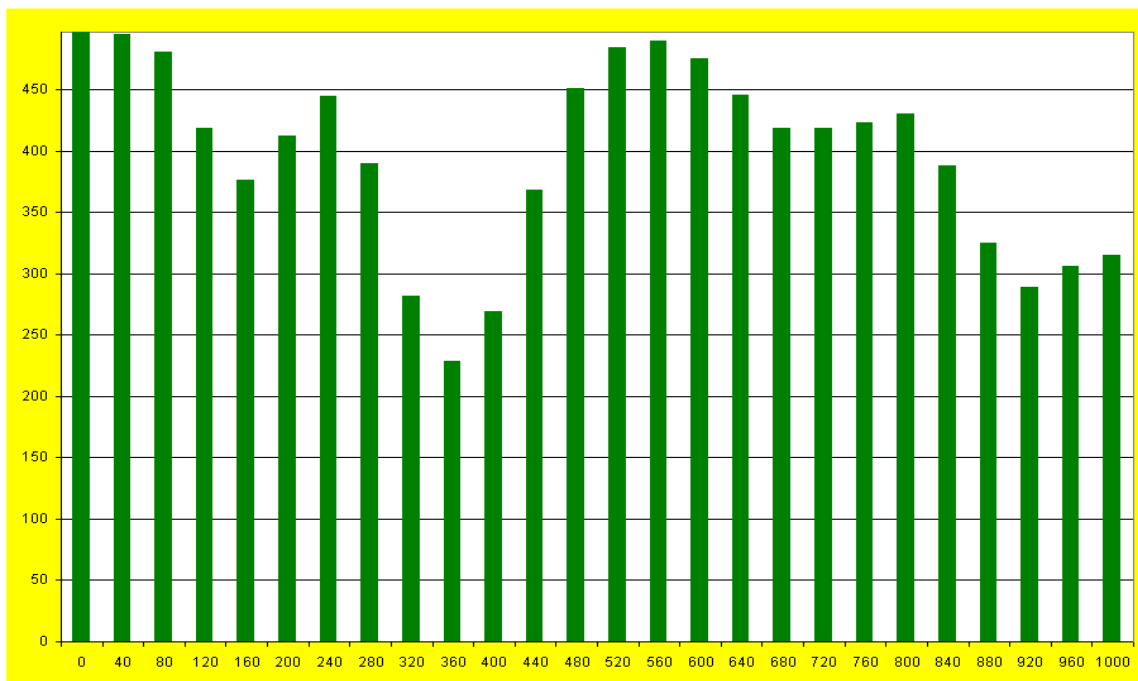


Figure 1: Relative Frequency Histogram of the Motion of Functionability through the life of 497 Systems at specific instances of time

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)	TIPS(Tst)	TINS(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 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.

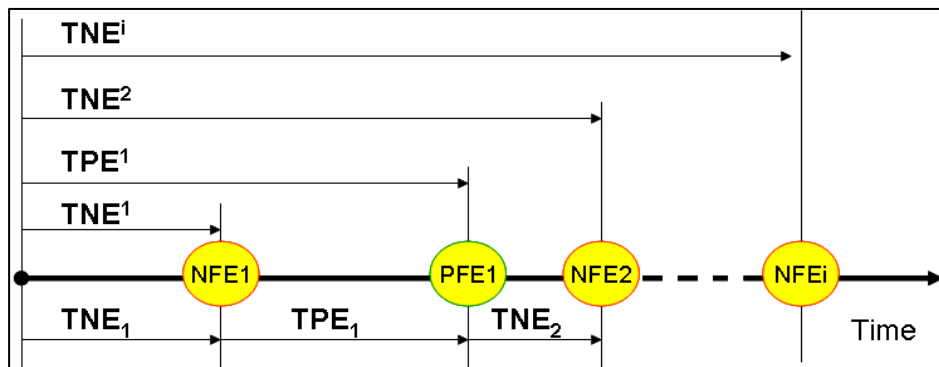


Figure 2: Individual and Cumulative Times to Functionability Events

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

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

$$F_i(t) = P(TNE_i \leq t), \quad i = 1, \infty. \quad 2.$$

Positive Function, $M_i(t)$, which define the probability that the i^{th} PFE will take place before or at instant of time t is defined by the following expression:

$$M_i(t) = P(TPE_i \leq t), \quad i = 1, \infty. \quad 3.$$

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 i^{th} sequential NFE will take place before or at instant of time t , is defined as:

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

Sequential Positive Function, $M^i(t)$, which defines the probability that the i^{th} sequential PFE will take place before or at instant of time t : is presented in the following manner:

$$M^i(t) = P(TPE^i \leq t), \quad i = 1, \infty. \quad 5.$$

Equations 3 and 4 define the sequence of functionability events for any maintainable 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:

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

Making use of equations 3 and 4, while bearing in mind that $M_0(0) = 1$, as a system starts its life in positive functionability state, the above expression of functionability equation could be presented in its final form:

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

where:

$\varphi(t) = \sum_{i=1}^{\infty} P(TNE^i \leq t)$ 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.

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

The author develops this expression and it is named Mirce Functionability Equation. It defines the trajectory of functionability through the probability of a system being in positive functionability state at a given instant of time t.

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

Making use of the equation 1 it is possible to calculate the average functionability over any interval of time, $Y(t)$, by using the following expression:

$$Y(t) = \frac{\int_0^t y(t) dt}{t} \quad 7$$

Average Functionability for a hypothetical example is shown in Figure 4 as the solid area in the plot.

Making use of the equation 1 it is also possible to calculate the expected time that system will spend in PFS during a stated interval of time, $E[TIPFS(t)]$, through the following equation:

$$E[TIPFS(t)] = \int_0^t y(t) dt \quad 8$$

Several other measures of the motion of functionability, which are essential for the system engineering and management could be derived and calculated. In fact any measure of system operational effectiveness could be calculated by making use of the Mirce Functionability Equation.

For the completeness of this paper equation for Negative Functionability trajectory will be presented together with the proof of the total concept. Hence, the probability of a system being in negative functionability state, denote with $n(t)$, could be calculated in accordance to this equation:

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

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.

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

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 red lines represents negative functions.

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

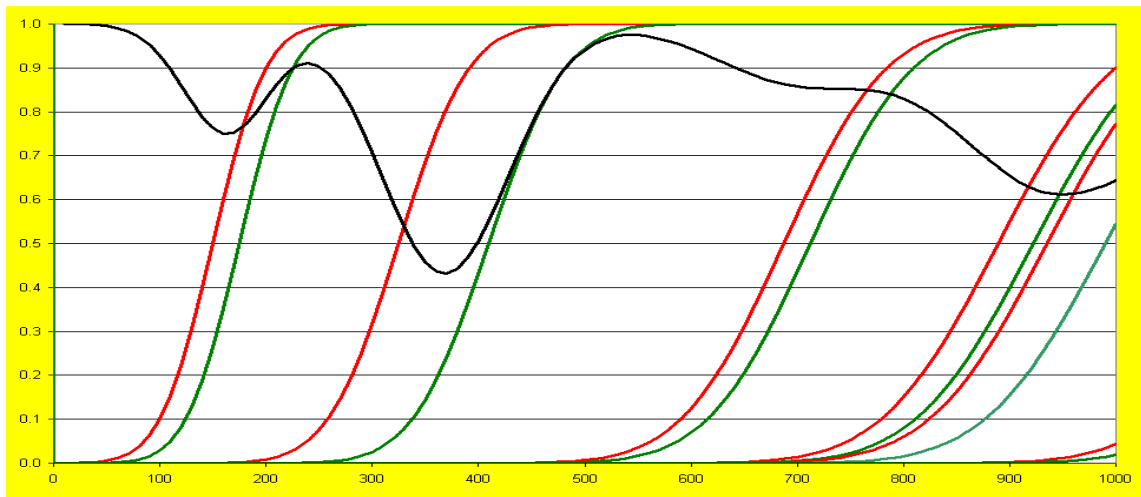


Figure 3: Functionability profile calculated by Mirce Functionability Equation (6) for the Example shown in Figure 1.

At the stated period of operational time, as shown in Table 2, the following functionability measures have been calculated by making of Mirce-mechanics Mathematics presented above.

Tst	MNNE(Tst0)	MNPE(Tst)	TIPS(Tst)	TINS(Tst)	y'(Tst)
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.

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. [9]

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. [10]

For the numerical example used in this paper the result of the application of the Monte Carlo simulation method performed to obtain quantitative solution of the Mirce Functionability Equation is shown in Figure 4 as blue dots.

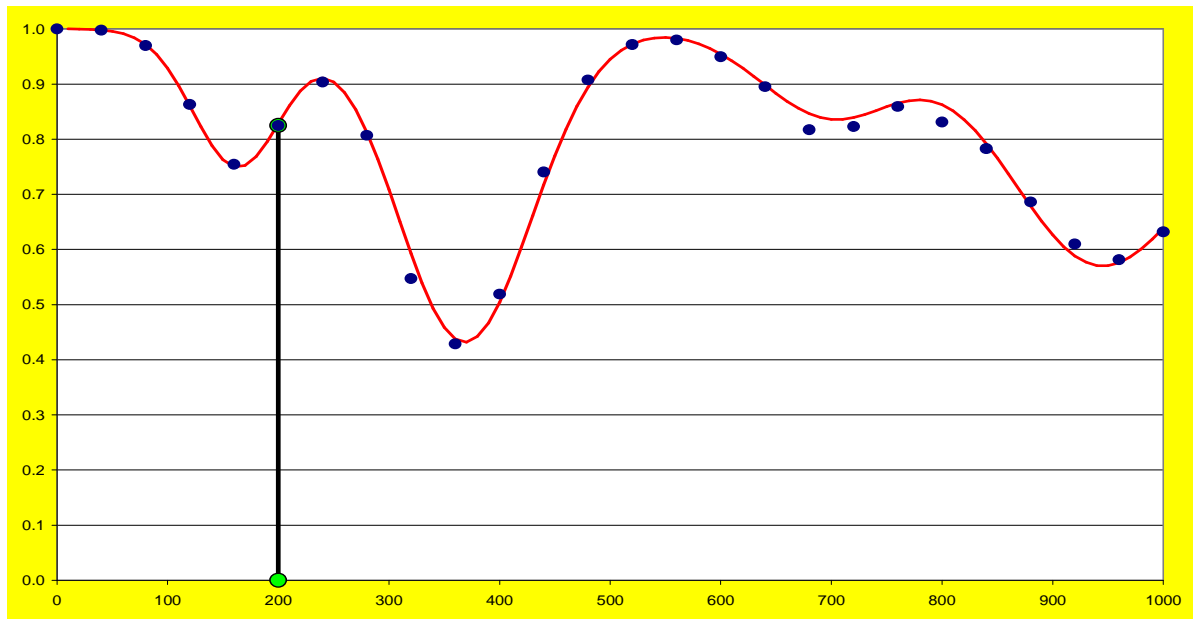


Figure 4: Functionability profile calculated by Mirce Functionability Equation

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

Although science has to be truthful, rather than 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 happen, the science proven method is needed, very much different from the classical scientific knowledge, described through 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 maintainable 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 maintainable system.

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Applied Genetic Programming in a Chemical Plant for Reducing Production Costs

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Abstract

The Genetic Algorithms (GA) is a model of “machine learning”, Goldberg (1985,1989). Whereas classical optimisation methods often rely on a local gradient search, a genetic algorithm keeps track of the population of potential solutions. It is thus less sensitive to an arbitrary initial guess of the solution, which imparts it with a degree of protection from the local optima trap. The GA is a model of machine learning, which derives its behaviour from a metaphor of the processes of evolution in nature. This is done by the creation within a machine of a population of individuals represented by chromosomes, in essence a set of character strings that are analogous to the base - 4 chromosomes that we see in our DNA. The individual in the population then goes through a process of evolution. A genetic algorithm is a trial and error process whose method of producing solutions imitates biological evolution and allows an improvement in the solution. The genetic algorithm has been tested on a variety of problems e.g., a model of an industrial flowability, customer service pH controls system etc.

1. Basic Principle

The basic strategy in a GA is to maintain a set of solution candidates which is called the *population*. Members of the population are picked randomly, biased by on their fitness (i.e the fitter a member, the more chance it as to be picked), to form a mating pool. A new population is generated from the mating pool, where each new solution candidate is created from a pair of candidates (i.e. parents) randomly selected from the mating pool. Some degree of randomness is normally allowed in the generation of offspring (new candidates). Randomness allows the ‘weaker’ building generation to have a chance to survive. One more possibility to continue search solutions efficiently is by ‘mutating’ the offspring.

2. Mechanics of GA

The basic genetic operators consider four basic steps;

a) **Reproduction**- during the reproductive phase of GA, individuals are selected from population and recombined, producing offspring which will comprise the next generation. Parents are selected randomly from the population. Each chromosome in the population is evaluated by the evaluation function, and fitness values for each chromosome are computed by the fitness technique. The method relies on the probability of good individuals being selected several times in a generation.

b) Crossover- recombines the genetic material in the two parent chromosomes to make two children. The children are made by splicing the parents (chromosomes string) at some randomly selected point to produce two 'head' segments and two 'tail' segments thus creating two children (Fig 2-8).

c) Mutation- it is usually considered to play a background role, preventing premature loss of genetic material and compensating for sample error. For binary string, mutation consists simply of changing any bit position in any string from 0 to 1 or 1 to 0. Mutation provides a small amount of random search, and helps to ensure that no point in the search space has a zero probability of being examined.

d) Inversion - The simplest GA does not require an inversion operator. Inversion is operated on a single chromosome. It inverts the order of the elements between two randomly chosen points on the chromosome.

Genetic Algorithms use mutation and crossover to create children who differ from their parents. From scientific point of view new generation contains equation that differ from those in the previous generation and which have higher probability of fitting the data.

3. Genetic Algorithm characteristics

- a) Solve large constraint satisfaction problems in which optimal or near optimal solutions are required.
 - b) To find relationship between the dependent variables and independent variables in highly non-linear models and to avoid local optima. Local optima are an obstacle to determining the true optimum.
 - c) high dimensionality and / or lack of auxiliary information e.g. derivatives.
- All these advantages achieve because GA's search from a population of solutions, rather than a single solution point, and are therefore able to explore a much greater part of a search space, and avoid getting stuck in a local optimum. Fig 1 and Fig 2 illustrate the genetic algorithm approach to problem solving.

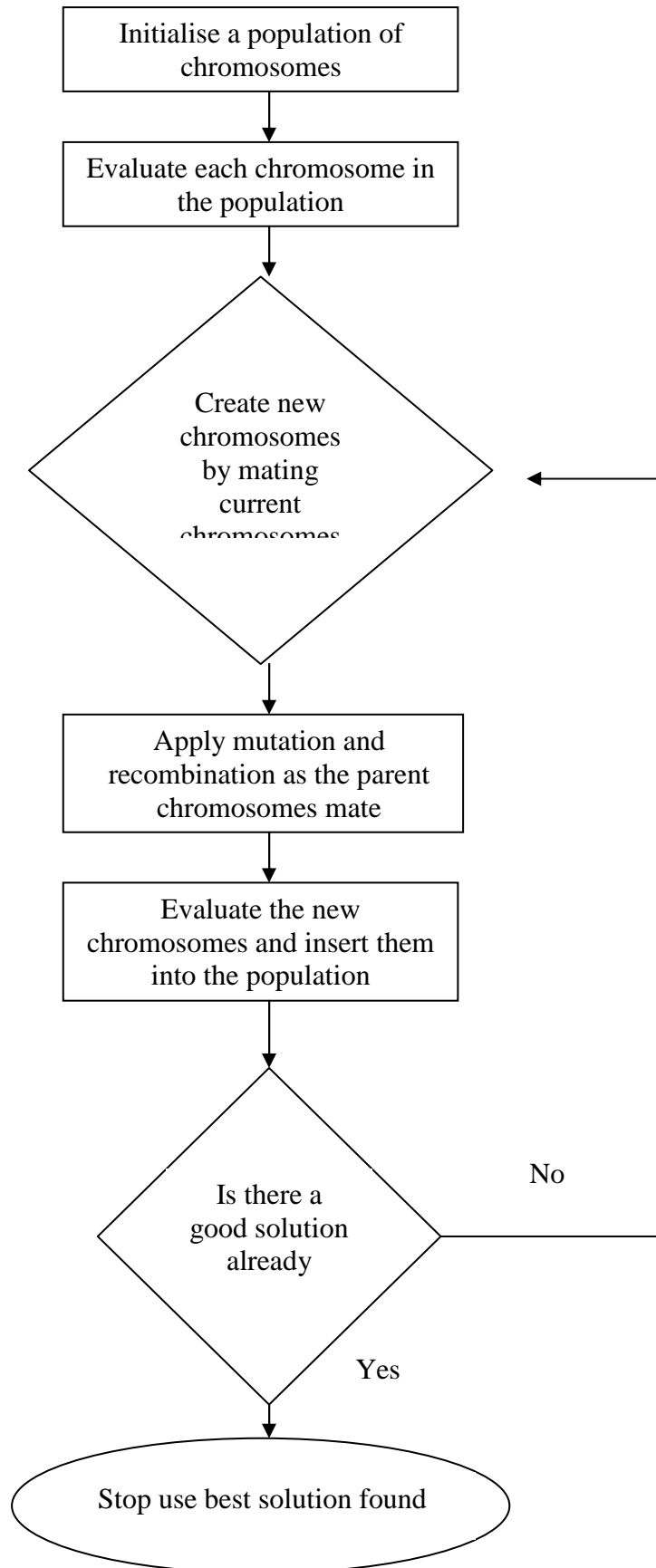


Fig 1 Basic genetic algorithm flowchart

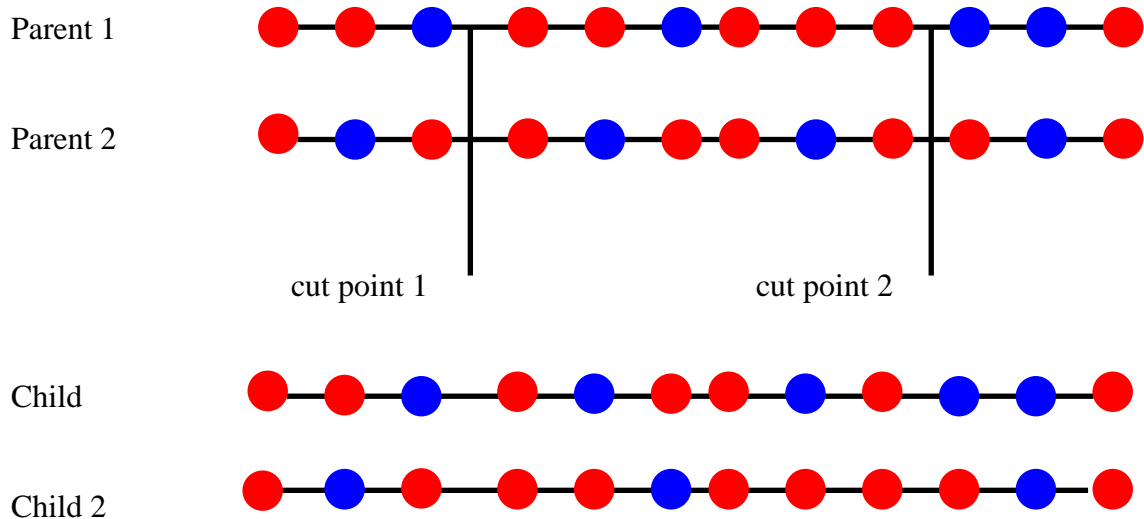


Fig 3a Two point crossover

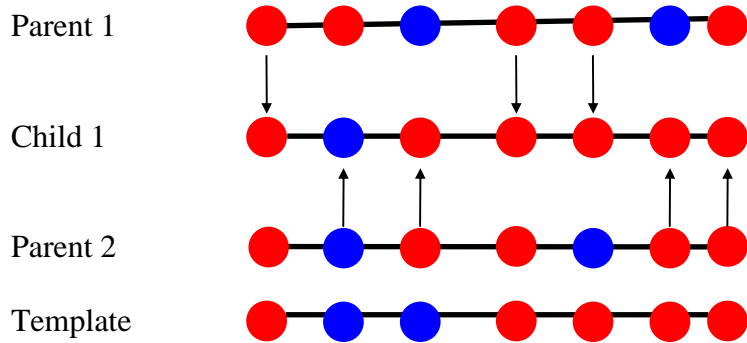


Fig 3b Uniform crossover

For each bit position on the child we decide randomly which parent contributes its bit value to which child. The number of effective crossing points is not fixed, but will be average of the chromosome length.

The nice thing about 1-point crossover is that it is easy to model analytically. It is also easy to show analytically that if one is interested in minimising schema disruption then 2-point crossover is better. However, operators that use many crossover points should be avoided because of extreme disruption to the schemata. Nevertheless disruption may not be the only factor affecting the performance of a genetic algorithm, Spears and Dejong (1991).

“With small populations, more disruptive crossover operators such as uniform or n -point ($n > 2$) may yield better results because they help overcome the limited information capacity of smaller populations and the tendency for more homogeneity”.

4. Genetic Programming

Genetic Programming (GP) is a new programming methodology which uses the Genetic algorithm. GP is the extension of a genetic model of learning into a space of programs. That is, the objects which constitute the population are not fixed - length character strings that encode possible solutions to the problem.

In genetic programming, populations of hundreds or thousands of computer programs are genetically bred. The breeding is done using the *Darwinian principle* of survival and reproduction of the fittest along with a genetic recombination *crossover* operation appropriate for mating computer programs. A computer program that solves a given problem may emerge from this combination of *Darwinian natural selection* and *genetic operations*.

The programs in the population are composed of elements from *Function set* and the *Terminal set*, which are a typically fixed sets of symbols selected to be appropriate to the solution of problems .

In GP the crossover operation is done by randomly taking selected genes in the individuals, selected according to fitness and exchanging them.

In respect of using GP in a chemical plant one can describe GP as an evolutionary computation technique for the discovery of a computer program that produces a desired output for particular inputs. In other words, instead of building an evolutionary algorithm to solve a particular problem, one should rather search the space of possible computer programs for the best fit. In the genetic programming approach, a population of computer programs is created, individual programs compete against each other, weak programs die, and strong ones reproduce and are subjected to crossover and mutation. This research carried out industrial applications of the GP techniques, and have shown that the main advantage of GP is that it could be applied to a wide variety of problems whilst adapting to the environment and are less likely to be trapped in local optima.

5. Mechanics of Genetic Programming

The individuals in the population in Genetic Programming are hierarchical compositions of primitive functions and terminals appropriate to the particular problem domain. The set of primitive functions used typically includes arithmetic operations, mathematical functions, conditional logical operations, and domain specific functions. The set of terminals used typically includes inputs appropriate to the problem domain and various numeric constants.

The composition of primitive functions corresponds directly to the parse tree that is internally created by the compilers of most programming languages. Thus genetic programming views the search for a solution to a problem as a search in the space of all possible compositions of functions that can be recurrently composed of the available primitive functions and terminals.

6. Genetic programming steps

1. Generate an initial population of random computer programs composed of the primitive functions and terminals of the problem.

2. Create a population of programs by selecting programs in the population with a probability based on fitness, and then applying the following primary operations;
Reproduction: copy an existing program to the new population.
Crossover : create two new offspring programs for the new population by genetically recombining randomly chosen parts of two existing programs.
3. Iteratively perform the following substeps until the termination criterion for the run has been satisfied.
4. Execute each program in the population so that a fitness measure indicates how well the program solves the problem.

Fitness techniques

The objective function is a main source of providing the mechanism for evaluating the status of each chromosome. This is an important link between the desired output and the system; it takes a chromosome as input and produces a number or list of numbers (objective value) as a measure to the chromosome's performance. To maintain uniformity over various problem domains, a fitness function is needed to map the objective value to a fitness value. There are number of methods, known as fitness techniques, used to perform this mapping. The commonly led techniques are given as follows:

- *Windowing*: Assuming that the objective value of the worst of the population is V_w , each chromosome can be assigned a fitness value f_t proportional to the 'cost difference' between chromosome t and the worst chromosome.
This can be expressed as:

$$f_t = C \pm (V_t - V_w) \quad (1)$$

where V_t is the objective value of chromosome t and c is a constant. If a maximization problem is encountered, a positive sign is adopted as in (1) On the other end, a negative sign is adopted if minimization is required.

- *Linear normalization* - The chromosomes are ranked in descending or ascending order under an objective value if the objective function is to be maximised or minimised.
Giving the best chromosome a raw fitness, f_{best} then the fitness of t -th chromosome in the ordered list is conducted by linear function,

$$f_t = f_{best} - (t - 1) * d \quad (2)$$

where d is the decrement rate. This technique ensures that the average objective value of the population is mapped into the average fitness.

- *Parent selection* - Parent selection emulates the *survival-of-the-fittest* mechanism in nature. It is expected that a fitter chromosome receives a higher number of offspring and thus has a higher chance of surviving in the subsequent generation. There are many ways to achieve effective selection, including ranking, tournament, and proportionate scheme Goldberg (1989) but the key assumption is to give preference to fitter individuals.

In the proportionate scheme, chromosome x with a fitness value $f(x,t)$ has a growth rate t_{sr} defined as:

$$t_{sr}(x,t) = \frac{f(x,t)}{F(t)} \quad (3)$$

where $F(t)$ is the average fitness of the population.

- A selection process which will more closely match the expected fitness values is the *remainder stochastic sampling*. Remainder stochastic sampling is most efficiently implemented using a method known as *stochastic universal sampling*. Assume that the population is laid out in random order as in a pie graph, where each individual is assigned space on the pie graph in proportion to its fitness. Next, an outer roulette wheel is placed around the pie with N equally spaced pointers. A single spin of the roulette wheel will now simultaneously pick all N members of the intermediate population. The resulting selection is also unbiased Baker (1987). After the selection has been carried out, the construction of the intermediate population is complete and recombination can occur. This can be viewed as creating the *next population* from the intermediate population.

The main features of genetic programming are;

1. The genetic variation inevitably created in the initial random generation.
2. The small improvement for some individuals in the population via localized hill - climbing from generation to generation.
3. The way particular individuals become specialized and able to handle correctly a certain subcase of the problem.
4. The creating role crossover in recombining valuable parts of more fit parents.
5. How the nurturing of a large population of alternative solutions to the problem (rather than a single point in the solution to the problem) helps avoid false peaks in the search for the solution to the problem
6. That it is not necessary to determine in advance the size and shape of the ultimate solution or the intermediate results which may contribute to the solution.
7. Application of a data processing system based on population genetics enables the development of a simulation method which imitates the way used by nature to produce optima solutions.

7. Analysis of the results using genetic programming

The classical optimisations algorithm used are *calculus optimisation* techniques which employ the gradient direction to search the mechanism in order to develop an objective function. If there are very many variables of potential relevance to an investigation, the only practicable procedure is to treat them a few at a time. In respect of a complex study the limiting of a variable is best done after the data have been collected. Initially, information on each variable should be collected as accurately as is feasible. By using engineering knowledge attempts are made to include all possible relevant variables and to limit the number of variables to be included in the analysis process. Via this procedure the number of the variables has been reduced from twenty three to ten.

A genetic program with a population of ten independent variables, one dependent variable (for each population) and 170 samples of data was constructed. The program was run over 500 generations in order to search for models with low residual variance.

8. Progress over the generations

Fig 4 shows the convergence of the genetic programming process over the generations by forming the equation and calculating the correlation. The performance curve is based on almost 500 generations. It shows the experimentally observed cumulative probability of success in

solving the problem by generation i (i.e. of finding at least one equation in the population which produces the correct value). As can be seen, the experimentally observed value of the cumulative probability of success is 30% by generation 250 and 60% by generation 350. This program is capable of optimising a function with a non-linear combination. The final best evolved model led to good understanding of the plant behaviour.

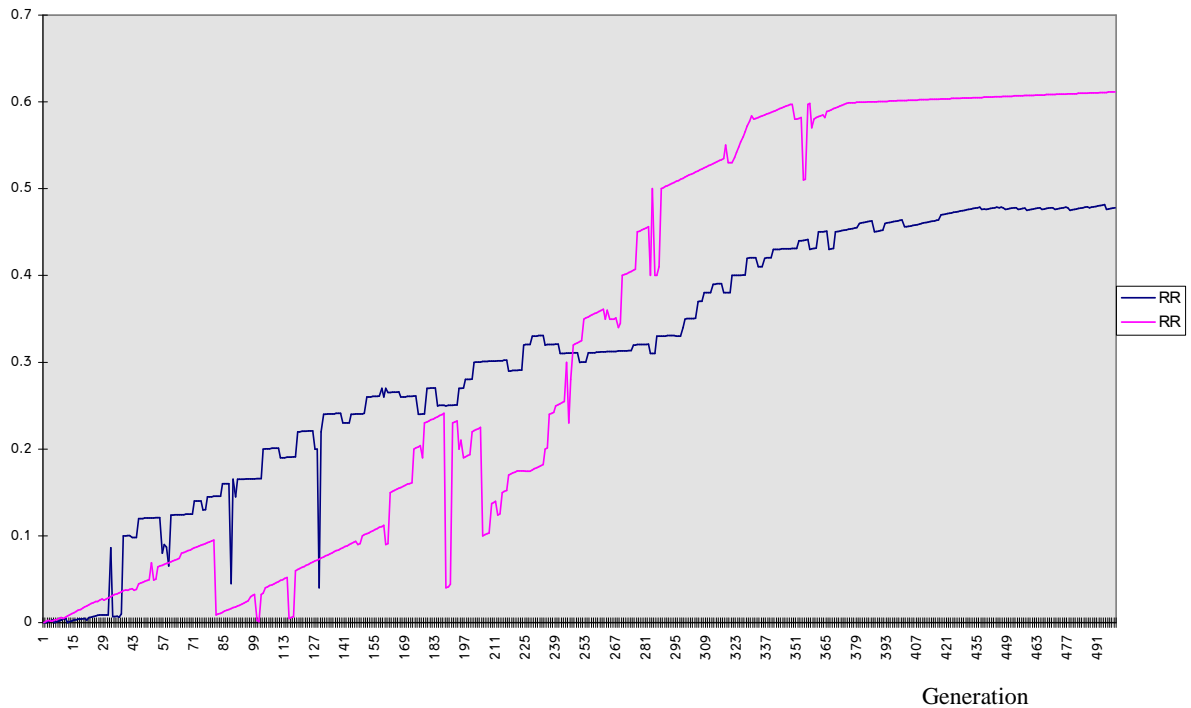


Figure 4: Feed-ward genetic programming training

9. Genetic programming convergence

In order to define the structure of the equations which are able to search for a solution, hundreds of genetic runs were carried out. Due to the initial random search and because of the fact that the system evolved by 'trial and error' different results may be obtained. Fig 5 gives an examples of different results from different runs. If there is good convergence, the results should differ only slightly. In the case of poor convergence the accuracy of the database (i.e. measurements, instruments calibration etc.) should be analysed which may not allow a mathematical model for describing the relationship between the variables (dependent & independent) to evolve. This research was carried out in an environment which involves highly non-linear models and relies on hundreds of measurements, and, in addition, is a very complex model. The algorithm convergence, slightly different for runs as shown in Fig 5. These results indicated that the program had achieved a sufficient confidence level to analyse non-linear relations. Fig 5 shows the best performance curves of the two dependent variables. The genetic programming has been well implemented, the population has evolved over successive generations so that the fitness of the best and the average individual in most generations increases towards the global optimum. It is clear that the computer programs in generation 0 have exceedingly poor fitness. The figure shows the cumulative RR during the generation. Although in some generations no progress and even retrogression occur, in general RR increased and essentially remained constant until the end of the run. The graph shows the correlation during the evolution trial. There were some local

failures before the system was brought into balance. In general the cumulative probability of success increases during the generation.

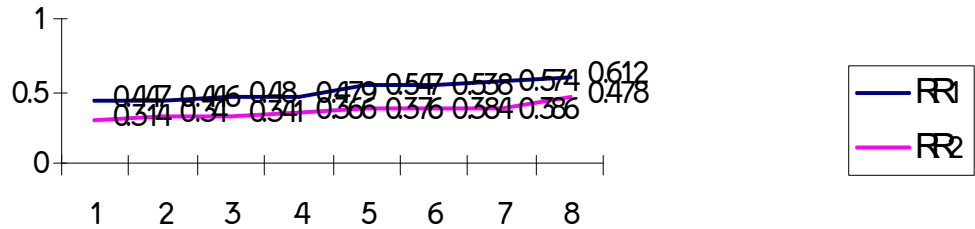


Figure 5: RR results of different runs

10. Analysis of the results

The relationship between the quality measurements and the on-line process has been captured. Fig 6 shows the quality of the fits obtained over a series of runs. This figure illustrates the ability of the GP model to learn the non-linear process characteristics. The graph was created by substituting the measurements from the matrix (data base of the independent variables) into the equation at the end of the evolution and calculating the output to give the dependent variable. This result was compared with the dependent variable which was measured in the off-line laboratory analysis. The curves are based on an evolved run with a population size of 167 and 500 generations. The curve has proved that the results achieved have the same profile with a shift of bias which means the performance of the non-linear combination has led to a high quality solution. The resulting model can be utilised within a controlled scheme to enhance process regulation.

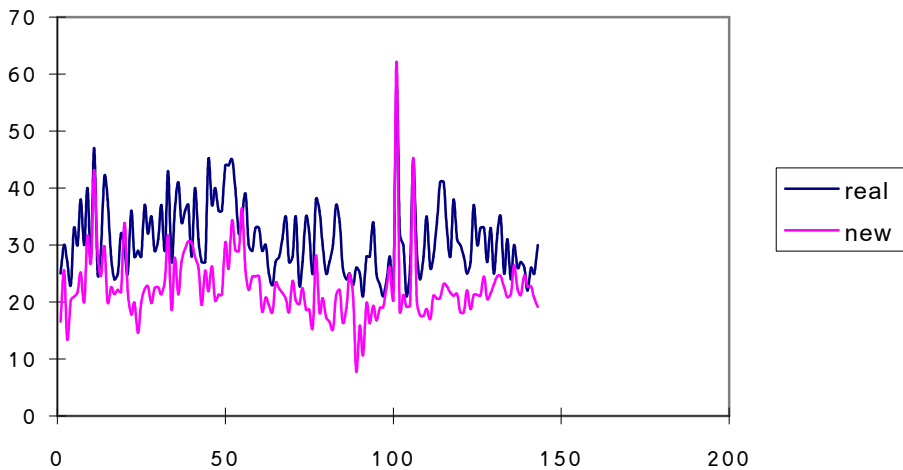


Fig 6 Comparison of the plant results and the fitted series computed from genetically produced model

11. Analysis of the effect of each independent variable on the dependent variable.

It was decided to determine which setting of the independent variables would yield the optimal value of a dependent variable where the functional dependence is known. In addition it should be taken into account that the total number n of performable experiments is limited, although multivariable problems have a structure entirely different from that a single variable. This work has been able to extend a single variable to the multivariable case without much trouble by taking into account the size of multidimensional space and seeking regions of certainty while treating one variable at a time. To find the effect of each variable in multi-dimensional spaces the effect of each independent variable in the extreme operation limit should be examined by using *Taylor's Series*. This is the experimental method as described above. One of the main aims in this research is to simplify the techniques to make them 'friendly enough' for use in a chemical plant by engineers and thus one able to deal and be applicable to industrial problems. At this stage the main effort has concentrated on gaining a better sense of the practicalities of *Taylor's Series*. Otherwise this research will appeal only to those in research at an academic level and will not have any industrial applications.

$$f(x+h) = f(h) + xf'(h) + \frac{x^2}{2!} f''(h) + \frac{x^3}{3!} f'''(h) + \dots + \frac{x^n}{n!} f^{(n)}(h) \quad (4)$$

The approach to solving this problem is by assigning nominal values to each variable as presented in the previous chapters and using the equation evolved by genetic programming and then to calculate the output to obtain the dependent variable. The second stage is the substitution in the equation of the extreme points based on the database recorded. This procedure considers of one variable and one extreme point each time while all the others are kept at the nominal values. The impact of this variable has been calculated based on its contribution on the value of the output (dependent variable).

The impact percentage is calculated as described in equation 5.

$$V\% = \frac{|Y_n - Y_{ie}|}{Y_n} \quad (5)$$

where Y_n is the output value by setting up the nominal values for all the variables, Y_{ie} is the value of variable i on the extreme point, and $V\%$ is the impact percentage of the variable i . The equation has been selected according to the highest R^2 achieved. The calculation has been done for the three best equations. Table 1 presents the best one.

Table 2 presents the contribution percentage for each variable. The contribution percentage is the average between the upper extreme point and the lower extreme point.

X4	X5	X6	X7	X10	X13	X14	X15	X16	X20	Y1	Y2
10	1850	600	1100	30	240	300	4	4	3	32.47	139.1
1.3	1850	600	1100	30	240	300	4	4	3	30.35	139.1
38.2	1850	600	1100	30	240	300	4	4	3	13.31	139.1
10	1899	600	1100	30	240	300	4	4	3	32.48	138.7
10	1800	600	1100	30	240	300	4	4	3	32.47	137.1
10	1850	1000	1100	30	240	300	4	4	3	32.48	138.0

10	1850	8	1100	30	240	300	4	4	3	32.47	139.1
10	1850	600	1222	30	240	300	4	4	3	35.06	146.5
10	1850	600	17	30	240	300	4	4	3	31.72	139.3
10	1850	600	1100	141	240	300	4	4	3	33.72	139.3
10	1850	600	1100	6	240	300	4	4	3	37.06	137.8
10	1850	600	1100	30	114	300	4	4	3	31.00	139.1
10	1850	600	1100	30	500	300	4	4	3	35.87	139.0
10	1850	600	1100	30	240	600	4	4	3	23.86	138.1
10	1850	600	1100	30	240	300	4	4	3	32.47	139.1
10	1850	600	1100	30	240	300	7.3	4	3	33.84	137.9
10	1850	600	1100	30	240	300	1.3	4	3	30.27	139
10	1850	600	1100	30	240	300	4	11	3	39.68	139.2
10	1850	600	1100	30	240	300	4	1.9	3	30.31	138.3
10	1850	600	1100	30	240	300	4	4	6	37.50	140.9
10	1850	600	1100	30	240	300	4	4	1.3	28.78	138.3

Table 1 Dependent variables results by substituting the extreme limit points for the independent variables

	X4 %	X5 %	X6 %	X7 %	X10 %	X13 %	X14 %	X15 %	X16 %	X20 %
CP Y1	32.7	0	0	5.95	8.9	7.25	13%	5.45	12.4	13.2
CP Y2	0	0.8	0.35	2.65	0.45	0	0.35	0.4	0	0.25

CP - Contribution percentage.

Table 2. The effect of the independent variables

Conclusion

Considering the extreme points for each variable led to this conclusion:

The quality of the product Y1 has been affected by the operational conditions of the variables X4, X7, X10, X13, X14, X15, X16, X20 which means that to stabilise the performance and to avoid variation in the quality of the product, the plant should operate in a strict domain for these variables. The operation conditions do not have a significant impact on the quality of the product Y2 by **one variable only** and the variation in the quality as a result of changing more than one variable at a time. In this case it is clear that by changing the operation conditions (more than one variable at time) during the process would lead to losing the control of the process. To avoid this situation the plant should operate under a strict domain.

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Space Weather as a Mechanism of the Motion in Mirce-mechanics

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Abstract

The main objective of this paper is to draw attention to the Mirce-mechanics approach to reliability and safety of maintainable system, which enables accurate predictions of the motion of functionability through their in-service lives to be made by design engineers. This paper focuses on the scientific understandings of the space weather phenomena as mechanisms of the motion of functionability through the life of systems like power networks, aviation, satellite services, pipelines, digital control systems and similar.

1. Introduction

Terrestrial weather, manifested through physical phenomena like wind, snow, rain, hail, thunder, lightning has significant terrestrial impacts on the functionability² of maintainable systems. Physical causes of these metrological phenomena are reasonably well understood and included in reliability analysis of majority of engineering systems.

Space weather, manifested through physical phenomena like evolving ambient plasma, magnetic fields, radiation, charged particle flows in space, has significant impact on the functionability of maintainable systems. The effects of space weather, although unfelt by human senses, are observed in the interruption or degradation of functionality and performance of space related systems during their lifetimes. In addition, increased radiation due to space weather may lead to increased health risks for astronauts participating in manned space missions. The aviation sector may also experience damage to aircraft electronics and slightly increased radiation doses at aircraft altitude during large space weather events. [1]

Space weather effects on ground can include damage and disruption to power distribution networks, increased pipeline corrosion and degradation of radio communications. Collateral effects of longer-term outage would likely include, for example, disruption of the transportation, communication, banking, and finance systems, and government services; the breakdown of the distribution of potable water owing to pump failure; and the loss of perishable foods and medications because of lack of refrigeration.

British Government considers space weather as the fourth most significant risk factor for the public safety, after human diseases, flooding and volcanic eruptions. [2] However, space weather science is a relatively young field and its impacts upon modern society have only recently come in to the fore as our dependence on technologies vulnerable to solar phenomena increases. Therefore, significant research efforts are made to better understand potential impacts of a severe space weather event. In particular, the Department of Energy and Climate Change, National Grid

² Functionability, ability to function in time, concept introduced in the book Reliability, Maintainability and Supportability,, J .Knezevic, McGraw Hill, London, 1993, ISBN 0-07-707691-5

and others in the energy sector are working closely to clarify the potential impacts of a severe event on electricity assets and networks. [3]

In Spain, various institutions have long been studying and analysing the phenomenon of space weather, the way it repeats itself, the areas of the planet that may be most affected, as well as developing various measures to mitigate and respond to the consequences that may result from this phenomenon. (<http://www.proteccioncivil.org/en/clima-espacial>)

The main challenge of in-service operation of any maintainable system is the true understanding of the impact of the environment that surrounds them. The reliability and safety of their operation are influenced by a multitude of different factors extending from the Earth's atmosphere to the far reaches of space beyond our own galaxy. In order to determine the probabilities of occurrence and the resultant functionability events and their impact on the motion of functionability through the life of maintainable systems, Mirce-mechanics methods are requiring a full understanding of the mechanisms that generate these environmental phenomena. [4]

Consequently, the main objective of this paper is to draw attention to the scientific approach to reliability and safety analysis promoted by Mirce-mechanics, of the future systems whose in-service performance is affected by the space weather, to enable accurate predictions of the occurrences of negative functionability events to be made. Only then, meaningful reliability and safety engineering actions could be taken towards reduction of the probability of occurrences of negative functionability events during the life of aviation, communication, power distribution and other, space weather, affected systems.

2. Scientific Principles of Mirce-mechanics

Mirce-mechanics: is a scientific theory of the motion of functionability through the life of maintainable systems. Its axioms, mathematical formulas, rules and methods enable accurate predictions of a system's measurable functionability performance characteristics like reliability, availability, punctuality and others to be made with probabilistic regularity. [4]

According to Mirce-mechanics the motion is the change of a state of a maintainable system in relation to functionability, in respect to time. All physical phenomena that cause the motion of a system from the positive to negative functionability states are known as negative functionability events, NFE. Mechanisms that generate negative functionability events belong to the following categories:

- **Over stress mechanisms**, where acting in-service stresses, generated by mechanical, electrical, thermal, radiation, chemical and other types of energy, exceed that strength of components and systems subjected, resulting from phenomena like foreign object damage (birds, hail, rain, snow), lightning, abuse by operator (pilots, driver and user errors), single event upset and similar.
- **Cumulative stress mechanisms**, where acting in-service stresses, generated by mechanical, electrical, thermal, radiation, chemical and other type of energy, are accumulated through in-service processes like, corrosion, fatigue, creep, wear and similar.
- **Inherent stress mechanisms**, where acting in-service stresses, generated by mechanical, electrical, thermal, radiation, chemical and other types of energy, have been introduced

into system prior to the operation process through activates associated with manufacturing, transportation, maintenance, storage and similar processes.

Hence, to understand the mechanisms that generate negative functionability events, at the MIRCE Akademy in UK, thousands of components, modules and assemblies of systems in defence, aerospace, transportation, motorsport, nuclear, communication and other industries, had been studied, since 1999. (www.mirceakademy.com). These studies have lead to the formulation of the 1st Axiom of Mirce-mechanics, which states, “*The probability of occurrence of a negative functionability event at any instant of in-service time is greater than zero*” [5]. Thus, in this paper physical phenomena named as space weather are considered as mechanisms that generate sufficient amount of energy to generate a negative functionability event that causes the motion of a system from positive to negative functionability state.

3. The concept of Space Weather

Space weather term refers to the environmental conditions in Earth's magnetosphere, ionosphere and thermosphere due to the Sun and the solar wind can influence the functioning and reliability of space-borne and ground-based systems and services or endanger property or human health. Space weather deals with phenomena involving ambient plasma, magnetic fields, radiation, particle flows in space and how these phenomena may influence man made systems. In addition to the Sun, non-solar sources such as galactic cosmic rays can be considered as space weather since they alter space environment conditions near the Earth.

The Sun has a major influence on the radiation environment at aircraft altitudes and on the Earth's surface. This section will review the impact of space weather on the avionics radiation environment and discuss each of the components that make up a solar storm.

The three constituent elements of a solar storm and their resultant space weather manifestations are shown in Table 1. The largest solar storms typically generate all three components whereas less powerful storms may not. [6]

Solar Storm Components	Space Weather Effects
Solar Flares	Intense EM Burst
Solar Photon Event	Ground level Events
Coronal Mass Ejection	Geomagnetic Storm

Table 1: Space Weather Constituents

Solar flares are magnetically initiated explosions that occur at or near the surface of the Sun that release intense bursts of electro-magnetic radiation in the form of x-rays, ultraviolet and radio emissions that can cause disruptions to the Earth's ionosphere leading to radio and communications interference.

Geomagnetic storms are large disturbances in the Earth's magnetic field caused by changes in the solar wind and interplanetary magnetic field (IMF) structure. These changes in the solar wind arise from disturbances on the Sun, such as in powerful coronal mass ejections (CMEs). Their effect can be felt for a number of days. With the right magnetic configuration, increases in solar wind speed and density, large amounts of energy can be transferred into the Earth's geomagnetic system. The ability to predict the magnetic orientation of CMEs as they leave the Sun's surface and the time taken to travel to the Earth are key to improving space weather forecasts.

Finally to provide an appreciation of the temporal characteristics of the Sun's effects on the radiation environment, the differences between the arrival times of each solar storm component will be addressed. Hence:

- X-Rays and radio waves travel from the Sun at the same speed as visible light, hence they take approximately 8 minutes to reach Earth.
- The speed of protons during SPEs is dependent on energy level and therefore typically takes between 15 minutes to a few hrs to generate atmospheric and ground level particle enhancements.
- The solar plasma cloud of CMEs takes between 2 and 4 days to impact the Earth's geomagnetic field and generate a geomagnetic storm that may take several days or even weeks to recover.

The Earth's magnetic field or magnetosphere is the first line of protection against energetic primary cosmic rays from space and is composed of electrons plus free ions held in place by magnetic and electric forces. This magnetic field surrounding the Earth acts on incoming charged particles like a shield directing particles below a threshold energy level along the magnetic lines of force towards the Polar Regions.

As a result, for each point in the magnetosphere there exists a minimum energy level for a particle with a vertical trajectory to create cascade of particles that will reach sea level. This energy level is defined as a point's geomagnetic rigidity or cut-off. For particles with a non-vertical trajectory a higher energy level is required for the same location.

Due to the nature and shape of the Earth's magnetosphere the values of geomagnetic cut-off value vary significantly with different latitudes, highest at the equator, approximately 15 GeV, reducing to less than 1 GeV at the poles. Cut-off values also vary with longitude but this affect is much less pronounced than the latitude variation. [8]

3.1 Measuring the Impact of Space Weather

Different aspects of space weather have a variety of impacts on mankind and our technology. There are worldwide-accepted methods for the classification of space weather conditions that are used to communicate the impact on people and technical systems. These are numbered scales similar to those used to describe hurricanes or earthquakes. They describe the level of disturbance and possible impacts for three types of space weather by the following three scales:

- Radio blackouts, R scale that quantifies disturbances of the ionosphere caused by X-ray emissions from the Sun
- Geomagnetic storms, G scale that quantifies disturbances in the geomagnetic field caused by gusts in the solar wind that blows by Earth
- Solar radiation storms, S scale that signifies elevated levels of radiation that occur when the numbers of energetic particles increase

Each scale provides lists of possible effects seen with each category of activity, the physical measure that determines the category of an event, and a climatological assessment that explains how often it can be expected to see events of each magnitude during a solar cycle.

The level of impact is dependent on the technological systems in service that vary widely across the globe. For example the UK power grid has much shorter and more highly connected transmission lines than those in North America so it is less susceptible to space weather.

4. Impact of Solar Effects on the Earth's Environment

The Sun is not a steady-state star. It continuously undergoes changes, which sometimes could be extremely violent. These changes are transferred by the solar wind to the Earth and disturb its magnetic field. The regular changes in the level of solar activity over long-periods are known as the solar cycle. The duration of the solar cycle varies between 9.5 and 11 years. Usually, solar activity is measured by the number of sunspots on the solar surface. The solar cycle is also seen in the number and strength of the solar flares, which are resulting from tremendous explosions in a localized region on the Sun. In a matter of just a few minutes they heat material to many millions of degrees. [6]

Thus, Earth does not float in empty and quiet space, but is immersed in the escaping outer atmosphere of the Sun. This 'solar wind' consists of ionized particles, mostly protons and electrons with a small admixture of helium ions. The density of solar wind is low, about 10 particles per cc. Solar wind also carries the Sun's magnetic field, which at the Earth's orbit has strength of only a few nT. The wind speed at the Earth's orbit is about 450 km/s or more. On its way the solar wind encounters the Earth's magnetic field, which deflects the particles and shields the Earth from the direct effects of the solar wind.

In the absence of solar wind the geomagnetic field can be approximated by a dipole field with an axis tilted about 11 degrees from the spin axis. The force of the solar wind modifies this field, creating a cavity called the magnetosphere. The boundary between the geomagnetic field and solar wind, the magnetopause, is located at a distance of about 10 Earth's radii from the Earth's centre, but can move closer during high solar activity periods. In the anti-sunward direction the magnetosphere is extended into a long tail, of the length approximately 80 times of Earth's radii, filled with magnetic field lines that connect to the polar regions of the Earth. At the low-altitude limit, the magnetosphere ends at the ionosphere. The magnetosphere is filled with plasma that originates both from the ionosphere and the solar wind. [7]

5. Reliability Significant Space Weather Events of the Past

Space weather events have always occurred, but as the biggest impacts are arguably on technology driven systems, it is only in modern times that our attention is drawn toward their susceptible threat. Different systems across the globe are exposed to varying levels of risk depending on their technical design, location and the type of space weather they are susceptible to. It is a reliability engineering challenge to ensure that future systems are designed with appropriate provisions to minimise the risk posed by space weather.

5.1 The 1859 Geomagnetic Storm

During the 1st and 2nd of September 1859, the Sun ejected a record-breaking coronal mass ejection of highly charged gases and plasma that may have weighed as much as a billion tons. Travelling through the solar system at several million miles per hour, it eventually collided with the Earth's magnetosphere that temporarily went into a state known as a geomagnetic storm. The physical manifestation of this event was that skies were set ablaze all over the world with multi-colour auroras that reached as far south as Cuba and El Salvador, and blew out global telegraph

systems, the highest-tech communication devices of the day. The spark discharged shock telegraph operators and set telegraph papers a light. Even when telegraph operators disconnected the batteries powering the lines electric current still in the wires allows messages to be distributed.

This specific geomagnetic storm was named as the Carrington Storm, after the British astronomer Richard Carrington who observed the ejected plasma cloud from the Sun, which took 18 hours to travel to the Earth. It was the largest geomagnetic storm ever recorded; the havoc it unleashed provided a preview of what would happen if today a Carrington-like storm were to hit our technology-dependent society. In fact, according to a report by the National Academy of Sciences of USA, a contemporary Carrington-like storm could trigger cascading catastrophes, including melted transformers that could shut down large, interconnected power grids, power outages affecting as many as 130 million people, backed-up sewage systems, the failure of electronic transportation systems, and the collapse of systems used to distribute drinking water, food, medicines and fuel.

However, a geomagnetic storm does not even have to reach Carrington's record-breaking strength to cause serious damage. In recent years, weaker geomagnetic storms have damaged technological systems like satellites, increased the radiation exposure of astronauts, disrupted communication and navigation systems and knocked out power to large populations.

5.2 The 1989 Geomagnetic Storm

On the 13th March 1989 the east-central province of Canada, known as Quebec, has experienced geomagnetic storm. It has a devastating affect on the functionability of the electrical power distribution systems that caused transformer saturation, which reduced or distorted voltage. Power supply systems with long lines and static compensators are particularly sensitive to such natural phenomena. Quebec utility's experts noted a correlation between the exceptional intensity of the geomagnetic storm and the tripping of several static compensators, at Chibougamau and La Verendrye substations. Immediately after this event took place records show voltage oscillations and power-swings increase until the lines from James Bay failed. Within seconds, the whole grid lost functionability. This negative functionability event was caused by the strongest geomagnetic storm ever recorded at this location. The storm, which resulted from a solar flare, tripped five lines from James Bay and caused a generation loss of 9,450 MW. With a load of some 21,350 MW at that moment, the system was unable to withstand this sudden loss and failed to function within seconds. The system-wide blackout resulted in a loss of some 19,400 MW in Quebec and 1,325 MW of exports. An additional load of 625 MW was also being exported from generating stations isolated from the Hydro-Quebec system. [8]

Consequently, the power supply system stayed in negative functionability state around nine hours. This can be explained by the fact that some of the essential equipment, particularly on the James Bay transmission network, was made unavailable by the blackout. Generation from isolated stations normally intended for export was made available to Quebec's needs and the utility purchased electricity from Ontario. By noon, the entire generating and transmission system was back in service, although 17 percent of Quebec customers were still without electricity. In fact, several distribution-system failures occurred because of the high demand typical of Monday mornings, combined with the jump in heating load after several hours without power. According to [4] the net cost of the 'Quebec blackout' was estimated at 13.2 million Canadian dollars. In addition to that, the purchase of replacement power cost about 17 million dollars.

5.3 Other Geomagnetic Storms on the Past

Other significant space weather events have been recorded since then. For example, a solar storm in 2003 interrupted the operation of satellites and caused the GPS augmentation system used by the aviation sector to go offline for approximately a day.

Records from solar storms in 1921 and 1960 describe widespread radio disruption and impacts upon railway signalling and switching systems.

6. Estimated Impacts of the Space Weather on System Functionability

Many of the described phenomena associated with solar activity also have important practical consequences and must be taken into account in the design and operation of systems whose functionability trajectory is affected by them. For example geomagnetic storms, as described above, can cause rapid variations in the Earth's magnetic field which, in turn, induce an electric field in the Earth's surface, which in turn generate negative functionability events during in-service life of a large number technological systems that are exposed to these space weather phenomena. Impact of space weather on several different categories of systems will be briefly examined below.

6.1 Impact on Avionics

Negative Functionability Event, known as a Single Event Effects, SEEs, have been the primary radiation concern for avionics since the late 1980's when the space weather phenomenon, which had previously only been observed in orbiting satellites, also began to appear in aircraft electronic systems. [9]

The principal SEE affecting avionic devices is the Single Event Upset, SEU caused when a sole incident particle creates a charge disturbance of sufficient magnitude in a memory cell, flip-flop, latch or register to reverse or flip its currently stored data state. Alternatively, in logic or support circuitry a transient voltage pulse can be generated that's dependent on the right conditions can propagate through the logic of the device and become latched into a memory cell. Voltage spikes on power supply lines and noise can also cause transient errors; however appropriate shielding and filtering design measures can suppress these types of disturbances. [10]

Radiation can affect electronic devices as the consequence of a single energetic particle strike, termed 'single event' or as multiple strikes over an extended period of time. The effects due to multiple events, Total Ionisation Dose, TID, and displacement damage manifest gradually in electronic components as damage is accumulated over time. These total dose effects and hard SEEs whilst relevant to electronic systems operating in the harsher space environment have a negligible effect on current semiconductor devices used in the terrestrial environment.

The second most prevalent SEE is the Multiple Bit Upset, MBU, that occurs when a single particle causes the upset of two or more memory cells. Fortunately MBUs only form a fraction of the total number of SEUs, hence they have little significance except for memory architectures employing Error Detection and Correction, EDAC, techniques. In these circumstances, dependent on the type of error correction technique employed, multiple bit errors could have

significant consequences if the protected memory is used for flight or mission critical applications. MBUs are generally assumed to attribute 3% of the total upset rate [7] although rates as high as 5% have been reported.

Following MBU, Single Event Functional Interrupt, SEFI, and Single Event Latch ups, SEL, account for the majority of the remaining proportion of SEEs affecting avionic devices. SEFIs occur when an upset initiates an IC test mode or reset mode that causes the device to temporary loose functionality. SELs arise when an incident particle creates a charge disruption sufficient enough to effectively short circuit the device resulting in its permanent change of state or in some circumstances permanent damage if excessive current flows as a result of the latch-up.

The last SEE of avionics relevance that can generate soft errors in the core logic of microprocessors and microcontrollers is the Single Event Transient, SET. They are transient and non-destructive in nature and are capable of producing a soft error, (i.e. the storage of an erroneous data value in registers, memories or latches) only if it is propagated through the logic pathways of the device. This is dependent on the dynamic state of the logic at the time of the particle induced nodal voltage transition and the configuration of the logic pathways within the device. If a soft error occurs normal system behaviour can be restored by resetting or rewriting the incorrect data. [8]

Of all the forms of SEE, SEUs are the most prevalent in avionic electronic devices; Table below illustrates the approximate distribution percentage values, between each type of SEE except SETs, for which no reliable data exists. [8]

Single Effect Event Type	Percentage
Single Event Upset	90 %
Multiple BIT Upset	5 %
Single Event Functional Interrupt	3%
Single Event Latchup	2%

Table 2 – Main SEE Apportionments – Avionics Environment

6.2 Radio Communications and Navigation

Radio communication links on all frequencies are affected by space weather. Especially sensitive are kHz and MHz links because they rely on wave reflection from the ionosphere. Changes in electron density may cause degradation, or disruption of radio waves propagating within the ionosphere. Ionospheric irregularities may produce signal fading so strong that a signal loss is encountered.

Broadband radio noise emitted by strong solar flares may interfere with a wanted signal making its detection impossible. At high latitudes streams of high-energy particles could increase ionization causing enhanced absorption of radio waves and preventing radio communication. Such radio ‘blackouts’ may last for many hours. Likewise, radio waves at higher frequencies (hundreds of MHz and GHz) that penetrate the ionosphere and are used on satellite radio communication links and navigation systems are affected when solar activity causes sudden variations in the density of the ionosphere. [7]

For example, the Global Positioning System, GPS, uses signals from several satellites to measure the range to the satellites and determine the position of the receiver. Actually the range is determined from the propagation time between the transmitter and the receiver. This propagation time is dependent on the ionosphere electron density and therefore will change with solar activity. Use of dual-frequency GPS receivers can, to some extent, compensate for this effect. However, another ionospheric effect, scintillation or rapid fading of the amplitude and phase of the signal, can not be conquered so easily. Scintillation is caused by electron density irregularities that scatter and diffract radio waves. When the depth of fading exceeds a certain limit, the receiver fails to track the signal and the propagation time can not be measured.

6.3 Satellite Industry

For most of the time the Earth's magnetosphere shields satellites from the high energy radiation in space. During significant space weather events this shielding breaks down and geostationary satellites can become exposed and prone to damage. Electrostatic build up on and within the satellites can cause errors and component damage when it discharges. Solar energetic particles can degrade the satellite's solar panels reducing the life expectancy of the satellite; surface charging can damage the electronics and can also produce single event upset, which in turn cause errors within the computer systems.

Forty seven satellites suffered temporary outages during the geomagnetic storm in October 2003 and two were damaged in 2012. Given the range of spacecraft in operation today the Royal Academy of Engineering in UK estimated 10% of the satellite fleet might suffer from a temporary outage during an extreme event. [3]

Two Canadian telecommunications satellite spent 6 months in a negative functionality state generating cost of \$50 million to \$70 million.

Global Navigation Satellite Systems, GNSS, often known as Global Positioning Satellites, GPS, would also be impacted making such systems inoperable for a number of days. This will cause operational impacts to industries such as aviation and shipping but could also impact those that rely on GNSS for critical timing information.

An extreme geomagnetic storm will also result in an expansion of the Earth's atmosphere that disrupts the orbit of satellites in a low Earth orbit degrading predictions of their position. It can take several days to reacquire positioning data and regain communication with the satellite.

6.4 Radiation hazards

Normally, the atmosphere and magnetosphere protect us sufficiently well from solar high-energy radiation, but satellite operations, astronauts, and even passengers in commercial jets travelling at high altitudes are subject to elevated dosages of radiation.

During severe magnetic storms, occurring on average 3 times per solar cycle, strong radiation affects computer memory chips causing loss of control, solar panels may be degraded, imaging equipment may be subject to noise, tracking instruments can loose orientation. At the same time, astronauts and aircraft passengers are exposed to the radiation equivalent of more than 10 chest x-rays.

6.5 The impact of loss of HF communication at high altitude routes

During last two decade several airlines started using high latitude polar routes in the attempts to reduce the operational cost. However, communication on these routes is only possible by using High Frequency radio communication systems, which means that space weather could generate negative functionability events in the form of radio blackouts. Aircraft in flight would follow well established procedures for such a loss of communications but those yet to take off may be diverted to lower latitudes routes which may be longer and result is disruption to flight schedules. For example in January 2005 United Airlines diverted 26 flights to less-than-optimum polar routes during several days of disturbed space weather.

6.6 Pipelines

A variable magnetic field can induce currents in long pipelines and surrounding soil. Under normal conditions, to protect against corrosion, the pipelines are equipped with special devices that keep the pipeline at a small negative potential with respect to the soil.

During a magnetic storm this potential may increase above the safe value, the pipeline corrosion protection system fails, corrosion attacks the pipeline joints and its lifetime is reduced. In addition to that, possible leaks through the pipeline cracks may constitute a threat to the environment. [7]

7. Conclusion

The main objective of this paper was to demonstrate the necessity of addressing all physical mechanisms that lead to the transition of a system from positive to negative functionability state during its life. Addressing the reliability and safety characteristics of any system in isolation from the investigation of the impact of the natural environment is not sufficient. Mirce-mechanics approach to reliability and safety has shown the necessity of considering impact of the operational environment on functionability trajectory of all maintainable systems.

In summary this paper states that reliability and safety considerations of a large number of modern technological systems must include the full understanding of the impact of the space weather the motion of functionability through the large number technological systems. 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 negative functionability events during the life of maintainable systems like power networks, aviation, satellite services, pipelines, digital control sand many others.

8. Referemces

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Hospital Logistics

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Abstract

There has been a lot of discussion about hospital logistics. So far there have been no definitions for that area. Also all the articles under this topic have handled only some single elements of hospital logistics without a wider context. This article is made in order to find and define the essence and the scope of hospital logistics. By doing so this article should establish a foundation for further research in the area of hospital and health logistics.

1. Introduction to the Hospital Logistics

To combine the words ‘logistics’ and ‘hospital’ in order to create a new theoretical framework is like collecting troubles. Both ‘logistics’ and ‘hospital logistics’ are fashionable expressions to use. Neither of the terms is defined universally and hence all the speakers use the words exactly as they like – no two speakers having the same definitions.

It seems to be so that we have to accept different definitions for logistics. By nature, logistics change its shape depending on the context. This emphasises the role of logistics as a supporting function.

Because there has not been any clear and unified way to apply logistics in hospital environment the practice has brought out several applications but always focusing on a very limited area of the topic: blood logistics, pharmaceutical logistics, surgery logistics, and so on. The common nominator for all of these is that those are direct business logistics applications without any connection to each other or primary process management.

To be able to establish a new hospital logistics framework it is necessary to examine the essence of logistics to find the most reasonable way to link it to the universal health and hospital environment.

2. Logistics

Logistics is one of the most often used words in business jargon. The problem with Logistics is that there is not any one broadly accepted definition for it. The meaning of the word has changed during the time, and step by step the meaning has covered more and more.

Basically the word logistics (or its origin) is about 2 000 years old. Originally “the word Logistics comes from the Greek *logistikos*, meaning skilled calculating”³. As the “father” of modern the logistics can be seen Antoine Henry Jomini, a quartermaster of Napoleons army. He raised the meaning and importance of logistics to the same level in military science as tactics and

³ Finkelstein-Guertin, 1988, p. 1

strategy⁴. The thoughts of Jomini were launched in to the United States by the Admiral A. T. Mahan who introduced logistics to the US Navy. During the World War I logistics was still used and applied in its narrowest meaning which means mainly the focus on transportation. World War II was a breakthrough for logistics. The war technology became more complex, which required more and more sophisticated methods to manage the equipment and support the military troops. By 1960's the benefits of logistics concept were so apparent that also the private sector started to use the logistics approach in business operations. The following list of the contents in logistics definitions through out the time gives an idea about the development of the logistics definitions. The list is made from the business point of view which means that it does not follow the development of the Integrated Logistics Support (ILS).

- Accounting of supplies
- Accounting of equipment and supplies, troop support
- Troops support and lodging
- Troops movement and support
- Movement and storage of materials
- + Procurement and maintenance
- + Information
- + From point of origin to point of consumption
- + By conforming the customer requirements

The definitions have changed but when the '+' is used it means that this element has come in addition to the previous content.

Nowadays there exist numerous definitions and the best way to describe them is to show some examples:

Council of Logistics Management (CLM), 1992:

“The process of planning, implementing, and controlling the efficient, cost-effective flow and storage of goods, services, and related information from point of origin to point of consumption for the purpose of conforming to customer requirements.”

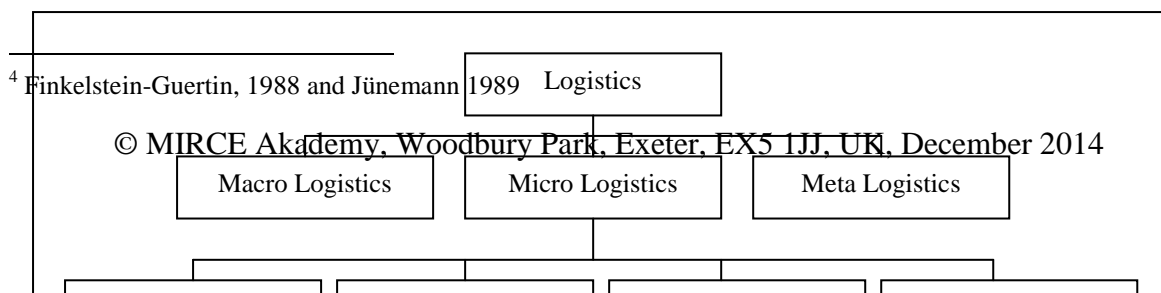
Webster's Encyclopaedic Unabridged Dictionary, (1996:

“The branch of military science and operations dealing with the procurement, supply, and maintenance of equipment, with the movement, evacuation, and hospitalisation of personnel, with the provision of facilities and services, and with related matters.”

R.H. Ballou (Basics Business Logistics: Transportation, Materials Management, Physical Distribution, 1987)

“Business logistics is the study of how management can best provide level of distribution services to customers through effective planning, organising, and controlling of the move and store activities that facilitate product flow.”

The logistics is applied in very different environments. Therefore logistics is structured according to the applied fields:



According to the name, macro logistics focuses on the location of industry, cities, harbours and so on in order to provide the best possible infrastructure solutions to manage material flow as well as transport of people.

Micro logistics concentrates on the logistics applied by individual companies while meta logistics focuses on the logistics co-operation between companies or other operators.

Business logistics has become very popular and that's the reason why there are so many books and articles about it. As it can be seen in the graph above, the business logistics is the only application with sub-categories. Industrial logistics is about logistics and materials handling, materials management in production environment. Commerce logistics is about the whole selling and reselling process. Service logistics is traditionally considered to be logistics services. That means transport and warehousing companies providing services. As an extension the service entity has led to the so called third-party logistics which means that a logistics service company takes care of all the logistical activities between the selling and buying companies. The more detailed handling of business logistics can be found in chapter 2.1.

Military logistics is the origin of the whole logistical thinking. There we can see two different approaches: conventional military transport oriented logistics and, on the other hand, System Engineering (SE) oriented Integrated Logistics Support (ILS).

Hospital logistics (Krankenshauslogistik in German, sairaalalogistiikka in Finnish) is at the moment in practise an extension of business logistics. Business logistics is applied directly to the materials handling procedures in hospital environment. This has been done without thinking of the environment as a whole with its requirements and constraints. This has led the hospital logistics to very fragmented approaches. There are researches about blood logistics, medicine logistics and so on but there is an apparent lack of the framework for the whole hospital logistics.

Logistics does not form a science in itself but is a cross-disciplinary approach to the complex operations and collection of linked activities. It contains technology, business, human resources, etc. by means of which it is possible to understand, analyse, create and manage a logistics system. The role of logistics is typically to prevent sub-optimisation and to ensure the total optimisation of the process. Sub-optimisation is a very human phenomenon: everyone of us wants to make it sure that his responsibilities are taken care of well – no matter if it cause extra costs to someone else. From the entity's point of view this kind of thinking is destructive. The process can be as efficient as the sum of all the separate activities is. This makes it clear that it does not count if

one factor is efficient – the sum is the only relevant fact to optimise. This leads us to look at the interfaces in the process. The interface may be inside of a company but as well it can be also an interface between the company and consumer. The customer service is one point of view to analyse these interfaces and their meaning to the whole process.

In the book written by Mr. Arthur D. Little the logistics in hospitals is handled in order to examine the role of logistics in health care environment. In the summary it is already mentioned that from the logistics point of view , hospitals are very complex systems. There are extensive requirements for materials handling, staffing and scheduling and these have enormous impact on the efficiency and customer satisfaction in hospitals⁵.

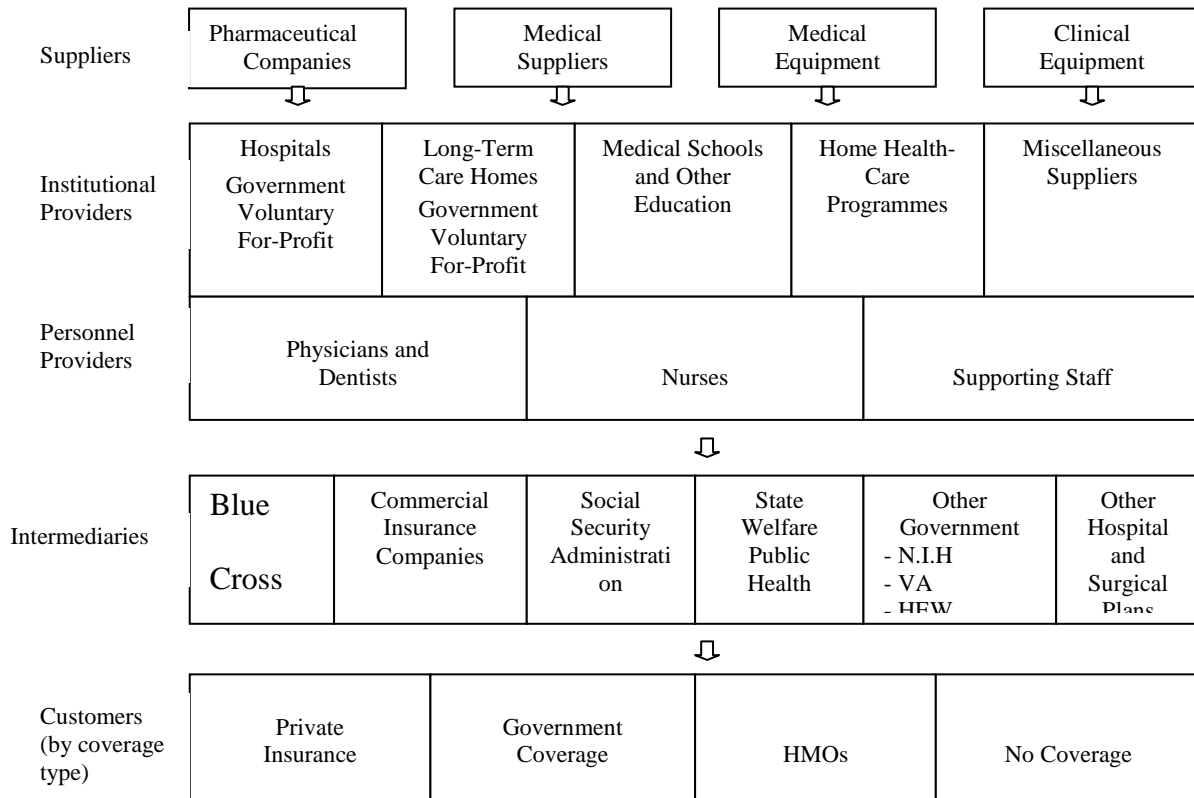


Figure 2.2: Overview of the health-Care Delivery System (Little, 1991, page 46)

Despite various cost-cutting efforts, there is still potential for cost reductions. The sources for ineffectiveness are e.g.

- the ineffective practice patterns
- the unnecessary tests that are run when results are delayed or assumed lost.

The possibilities lie e.g. in better decision making on the type of services to provide to each patient and developing effective strategies with the medical staff.⁶

All this emphasises the fact that hospital logistics is seen in a very narrow sense as a flow of materials. Supply chain is the term often mentioned. However, there should always be the logistics process in mind and derived from it the hospital logistics should be seen as a combined flow of patients and materials. By doing so, the System Engineering approach shows the

⁵ Little, 1991, p. 43 - 76

⁶ Little, 1991, p. 50

profound research scheme: first the definition of functional requirements for the whole system, and after that the physical design. In case of hospital logistics the object is not tangible but service – the scheme is still useful.

It is clear that to handle a logistics process as a whole brings great dangers. Logistics professionals do not have professionalism in medical science. Based on this the relevant question can be stated: how can a person who has not studied medical science do research in hospitals where the patients and treatment processes are included. In this research this is inevitably a problem but it does not paralyse the development of logistics processes in hospitals. New questions can be asked, the help and feedback from medical staff will guide the research. And in the end, there will be proposals which require even medical research in order to justify some of the improvements.

3. Integrated Logistics Support

During World War II logistics started to get more interest. Until that logistics was understood in its narrowest sense meaning mainly procurement, warehousing and distribution. After the war the US Army broadened the definition to cover the following elements⁷:

- Procurement
- Storage and distribution of equipment and supplies
- Transportation of troops and cargo
- Construction and maintenance of facilities
- Communication
- Care of the sick and wounded
- The instruction, classification, assignment, welfare and separation of personnel.

Integrated Logistics Support (ILS) emerged in the early 1960's with the explosion of technology. The need to combine the complex system planning and support as well in peace and war time became crucial.

Finally in 1964 logistics was refined in the US Army in to integrated logistics support (ILS). Because the development is made by military force and the applications are in army environment, ILS is mainly recognised as one approach of military logistics. The following graph illustrates the role of ILS in system management:

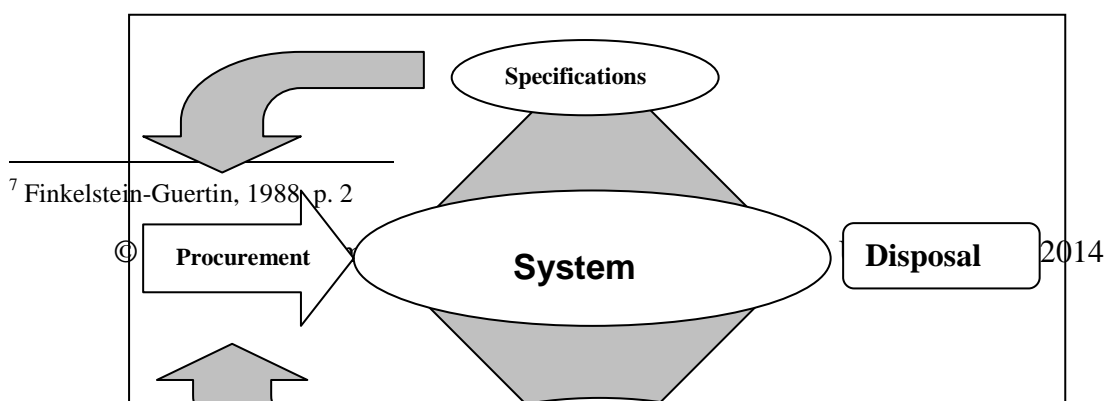


Figure 3.1: Structure of thinking in integrated logistics

The first written document about ILS was published in 1964 and the best comment for justification of the ILS was given in May 1969 by Admiral Galantin, United States Navy (USN):

“The small cost of ILS planning, less than one percent of the first article acquisition cost, is well worth the investment in the light of the large support cost: i.e., six to ten times the acquisition cost. Based on past experience in other programs and results of initial ILS efforts in current programs, ILS planning is expected to lead to reduction in life cycle support of \$100 to \$200 million per major ship program.”⁸

The ILS emphasises the comprehensive approach to the systems. The following figure⁹ points that out.

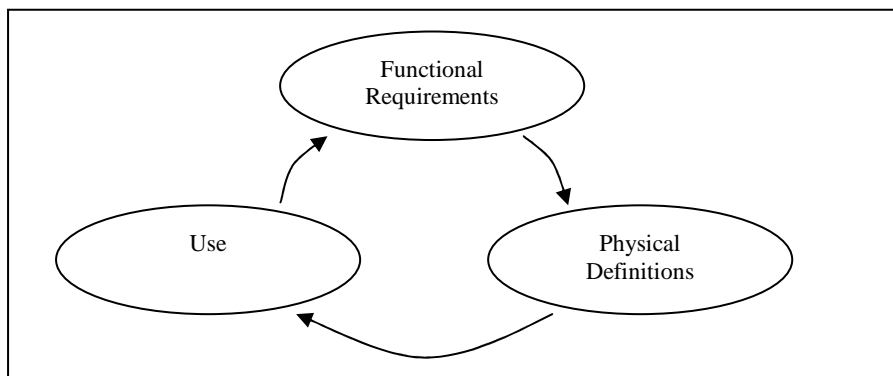


Figure 3.2: Logistics Life Cycle

In order to enable the comprehensive approach ILS interprets logistics widely. In this concept, logistics includes the following elements¹⁰:

- Maintenance planning
- Manpower and personnel
- Supply support
- Support and test equipment
- training and training devices

⁸ Admiral Galantin, US Navy department, 1969; source Finkelstein-Guertin, 1988, p.3

⁹ Jones, 1995, p. 1.3

¹⁰ Jones, 1995, p. 1.5., Finkelstein-Guertin, 1988, p.101-149

- Technical documentation
- Computer resources
- Packaging, handling, storage, and transportability
- Facilities
- Reliability and maintainability.

After this coverage it is a reasonable question what logistics does not include. On the other hand, logistics as a definition is clearly heading / developing from the concept of materials handling and transportation to the concept of “managing complex (business) operations”.

The most powerful element in the ILS approach is the ideology. The primary task provides the functional requirements. This sets the baseline for all the following planning activities. This also enables the concurrent engineering. The emphasis fits well in the process reengineering: the primary question is what the functional requirements are – after that comes the planning of everything else. With this approach the existing systems should not be considered at all during the preliminary system design because most often they become a burden for the planning and prevent from finding out the brand new ideas.

System Engineering (SE) forms an essential part of the ILS concept. In SE the key terminology consists of the following definitions¹¹:

Reliability

The probability that an item of equipment will perform its intended mission without failing, assuming that the item is used within the conditions which it was designed for.

Maintainability

The probability that a failed item can be repaired in a specific amount of time using a specified set of resources.

Supportability

The combination of support-related design requirements and ILS management, LSA (Logistics Support Analysis), and ILS element requirements.

Availability

Ability to use a system when required.

Availability is explained in various equations. Here some of those are shown¹²:

$$A = \frac{MTBF}{MTBF + MTTR} ; A = \frac{MTBM}{MTBM + M_{CMT} + M_{PMT}} ; A = \frac{MTBM}{MTBM + MDT}$$

- A = Availability
- MTBF = Mean Time Between Failure
- MTTR = Mean Time To Repair
- MTBM = Mean Time Between Maintenance
- M_{CMT} = Mean Corrective Maintenance Time
- M_{PMT} = Mean Preventative Maintenance Time

¹¹ Jones, 1995; Biedenbender etc, 1993, p. 7

¹² Jones, 1995, p. 5.2. – 5.4.

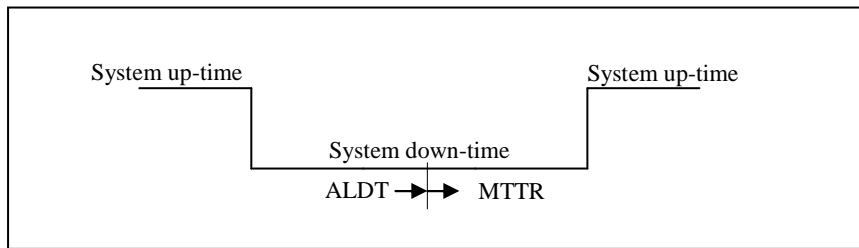
MDT = Mean Delay Time

The operational availability formula gives a bit different approach and is most applicable for hospital environment while focusing on the primary process:

$$A = \frac{OT + ST}{OT + ST + TCM + TPM + ALDT} , \text{ where}$$

A = Availability
 OT = Operating Time per year
 ST = Standby Time per year
 TCM = Total Corrective Maintenance time
 TPM = Total Prevent, Maintenance time
 ALDT = Administrative/Logistics Delay Time

To get practical understanding about the equation the time categories are shown here in the graph:



Graph 3.3: The system availability and support delays

This relates closely to time based management. The key issue is to focus on the time and time-based effectiveness. In the graph above the system availability can be improved if the delay times can be reduced as much as is reasonable. The availability behaves as the customer service: it can be improved but the closer to 100% it is the faster the costs increase. Therefore there is always a trade-off analysis to be made.

4. Framework for Hospital Logistics

In chapter 2 there were several definitions for logistics introduced. While examining the logistics research and consultation in hospital and medical environment it becomes very clear that all those are direct applications of business logistics. They are adapted in hospital environment only to examine – not the main flow, which is the primary process in business logistics – but the sub processes like blood logistics, supply logistics and the logistics of pharmaceuticals. All these applications are bottom-up approaches and thus details without the “big picture”. What has been missing is the top-down approach where the logistics is bound to the primary process in health care systems.

Little has made surveys in 50 hospitals in the USA and in this context he has given some comments and definitions. The other two definitions refer to service logistics.

”Supply chain is the traditional process associated with the acquisition and distribution of goods”¹³

The first one refers directly to business logistics. A good word to emphasise here is *traditional*: the traditional logistics which is applied as such directly in medical environment without any major modification.

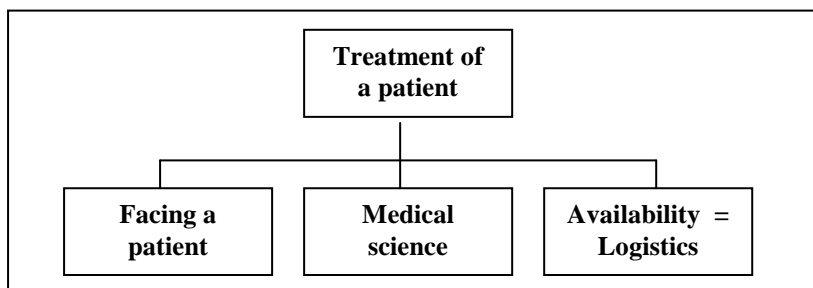
“Service response logistics is the process of coordinating nonmaterial activities necessary to the fulfilment of the service in a cost- and customer service-effective way”¹⁴

This definition pays attention to service and its impact on logistics approach. In medical environment the primary process – treatment of patients – is most of all service.

“Logistics is the process of anticipating customer needs and wants; acquiring the capital, materials, people, technologies, and information necessary to meet those needs and wants; optimising the goods- or service-producing network to fulfil customer request; and utilising the network to fulfil customer request in a timely way.”¹⁵

The last definition here shows the model of how to approach logistics in medical application. To get a sound foundation for the medical/hospital logistics considerations it is necessary to define the primary process, other processes, the relation between the medical science and logistical science and to find out the interfaces.

Customer service is the key word both in medicine and logistics. Based on that it is possible to accept that the hospital logistics framework must be based on the customer needs and customer satisfaction. The treatment of the patient is the thus the start for the whole framework. After that we have to divide the treatment into the elements to get in details. Logically the first step of the hospital logistics framework can be stated as in graph 4.1.



Graph 4.1: The role of logistics in medicine and medical care.

The only important issue is how well the patients can be taken care of. Based on medical and nursing literature the treatment can be divided into three main categories:

1. Facing a patient

The treatment is not only a moment when to show and use the knowledge of medicine. The patient has often a serious illness or defect. Therefore they are in a very sensitive

¹³ Little,1991, p. 10

¹⁴ Little, 1991, p. 11

¹⁵ Little, 1991, p. 11

mental condition. In order to get the patient along to the recovery process it is important to be able to take care of his mental condition as well.

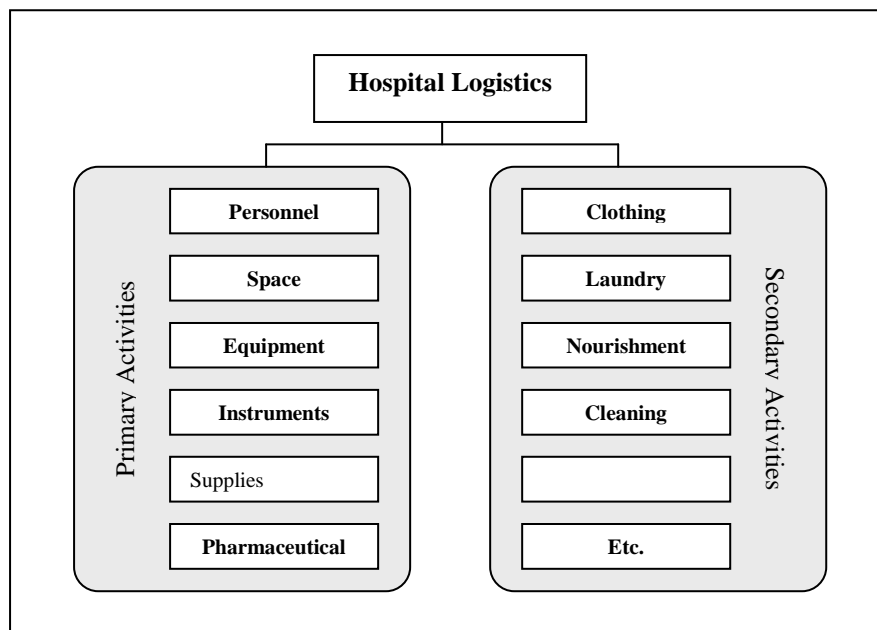
2. **Medical Science**

The foundation of the treatment is medical science and skilful doctors who can use their knowledge there.

3. **Availability**

We may have excellent personnel with unbeatable medical knowledge but it is not enough for successful treatment of a patient. The critical element needed can be called availability. And actually, availability is exactly what it is all about logistics.

From this moment we concentrate on the availability. The word logistics can be used as a synonym for it. The availability consists of the availability of personnel, space, equipment, instruments, supplies, pharmaceuticals and the support activities. The support activities are hospital clothing, laundry, nourishment, cleaning, and so on. In this research the support activities are excluded. In comparison with the ILS the similarities are relatively clear. The elements of the logistics support are now applied to the hospital environment. The whole logistics scheme can be described as in the following graph.

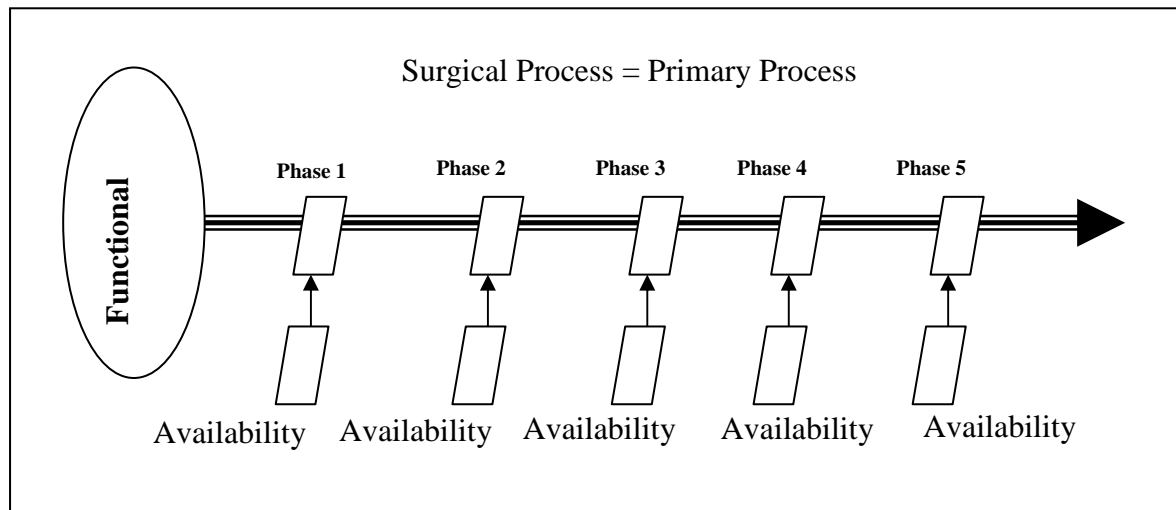


Graph 4.2: The scope of hospital logistics

The second step is to define the way to apply logistics in hospital environment. As said earlier, most of the logistics research concentrates on the small application areas in hospitals. The key question is how we see logistics. If we can accept the sub optimisation instead of total optimisation, the existing practice can continue. If we require total optimisation for the process, the approach must be different. The starting point is the examination of the functional requirements for the primary process¹⁶. In surgery the logistics focus cannot be the logistics of supplies nor the logistics of pharmaceuticals – it must be **the primary process which is the flow of patients**. In order to achieve the total optimisation we have to look at the functional requirements for **the surgical process** both from the medical science and patients point of view.

¹⁶ See the figure 3.2.

Based on the requirements the process can be defined. After that the logistics concept will be attached into it. The following graph visualises it.



Graph 4.3: Primary process and logistics

Medical science rules the foundation of the design of the primary process. The planning of the primary process must also follow the logistics principles in order to run the effectiveness and efficiency from the top of the system to its lower levels. If the system architecture is already made ineffective the logistics cannot contribute very much while adopted only in sub-processes.

4. The research challenges in future

The framework for the hospital logistics is made. Yet the name is still a question: should it be health logistics, medical logistics or hospital logistics? The continuing research will probably give an answer to that.

The next question is the tool box to design and plan the hospital logistics. The time-based management seems to be the most important area to examine first. That will provide a theoretical tool collection for this part of the framework. After time management most probably the supplies can be designed and managed with the business logistics tools. Anyway it seems to be important to form a ready-set tool box for hospital logistics in order to create a clear area of logistics application.

The constant problem is the invisible border between the logistics know-how and medical know-how. How far can a logistician go without having medical education? How far can a logistician plan medical processes? On the other hand, there are always medical specialists to give assistance when the process design needs their expertise.

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Bird Strike as a Mechanism of the Motion in Mirce-mechanics

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Abstract

Birds represent a serious, but often misunderstood, threat to aircraft. Most bird strikes do not result in any aircraft damage, but some bird strikes have led to serious accidents involving aircraft of every size. According to Bird strike Committee USA, bird and other wildlife strikes to aircraft result in over \$600 million in damage to U.S. civil and military aviation each year. The lives of the crew and passengers are also at risk. Since 1988, over 200 people have been killed worldwide as a result of encounters with birds and other wildlife. Thus, this paper addresses bird strike from Mirce-mechanics point of view, which means that it is considered as a mechanism that generates a functionability event which causes the motion of a system from positive to negative functionability state. The paper provides vital information about the physical properties of most common birds that are required for predictions of their impacts on aircrafts, at the design stages as a scientific method for the evaluation of alternatives.

1. Introduction

Birds first took to the air about 150 million years ago. Humans first took to the air on 17th December 1903. Consequently, when aircraft and birds are destined to use the same airspace at the same time, collisions occur. The first collision came soon, on 7 September 1905. From the Wright Brothers diaries, “Chased flock of birds for two rounds and killed one which fell on top of the upper surface and after a time fell off when swinging a sharp curve.” [1] This was the first reported bird-aircraft strike. Because of the location near Dayton, Ohio, and time of year, the bird struck was probably a red-winged blackbird. The first fatally came on April 3, 1912, while making an exhibition flight over Long Beach in California, Calbraith. Perry Rogers flew into a flock of birds, causing the plane to crash into the ocean. He died from a broken neck and damaged thorax by the engine of the aircraft.

Since those initial bird strikes, aircraft designs and performance have changed dramatically and bird strike populations increased together with air traffic. As a result, over 125 civil aircraft have been destroyed and over 255 civilian lives have been lost worldwide due to bird strikes from 1960 to 2004. [2] During this same period, bird strikes have resulted in at least 333 military aircraft destroyed and over 150 military personnel killed. [5]

The onset of the jet age revolutionized air travel, but magnified the bird strike problem. Early piston-powered aircraft were noisy and relatively slow. Bird strike could usually avoid these aircraft, and strikes that did occur typically resulted in little or no damage. However, modern jet aircraft are fast and relatively quiet, and their engine fan blades are often more vulnerable than

propellers to bird strike damage. When turbine-powered aircraft collide with birds or other bird strike, serious structural damage and engine failure can occur.

Multiple-engine damage from the ingestion of flocks of birds is of particular concern as the fleet of two-engine passenger aircraft increases in the USA. In 1969, 75% of the 2,100 passenger aircraft had 3 or 4 engines. In 1998, the fleet had grown to 5,400 primarily turbine-powered aircraft, of which only 30% had three or four engines. By 2008, the fleet consisted of about 7,000 aircraft, and less than 10% have had three or four engines.

Air travel has become a global phenomenon. Aircraft have also assumed a vital role in tactical and logistical military operations. These factors have resulted in increased air traffic. For example, commercial air movements in the USA increased about 3% per year between 1985 and 2004.

Environmental protection programs, world wide, have contributed to considerable increases in populations of many large-bodied species such as cormorants, cranes, geese, gulls, herons, pelicans, falcons, hawks, eagles, owls, vultures and wild turkeys.

Almost all of these species have body masses over 4 pounds (1.8 kg), which exceed the airframe and engine certification standards for bird strike strikes. These concurrent increases in air traffic and bird strike populations contribute to an increased probability of damaging bird strikes. These two factors, combined with the increased speed, quietness, and vulnerability of modern aircraft, interact to form the basis of the bird strike problem that airport manager's face. As a final factor, airport managers also face increased concerns about airport liability in the aftermath of damaging bird strike strikes

Bird strike is attracted to an airport environment because desirable food, water, or habitat is present. The majority of bird strike strikes occur within the immediate airport environment: 74% of all strikes occur at or below 500 feet above ground level (AGL). Eighteen of the 19 civil and military large-transport aircraft destroyed because of bird strikes between 1960 and 2004 resulted from strikes that occurred on the airport. Therefore, most bird strike involved in strikes is using the airport or its immediate vicinity, and the most logical place to begin correcting the problem is on and near the airport.

Consequently, using principles of Mirce-mechanics this paper considers a bird strike as a mechanism that generate sufficient mechanical energy to cause occurrence of a negative functionability event, NFE, that causes the motion of a system from positive to negative functionability state, NFS.

2. Mirce-mechanics

Mirce-mechanics: is a scientific theory of the motion of functionability through the life of maintainable systems. Its axioms, mathematical formulas, rules and methods enable accurate predictions of a system's measurable functionability performance characteristics like reliability, availability, punctuality and others to be made with probabilistic regularity. [3]

According to Mirce-mechanics the motion is the change of a state of a maintainable system in relation to fissionability, in respect to time. All physical phenomena that cause the motion of a system from the positive to negative functionability states are known as negative functionability

events. Mechanisms that generate negative functionability events belong to the following three categories:

- **Overstress mechanisms**, where acting stresses generated by mechanical, electrical, thermal, radiation, chemical and other type of energy exceed that strength of components and systems subjected, resulting from phenomena like foreign object damage (birds, hail, rain, snow), lightening, abuse by operators and similar
- **Wearout mechanisms**, where cumulative damage, generated by mechanical, electrical, thermal, radiation, chemical and other type of energy, is accumulated through processes like, corrosion, fatigue, creep, wear and similar.
- **Human actions**, where the transition from positive to negative state results from direct decision taken by humans. Most frequently these actions are performed as a part of scheduled maintenance tasks performed to check the state of a system, to preventively replace predetermined components or to install modified components.

Hence, to understand the 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. It has lead to the formulation of the 1st Axiom of Mirce-mechanics, which states, *“The probability of the motion to negative functionability state at any instant of time is greater than zero”* [3]. As it has a profound impact on all aspects of the in-service life on any maintainable system several research studies have been performed by the Master and Doctoral students of the MIRCE Akademy with aim to understand the physical mechanisms that caused their occurrences.

Using the same method and principles of Mirce-mechanics as Zaczyk [7] this paper addresses bird strike from Mirce-mechanics point of view. It means that a bird strike is considered an overstress mechanism that generate sufficient mechanical energy to generate a negative functionability event, NFE, that causes the motion of a system from positive to negative functionability state, NFS.

3. Selected Examples of Bird Strikes in Aviation Industry since 1960

The U.S. Department of Agriculture, through an interagency agreement with the Federal Aviation Administration, compiles a database of all reported bird/wildlife strikes to U.S. civil aircraft and to foreign carriers experiencing strikes in the USA. Over 87,000 strike reports from over 1,650 airports have been compiled, 1990-2008 [2]

The FAA estimates that this represents only about 20% of the strikes that have occurred. The following historical examples of strikes from 1905-1989 and examples from the database from 1990-2008 are presented to show the serious impact that strikes by birds or other wildlife can have on aircraft. These examples demonstrate the widespread and diverse nature of the problem and are not intended to criticize individual airports. Many of the strike examples reported here occurred off airport property during descent, approach or climb.

Selected examples of the bird strikes from [2] are presented below:

- A Lockheed Electra turbo-prop ingested European starlings into all four engines during takeoff from Boston Logan Airport (Massachusetts). The plane crashed into Boston

Harbor, killing 62 people, on 4th October 1960. Following this accident, the FAA initiated action to develop minimum bird ingestion standards for turbine-powered engines.

- On 26th February 1973 at the departure from Atlanta's Peachtree-Dekalb Airport (Georgia), a Lear 24 jet struck a flock of brown-headed cowbirds attracted to a nearby trash disposal area. Engine failure resulted. The aircraft crashed, killing seven people and seriously injuring one person on the ground. This incident prompted the FAA to develop guidelines for the location of solid waste disposal facilities on or near airports.
- On departure roll from John F. Kennedy International Airport (New York), the pilot of a DC-10 aborted takeoff after ingesting gulls into one engine, on 12 November 1975. The plane ran off runway and caught fire as a result of engine fire and overheated brakes. The resultant fire destroyed the aircraft. All 138 people on board were evacuated safely.
- A Convair 580 departing Kalamazoo Airport (Michigan) ingested one American kestrel into an engine on take-off, on 25 July 1978. The aircraft crashed in a nearby field, injuring 3 of the 43 passengers.
- In 1980; Royal Air Force Nimrod aircraft lost control and crashed after ingesting a number of birds into multiple engines at Kinross, Scotland.
- The pilot of a Bellanca 1730, during the landing process at Clifford, Texas, saw two "buzzards" on final approach. Hence, he added power and maneuvered to avoid them, then continued approach, which resulted in a landing beyond the intended point. As the middle of the runway was higher than either end, the pilot was unable to see a large canine moving toward the landing area until the aircraft was halfway down the runway. A go-around was initiated, but the lowered landing gear hit some treetops causing the pilot to lose control. The aircraft came to rest about 250 yards from initial tree impact after flying through additional trees. The aircraft suffered substantial damage, and two people in the aircraft were seriously injured. The event took place on 18 June 1983.
- In September 1987; U.S. Air Force B1-B lost control and crashed after an American white pelican struck the wing root area and damaged the hydraulic system. The aircraft was on a low level, high speed training mission in Colorado, USA. Only three of the six occupants have survived this negative functionality event.
- On the 5th November 1990, during takeoff at Michiana Regional Airport (Indiana), a BA-31 flew through a flock of mourning doves. Several birds were ingested in both engines, and take-off was aborted. Both engines were destroyed. Cost of repairs was \$1 million, and time in NFS was 60 hours.
- A Citation 550, taking off from Angelina County Airport (Texas), on 30th December 1991, struck a turkey vulture. The strike caused major damage to the engine number 1 and resulting shrapnel caused minor damage to the wing and fuselage. Cost of repairs was \$550,000 and time in NFS was 2 weeks.
- On the 3rd December 1993, a Cessna 550 struck a flock of geese during the initial climb out of Du Page County Airport (Illinois). The pilot heard a loud bang, and the aircraft yawed to the left and right. Instruments showed loss of power to engine number 2 and a substantial fuel leak on the left side. An emergency was declared, and the aircraft landed

at Midway Airport. The cost to repair two engines was \$800,000, and time the aircraft spent 3 months in NFS.

- An Air France Concorde, at about 10 feet AGL while landing at John F. Kennedy International Airport (New York), ingested one or two Canada geese into engine number 3, on the 3rd June 1995. The engine suffered an uncontained failure and its shrapnel destroyed the engine number 4 and cut several hydraulic lines and control cables. The pilot landed safely, but the runway was closed for several hours. The repair cost was around \$7 million.
- Airborne Warning and Control System aircraft (known as AWACS) crashed on 22nd September 1995 killing all 24 on board. The cause of accident was ingestion of four Canada geese into engines 1 and 2 during take-off from Elmendorf Air Force Base (Alaska).
- NATO E-3 AWACS aircraft struck a flock of birds during takeoff at Aktion Airport in Greece, on 14 July 1996. The crew aborted the takeoff and the aircraft overran the runway. The aircraft was not repaired; none of the crew was seriously injured.
- On the 15th July 1996; Belgian Air Force Lockheed C-130; struck a large flock of starlings during approach to Eindhoven, Netherlands and crashed short of the runway. All four members on the crew and 30 of the 37 passengers were killed.
- A Boeing-727 departing Washington DC Reagan National Airport struck a flock of gulls just after takeoff, ingesting at least one bird, on 5 October 1996. One engine began to vibrate and was shut down. As the burning smell entered the cockpit, the pilot declared an emergency, and the aircraft, carrying 52 passengers, landed at Washington Reagan National. Several engine blades were damaged
- On the 7th January 1997, an MD-80 aircraft struck over 400 blackbirds just after take-off from Dallas-Fort Worth International Airport (Texas). Almost every part of the plane was hit. The pilot declared an emergency and safely landed. Substantial damage was found on various parts of the aircraft, and engine number 1 had to be replaced. The runway was closed for 1 hour. The birds had been attracted to an un-harvested wheat field close to the airport.
- While climbing through 3,000 feet, following takeoff from Houston Intercontinental Airport (Texas), on 9 January 1998, a Boeing-727 struck a flock of snow geese with three to five birds ingested into one engine. The affected engine lost all power and was destroyed. The radome was torn from aircraft and leading edges of both wings were damaged. The Pitot tube for the first officer was torn off. After declaring emergency the flight returned safely to Houston with major damage to aircraft.
- On the 22nd February 1999, a Boeing-757 departing Cincinnati/Northern Kentucky International Airport was forced to return and make an emergency landing after hitting a large flock of starlings. Both engines and one wing received extensive damage. Around 400 dead starlings were found on the runway area.
- DC-10-30, belonging to an American-owned cargo company, ingested a fruit bat into one engine at 250 feet AGL, while departing from Subic Bay, Philippines, on 7th February

2000. The aircraft returned to the airport safely. Five damaged fan blades had to be replaced keeping aircraft negative functionability state for 3 days. Total repair and related costs exceeded \$3 million.

- An MD-11 departing Portland International Airport (Oregon), on 21st January 2001 ingested a herring gull into engine number 3 during the takeoff run. The engine stall blew off the nose cowl that was sucked back into the engine and shredded. The engine had an un-contained failure. The pilot aborted take-off and safely landed 217 passengers, with two blown tires.
- On the 9th March 2002, a Canadair RJ 200 at Dulles International Airport, Washington DC, struck two wild turkeys during the takeoff roll. One of them shattered the windshield spraying the cockpit with glass fragments and remains.
- A Boeing 767 departing Logan International Airport in Boston, encountered a flock of over 20 double-crested cormorants, on 19 October 2002. At least 1 cormorant was ingested into engine number 2. There were immediate indications of engine surging followed by compression stall and smoke from the engine. The engine was shutdown. An overweight landing with one engine was made without incident. The nose cowl was dented and punctured. There was significant fan blade damage with abnormal engine vibration. One fan blade was found on the runway. The aircraft was towed to the ramp. Hydraulic lines were leaking, and several bolts were sheared off inside engine. Many pieces fell out when the cowling was opened. The aircraft spent 3 days in negative functionability state and the total repair bill was \$1.7 million.
- A Bombardier de Havilland Dash 8 collided with a flock of lesser scaup ducks at 1,300 feet AGL on approach to Rogue Valley International Airport (Oregon) on the 8 January 2003, At least one bird penetrated the cabin and hit the pilot who turned control over to the first officer for landing. Emergency power switched on when the birds penetrated the radome and damaged the DC power system and instruments systems.
- On the 4th September 2003, a Fokker 100 struck a flock of at least five Canada geese over the runway shortly after take-off at LaGuardia Airport (New York), ingesting one or two geese into engine number 2. The pilot was unable to shut the engine down with the fuel cutoff lever, so the fire handle was pulled and the engine finally shut down. The flight was diverted to nearby JFK International Airport where a landing was made. A depression on the right side of nose behind radomes was found with a maximum depth of 10 cm. Impact marks were found on the right wing. A fan blade separated from the disk and penetrated the fuselage. Several fan blades were deformed. Holes were found in the engine cowling. Bird remains were recovered and identified by Wildlife Services.
- A Boeing 757 during a takeoff run from Portland International Airport (Oregon) hit five mallards and returned with one engine out, on 17 February 2004. At least one bird was ingested, and parts of five birds were collected from the runway. As the damaged engine was beyond repair, the new one was fitted at the cost of \$2.5 million, keeping the aircraft 3 days in NFS.
- An Airbus 319 climbing out of Portland International Airport (Oregon) ingested a great blue heron into engine number 2, causing extensive damage, on 15 April 2004. The pilot shut the engine down as a precaution and made an emergency landing. The runway was

closed 38 minutes for cleaning. The engine and nose cowl were replaced at the cost of \$388,000, keeping aircraft in NFS for 72 hours.

- A great horned owl, on 14 June 2004 struck a Boeing 737 during a nighttime landing roll at Greater Pittsburgh International Airport (PA). The bird severed a cable in front main gear and disabled the steering system causing the aircraft ran off the runway and became stuck in mud. Passengers were bused to the terminal. Repair team replaced 2 nose wheels, 2 main wheels and brakes keeping the aircraft negative functionality state for 24 hours at the total cost of \$20,000.
- Departing Chicago O'Hare (Illinois), on 16 September 2004, a MD 80 hit several double-crested cormorants at 3,000 feet AGL and 4 miles from airport. Engine number 1 caught fire and failed, sending metal debris to the ground in a Chicago neighborhood. The aircraft made an emergency landing back at O'Hare with no injuries to any of the 107 passengers.
- On the 24th October 2004. A Boeing 767 departing Chicago O'Hare (Illinois) hit a flock of birds during the take-off run. A compressor stall caused the engine to flame out. A fire department got calls from local residents who reported seeing flames coming from the plane. The pilot dumped approximately 11,000 gallons of fuel over Lake Michigan before returning to land.

4. Effects of Bird Strike

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

Small, propeller-driven aircraft are most likely to experience the hazardous effects of strikes as structural damage, such as the penetration of flight deck windscreens or damage to control surfaces or the empennage.

Larger jet-engined aircraft are most likely to experience the hazardous effects of strikes as the consequences of engine ingestion. Partial or complete loss of control may be the secondary result of either small aircraft structural impact or large aircraft jet engine ingestion. Loss of flight instrument function can be caused by impact effects on the Pitot Static System air intakes which can cause dependent instrument readings to become erroneous.

Complete Engine failure or serious power loss, even on only one engine, may be critical during the take-off phase. In the case of bird ingestion into more than one engine, all aircraft are vulnerable to loss of control. Such hazardous ingestion is infrequent but may result from the penetration of a large flock of medium sized birds or an encounter with a smaller number of very large ones.

In some cases, especially with smaller fixed wing aircraft and helicopters, windscreen penetration may result in injury to pilots or other persons on board and has sometimes led to loss of control. Although relatively rare, a higher altitude bird strike to a pressurised aircraft can cause structural damage to the aircraft hull which, in turn, can lead to rapid depressurisation. A more likely cause of difficulty is impact damage to extended landing gear assemblies in flight,

which can lead to sufficient malfunction of brakes or nose gear steering systems to cause directional control problems during a subsequent landing roll.

A relatively common but avoidable significant consequence of a bird strike on the take off roll is a rejected take off decision which is either made after V_1 or which is followed by a delayed or incomplete response and which leads to a runway excursion off the departure end of the runway.

5. Determination of Impact Force

In classical mechanics impulse or impact refers to something that changes momentum of an object. The impulse of force acting for a given time interval is equal to the change in linear momentum produced over that interval. It is denoted as J and it is quantified through the product of a force, F , and the time, t , during which it acts. Impulse is a vector quantity since it is the result of integrating force, a vector quantity, over time. The SI unit of impulse is the Newton second (Ns) or, in base units, the kilogram meter per second (kg·m/s).

Based on the above, for the cases where the mass is constant, the impulse is defined as:

$$J = F\Delta t = mV_f - mV_i \quad 1.$$

where

F is the resultant force applied,

Δt duration of impact

m is the mass of the object,

v_2 is the final velocity of the object at the end of the time interval,

v_1 is the initial velocity of the object when the time interval begins.

Under the following assumptions the equation 1 becomes equation 2:

- Head on collision
- Bird is riding with the aircraft after the collision
- Bird's velocity is negligible compared to that of the aircraft
- Total time taken to crush the bird (estimated impact time)
- Impulsive applied to the bird

$$F = \frac{mV_f}{\Delta t} \quad \left[\frac{kgm}{s^2} \right] \quad 2.$$

The above expression could be used for the calculation of the force generated by the collision between an aircraft. The estimated impact time, for all practical purposes, could be determined as a ratio of the length of the bird, LB , and the speed of the aircraft, AV , thus:

$$\Delta t = \frac{BL}{AV} \quad [s] \quad 3.$$

For example, the impact force will be 101338 N (10.3 tonnes) will be generated in the collision between an aircraft that flies 260 m/s and a bird whose length is 20 centimeters and weight 300 grams.

6. Bird Strike Related Research at the MIRCE Akademy

During the last 15 years extensive research studies were performed, by numerous students and members of staff of the MIRCE Akademy, where a large number of negative functionability phenomena were observed and analysed like inherent failures, maintenance errors, foreign object damage, as-bad-as-old repairs, not fault found, ageing processes, storage and transport related phenomena, fatigue cracks, impact of solar radiation, sand, wind, ice on system machine durability, material vacancies and many others.

6.1 Dimensions and Habitation Analysis of Birds

During the summer 2013 the research was conducted to determine the physical characteristics of birds that have the most frequent and consequential impact on the aircraft safety. The objectives of the research were to collect the data regarding the physical properties of birds, like their weight and length, which is necessary information for the calculation of the impulse force to be made in accordance to the equation 2, for various types of aircraft.

The same research was also focused on the determination of the geographical locations of their habitats, as vital information for the flying public in the related area of the world. The following two examples will be used to illustrate the importance of location and the seasonal impacts on the birds

1. It has been determined that Israel has the world's largest density of migrating birds during the migration season. Consequently, since 1972 the total number of bird strikes recorded in Israel was [10]:
 - 637 with transport planes and light aircraft.
 - 696 with helicopters,
 - 1,282 with military aircraft,
2. From their Arctic breeding grounds in Canada and Greenland, each autumn, greater snow goose arrive to Chincoteague National Wildlife Refuge, Virginia and near by Atlantic coast of USA The greater snow goose population increased from about 50,000 birds in 1966 to over 700,000 birds in 2004.

A concise summary of the information obtained, regarding the weight, height and habitation of birds most frequently involved in collisions with aircraft, during this research project is presented in Table 1.

Family	Type of bird	Weight [kg]		Length [m]		Where found
		min	max	min	max	
Penguins	Emperor	22.70	45.40	1.10	1.30	Antarctica
	Southern					Pacific and Indian Oceans, South
	Rock hopper	2.00	3.40	0.48	0.58	America
	Magellanic	2.70	6.50	0.61	0.76	Chile, Argentina, Falkland Islands
	American Robin	0.06	0.09	0.23	0.28	Southern Canada, USA (Towns, parks, gardens)
Robin	European					All over Europe (Towns, parks, gardens)
	Robin	0.02	0.02	1.25	1.40	
Eagle	Harpy Eagle	4.00	9.00	0.97	1.00	Near rainforests in Central and South America
	Golden Eagle	2.50	3.25	0.66	1.02	Asia, USA, Scotland, Spain etc
	African Crowned Eagle	2.55	4.70	0.80	0.99	Southern Africa-(forests)
Hawk	Red shouldered Hawk	0.55	0.70	0.43	0.58	USA
	Ferruginous Hawk	0.95	2.30	0.51	0.69	North America
	Sparrow Hawk	0.19	0.34	0.29	0.41	Europe, Ireland, Canary Islands
Gulls	Black-headed Gull	0.25	0.33	0.38	0.44	North America, Canada, Europe
	Common Gull	0.29	0.48	0.40	0.46	Asia, Northern Europe, American
	Iceland Gull	0.82	1.10	0.50	0.64	Iceland, Arctic
Geese	Canadian	2.50	6.50	0.75	1.10	North America, Northern Europe
	Chinese	4.00	10.00	0.50	0.76	Asia
	Bar Headed	1.87	3.20	71.00	76.00	Central Asia
Raven	White-necked	0.76	0.87	0.50	0.54	Eastern and Southern Africa
	Northern	0.69	2.00	0.56	0.78	Northern hemisphere
Vulture	Black vulture	1.60	2.75	0.56	0.74	Canada, USA, Mexico, South America
	Red headed	3.50	6.30	0.76	0.86	Southeast Asia, Indian Subcontinent
	Ruppell's	6.40	9.00	0.85	1.03	Central Africa
Sparrow	Chestnut	0.01	0.02	0.11	0.12	East of Africa, Darfur, Tanzania
	House	0.02	0.04	0.14	0.18	Europe, Asia, Australia, Africa, America
	Eurasian tree	0.02		0.13	0.14	Eurasia, Southeast Asia
Swans	Coscoroba	3.20	5.40	0.88	1.15	South America
	Black swan	3.70	9.00	1.10	1.42	Australia, New Zealand
	Whooper swan	8.20	11.40	1.40	1.65	Iceland, Subarctic Europe, Asia
	American Hooded	0.32	0.62	0.40	0.53	North America, Arctic
Crows		0.51		0.48	0.52	Northern, Eastern and South-Eastern Europe, Middle East
						Europe, Asia, North Africa,
Ducks	Mallard	0.72	1.58	0.50	0.65	America, New Zealand, Australia
	Mandarin	0.63	1.08	0.41	0.49	East Asia, Europe
	Gyrfalcon	0.81	2.10	0.48	0.65	Arctic, islands of North America,
Falcon						Europe and Asia
	Peregrine	0.42	1.50	0.34	0.58	Canada, Europe, parts of Asia

Table 1. Physical Characteristics and Habitats of the Birds Significant for the Aviation

The information presented in Table 1 is of significant importance to the aircraft designers that continuously face decisions regarding the shapes and forms of the future aircraft in the respect to the strengths of materials used for fuselage and wings. This is one of the main drivers of the design, as the negative functionality events will take place at any instant of time when the acting loads on the aircraft exceed the strength of materials used, thus:

$$\{NFE\} = \{Acting\ Load > Strength\ of\ Material\} = (L > S) \quad 4.$$

Impact of the collision between high velocity flying aircrafts and birds of a mass of several kilograms generates significant stresses on aircraft structure, which could be quantified by applying approximation method presented above (Equation 2.) Hence, the results of this research are the basis on which the active loads, generated by bird strike, could be calculated and the impulse forces quantified.

Also the information gathered in this research is beneficial to the planners and designers of the future airports and their wild life managers, as the evolutionary habits and migration paths of birds cannot be instantly changed with opening of a new airport; however it may be important to the local businesses and population.

6.2 Further Research

One approach to resolve the aircraft bird strike problem is to design aircraft components that would withstand loads imposed by striking birds, allowing safe operation until landing. The most vulnerable components, transparencies and jet engines, are designed and evaluated using computer models and full scale tests. These testing techniques utilize bird measurement data. Currently, due to a lack of available data, scientists and test engineers assume that the bird density is constant.

However, in zoology it is readily available information that the percent of body mass represented by feathers differed among species, but not by sex species. For example herring gulls, vultures and laughing gulls had around 10 % of their body mass in feathers while starlings, sparrows and rock dove have around 3 % of their body mass in feathers.

Bird density appears to reflect their life history. For example gulls and waterfowl both associated with long, continuous flights and floating on water, are the examples of low density species, while turkeys and vultures were a low density species that exhibit good soaring efficiency. European Starlings, House Sparrows, Common Grackles, and Brown-headed Cowbirds, among the densest species, do not depend upon these qualities for survival.

As domestic chickens are primarily terrestrial birds and have been bred to increase the muscle mass they carry, they are much denser than the wild bird species. Consequently, to use the domestic chicken for an aircraft bird strike test species may be appropriate as it represents a worst case due to its high density.

Consequently, to increase the accuracy of the predictions of the impulse forces impacting the structure of an aircraft resulting from the collisions with birds it is necessary to know bird densities. To know bird density it is necessary to determine mass, wingspan, and circumference

measurements of birds. Determining these measures for the family and type of birds listed in Table 1 is the next project to be completed at the MIRCE Akademy.

7. Conclusion

Since birds and aircrafts share the same space it is inevitable that collisions between them will take place. Evidently, these collisions have negative impact on both parties. Hence, it is necessary to establish a scientifically based relationship between both parties in respect to each other and with the natural environment they share.

Using principles of Mirce-mechanics, in this paper a bird strike is considered as a mechanism that generate sufficient mechanical energy to cause the occurrence of a negative functionality event resulting in the motion of a system from positive to negative functionality state.

The results of the research conducted at the MIRCE Akademy to determine the physical characteristics of a selective group of birds, namely those that have the most frequent and consequential impact on the aircraft safety, is presented in this paper. The objectives of the research were to collect the data regarding the physical properties of birds, like their weight and length, which is necessary information for the calculation of the impulse force to be made for various combinations of aircrafts and birds.

Ability to predict a magnitude of the future acting loads, generated by the impact of birds on aircrafts is crucial for many design decisions that have to be made at conceptual stages of the creation of the future aircrafts, regarding their safety and reliability, starting from material selections engine location, fuselage shape and many others. Naturally, all of these decisions are sensitive to the geographical locations expected to be used for the aircraft under consideration as well as the potential limitations that might be applied for a restricted flights during the migration seasons over certain corridors.

8. Acknowledgment

All the information contained in the Table 1 has been collected and produced at the MIRCE Akademy, under author's supervision, by Miss Amy Wyatt a student of the Exmouth Community College, as a part of the collaboration between these two Educational Institutions in Devon, UK.

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Efficient Learning of Failure Detection, Understanding and Prevention: Case Trial Bike

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Abstract

Authors lectured this spring a course titled Supportability Analysis and Design for a group of about 20 second-year engineering students in Jyväskylä University of Applied Sciences. The course aimed at showing how various logistic support analyses help the engineers to improve design, maintenance and support of systems while keeping the life cycle cost at a reasonable level. These analyses included elements of reliability theory; failure identification methods; failure rate calculations; criticality estimations; availability, maintainability and safety issues; reliability centred maintenance topics; level of repair analysis; and cost calculation. To bring the theory into practice we presented a case study.

1. Introduction

Authors lectured this spring a course titled Supportability Analysis and Design for a group of about 20 second-year engineering students in Jyväskylä University of Applied Sciences. The course aimed at showing how various logistic support analyses help the engineers to improve design, maintenance and support of systems while keeping the life cycle cost at a reasonable level. These analyses included elements of reliability theory; failure identification methods; failure rate calculations; criticality estimations; availability, maintainability and safety issues; reliability centred maintenance topics; level of repair analysis; and cost calculation. To bring the theory into practice we presented a case study. The students were divided into five groups and given the following problem.

You run a team taking part in an outdoor trial racing season for the summer 2007. Your team consists of the driver and yourself playing all the other roles from mechanic to manager. Your team has purchased a second hand Italian 250 cc 2-stroke race trial bike Beta rev3 and is going to run it for one season. Your task is to maintain and support the bike as a system. This includes modifying the bike to better fit your team's purposes, organizing the preventive maintenance during off-race periods, repairing the bike after the races, ordering spares and the rest. Of course, your budget is limited. After the season, you sell the bike.

We would like to share with you our students' findings. Our point of view is that of learning. But after all, aren't we all learning from our systems?

Most of the students had very little practical experience on mechanical or electrical systems. Therefore the course included several practical tasks that aimed at getting the students familiar with the system at hand. The bike was put in a garage for the students to have their hands get dirty.

Learning task 1. At the moment, the bike is not fully operational due to incomplete repair after the previous season. Identify the existing failures.



Figure 1. Beta rev3 trial bike



Figure 2. Front suspension

The following five failures – all of which had accumulated during last racing season – should have been detected:

1. Punctured rear tyre
2. Leaking seal in the front suspension, see figure 2
3. Loose foot rest seat, see figure 3
4. Loose dust seals in clutch and front brake levers, see figure 4
5. Loose front wheel bearings



Figure 3. Foot rest



Figure 4. Clutch lever

With the help of the teacher, it took approximately 20 minutes for a typical student to spot all five. Obviously quite a lot of experience is needed for one to see what makes the system fail. Even more experience is needed to repair the failure.

Learning task 2. Remove the rear wheel. Install and align a spare. How long does it take?

Replacement or repair typically consists of four activities shown in the following diagram.

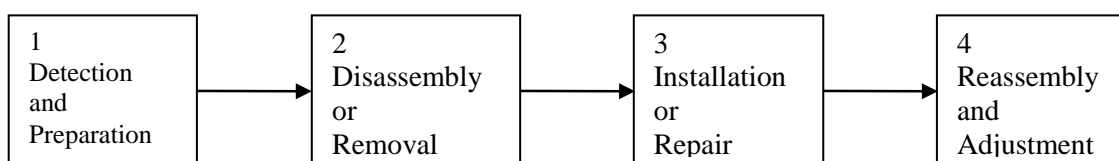


Figure 5. Corrective maintenance activities

The five student groups– having names from A to E – were timed. The results they achieved were very different and are shown in the following table.

Group	A	B	C	D	E
Activity 1	8:15				
Activities 2-4	11:05	4:48	6:56	1:15	2:10
Total time	19:20	13:03	15:11	9:30	10:25

Table 1. Times to finish activities in min:sec

The time to detect the puncture (activity 1) had to be chosen the same for all groups since the first student to spot it could not keep it to himself.

The mean removal time turns out to be 30 minutes and the standard deviation 4 minutes. The average time seems to be too long to be accepted in a racing situation. What is more interesting; the data shows a nice learning effect.

Learning task 3. Estimate how fast an experienced mechanic would change the tyre.

The idea here is show the effect of learning that is supported by good documentation. The graph below is produced by Microsoft Excel.

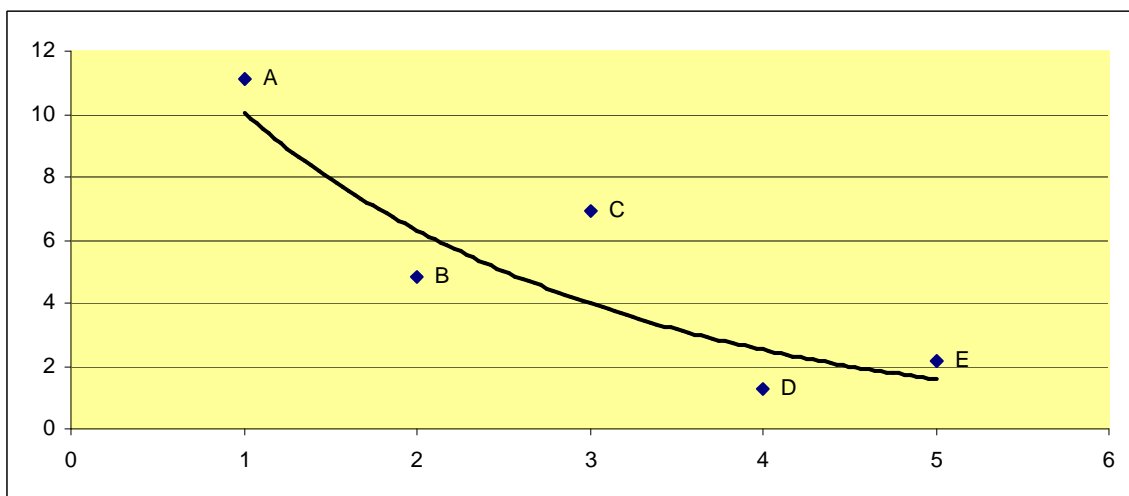


Figure 6. Learning curve estimation

Obviously, mean or median times tend to give too large estimates for the repair time.

Learning task 4. Identify the critical failures during a race. How can you prepare for them?

The students were asked to analyse the failure modes, their rate of occurrence and their severity. As no one of them had much prior experience on motorbikes, a possibility to ask for expert opinion was given. They were also given an event log (see Appendix 1) showing the maintenance actions on a similar bike.

The students proceeded to estimate the number of different failures and the need of spares after which they contacted the motorbike importer to find out current spare part prices. Finally they wrote a maintenance and support plan including cost calculation for the racing season. A part of this analysis is shown in Appendix 2.

Each student group focused on specific parts of the bike. Below is a list of questions and remarks the students thought to be relevant to supporting the functionality of their subsystems.

A. Lubrication, fuel and suspension

- how to ensure that correct 2-stroke oil is used
- how to be sure that 2-stroke oil is added in the gasoline
- how to ensure that different types of oils are not mixed accidentally (hydraulics vs. 2-stroke)
- how to keep the front brake working in case of leakage in the suspension
- is it reasonable to have a shock absorber in stock (it costs over 700 €)
- how often should gear box and hydraulics oil be changed? (wet conditions vs. fine sand)
- is chemical analysis of oil needed?

B. Brakes, tires and change of tires

- how often and how to check wear of the brake pads and the discs
- how to clean the brake pads during the competition (excellent grip needed)
- how to be prepared for puncture (tubeless back tire/tube type front tire)
- is it enough to avoid sharp stones?
- which level of wear in the tires is acceptable (costs vs. benefits)

C. Chains and sprockets, wires and hoses

- how to lubricate the chain (during service/training/competition)
- can you at all prepare for an accidental chain break
- these are all critical parts
- chain, sprockets, wires and cooling hose are cheap and easy to change (have them always available)
- hydraulic hoses are difficult to change (keep in team stock, training required?)

D. Crankshaft, piston and gaskets (Engine)

- training and competition circumstances are very different (dust/sand/mud/sharp stones etc.)
- how to keep the air filter and carburettor clean
- how often to adjust the carburettor (altitude, air imperfections and humidity)
- wearing of bearings and seals in the crankshaft system
- correct changing interval of the piston (depends on operation profile)

E. Electrical components and cooling

- electrical system as a whole is very simple and robust

- easy to maintain

Common questions to all groups were those concerning the stock keeping. Which spares must be available at all times at the team's use, which is ordered from the importer and which from the manufacturer? How can one accurately estimate the number of spares needed?

Figure 7 shows a typical motorbike wiring diagram. The design in the Beta racing bike is much more simplified as can be seen from Figure 8.

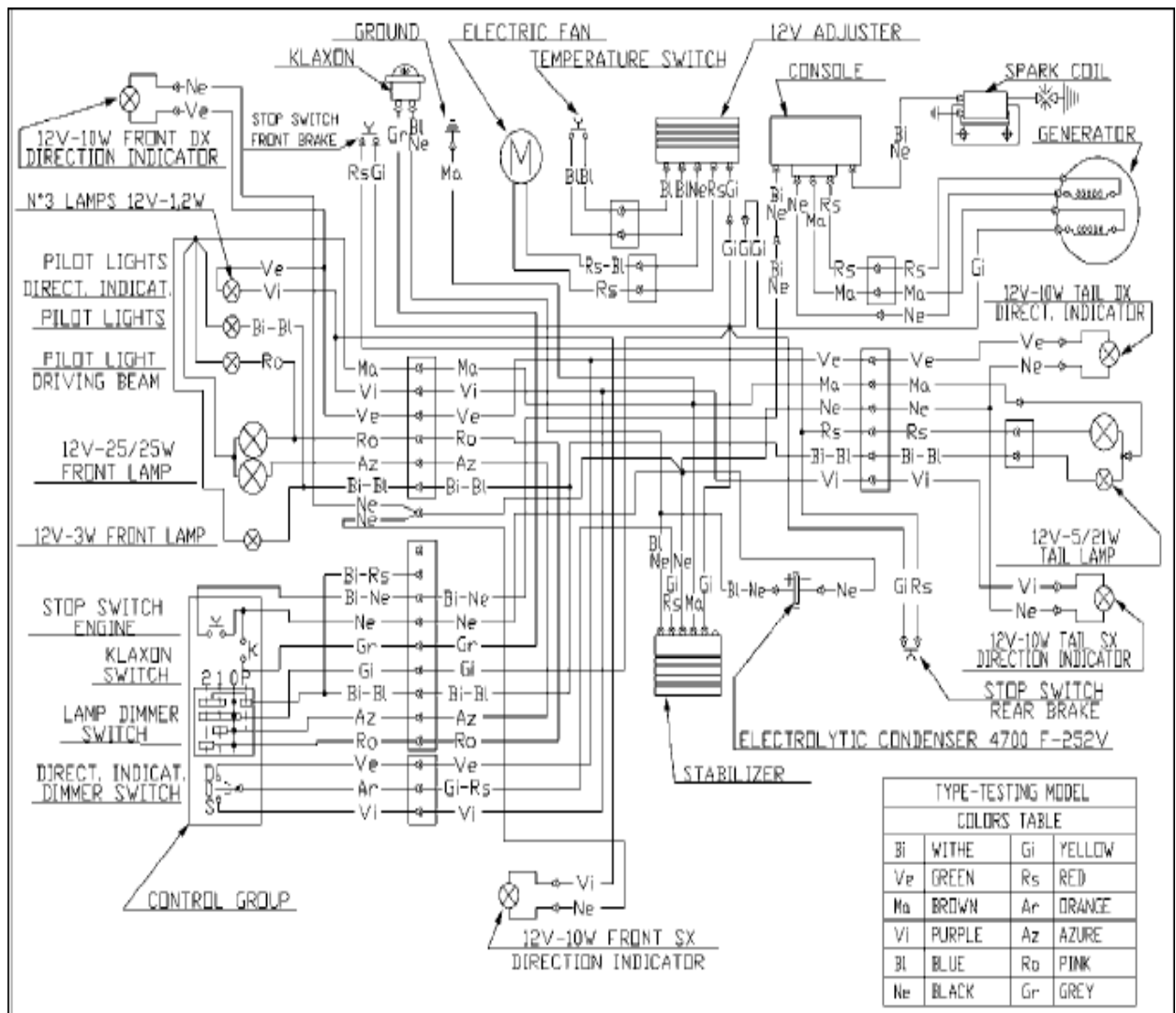


Figure 7 Motorbike wiring diagram. Source: <http://www.betamotor.info/download/manuals/items/rev3-2t.pdf>

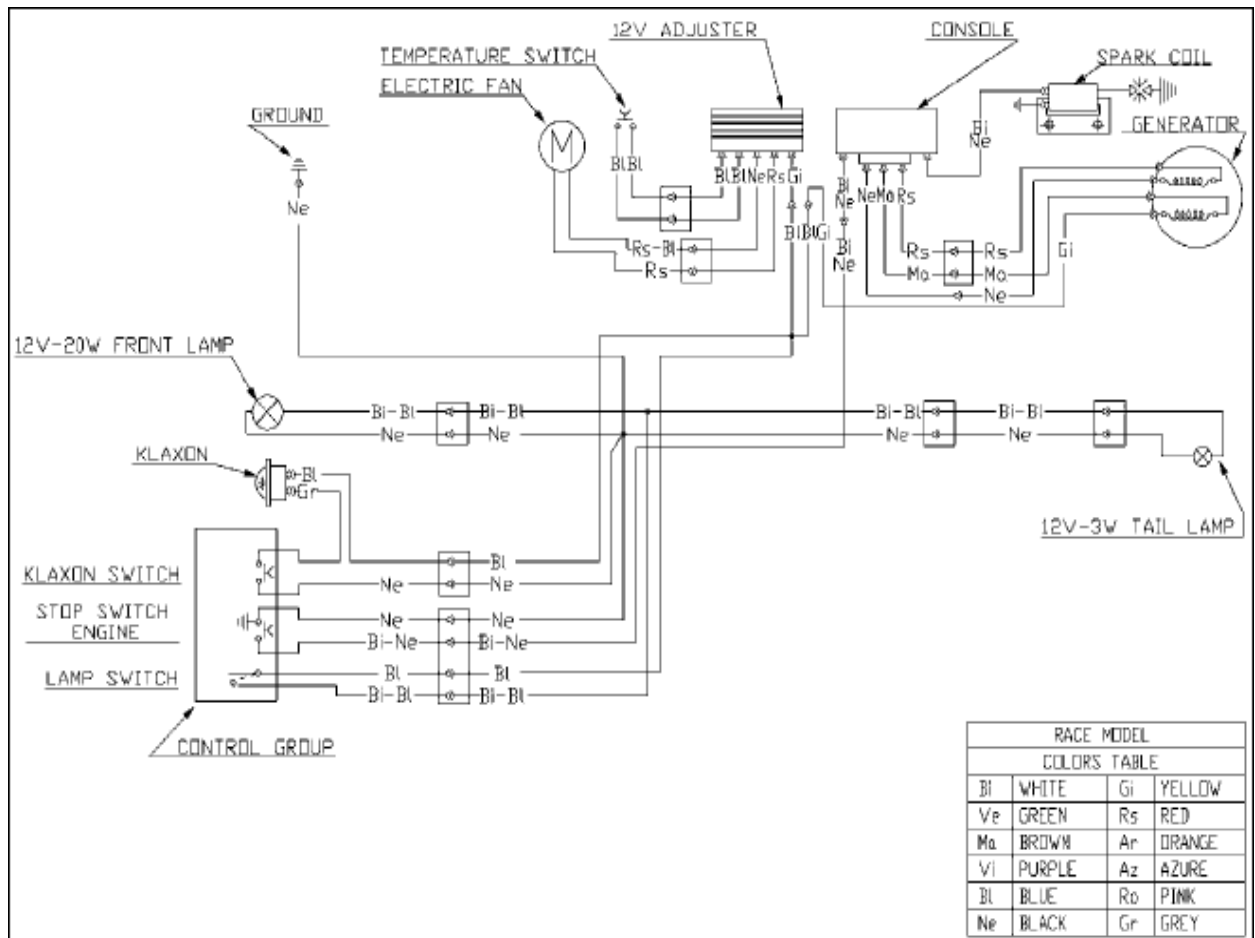


Figure 8 Trial bike wiring diagram. Source:

<http://www.betamotor.info/download/manuals/items/rev3-2t.pdf>

Each group will design supportability analysis and maintenance plan for one of subsystems A to E. It is recommended, that this following eight-step -model is used as a tool.

1. Create the plan to implement LSA (LSAP)
2. Tailor LSA to fit the purpose
3. Define goals and technical performance measures
4. Choose applicable analysis, gather them into toolbox
5. Analyse and gather the results
6. Compare the alternative solutions on basis of results
7. Define logistics support
8. Observe results, verify, make suggestions for development

Learning task 5 Analyse the necessary repair levels

The students came to the conclusion that, except for two, all maintenance tasks can be performed by the team using existing tools and equipment. They suggested that the rear suspension element should be preventively maintained every 100 hours. As the element contains nitrogen and requires special tools to be disassembled the maintenance is left for a dedicated service to complete. Another intermediate level repair is that of rebalancing the crankshaft. It requires special measuring and adjusting tools and skilled personnel. Axial and radial line of the crankshaft must be within $\pm 0,01$ mm in order to ensure smooth running of the engine.

Learning task 6 Look for possible places for redesign or modification

In the original construction, one needs to remove the exhaust pipe before the bumper can be disassembled and replaced. This is because the space between the bolt and pipe is too narrow. Removing the pipe in turn requires installation three new seals. A better design is shown below in Figure 9. All you need to do is to replace the original bolt by a stud bolt.



Figure 9 Bumper fastening bolt

In order to keep hydraulic oil from destroying the front break pads it is necessary to prevent the front suspension tube and sealing to get dirty or scratched. This is accomplished inexpensively by attaching covers on the suspension tubes as shown in the following two figures. The total cost of these self-made covers was 5 euros or 3 pounds.



Figure 10 Original construction



Figure 11 Modification

Appendix 1 Typical maintenance actions by item and type during the first 420 operation hours of Beta trial bike from May 2004 to April 2007

Item	Action	Cause	Frequency
Carburettor	adjustment	altitude, temperature, dirt	8
Air filter	change	blocked due to dirt	6
Engine oil	change	wear, dirt, wet	6
Front suspension oil	change	wear, dirt, wet	4
Front suspension seal	change	wear, dirt, wet	3
Spark plug	change	carburettor adjustment	4
Drive chain + sprockets	change	wear due to dirt	2
Clutch lever	adjustment	clutch discs wear	4
Handlebar	change	1 accident, 1 wear	2
Fenders	change	accidentally cut	2
Bumper	change	wear, accidental hits	2
Tires	change	wear (no punctures)	1
Foot rests	change	accidental collisions	3
Bearings, wheels	change	wear due to dirt	1
Bearings, engine	change	unexplained wear	1
Piston	change	normal wear	1
Total			50

One catastrophic failure occurred in March 2007. The crankshaft bearings destroyed without any warning. Both bearings were loose, balls and the bearing seats were damaged. The crankshaft was also out of it's line. It had to be rebalanced.



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Possible Approach to Reliability Prediction with Strength Degradation Process

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Abstract

In this paper, the reliability model is analysed. The strength is described as degrading process. The stress is considered as static or Poisson process. Probability of failure is obtained by general stress-strength interference. The reliability, as probability of surviving given time interval, is derived as function of instantaneous probability of failure. Numerical examples are calculated for different (Weibull and normal) distributions of strength and stress, and for static and Poisson load.

1. INTRODUCTION

The unit (mechanic or electronic) fails where and when the load exceeds the strength. In engineering practices is important to know the probability of failure and reliability. For reliability prediction it is necessary to model strength and stress as random variables.

The simplest case is to consider strength and stress as static random variables. But, in real situation, both strength and stress change in time. The strength is degrading function of time due to different effect mostly fatigue, wear, corrosion. The possible representation of strength degradation is by continues random process. The stress is function of static and dynamic load (variable amplitude and variable frequency). But, occasionally, unpredicted (over)load appears as impact, sudden shut-down, etc. So, the stress might be represented as continues process or discrete (usually) Poisson process.

The random strength degradation function and the stress as stochastic process effect the probability of failure (instantaneous) to change (increase) in time and the reliability to decrease with time.

This paper describes the way of determination probability of failure and reliability under degradation strength process and static and Poisson stress situation.

2. STRENGTH DEGRADATION PROCESS

The strength degradation of the materials over time has to be taken into account in most engineering problems. Strength degradation comes from fatigue, corrosion, wear-out, etc. For practical calculation, it is necessary to establish convenient degradation model. Xue & Yang [1] listed 3 degradation models:

1. Deterministic degradation of the form

$$s(t) = s_0 - a \cdot t \quad (1)$$

2. Random-coefficient degradation model

$$S(t) = A - B \cdot t \quad (2)$$

were A & B are random variables.

3. Random increment degradation model, like normal distribution

$$S(t) \sim N(\mu(t), \sigma_s^2(t)), \quad \text{for } t \in R^+ \quad (3)$$

with distribution parameters as the function of time.

Measuring one unite gives record as deterministic strength degradation, while n - units time history gives strength degradation process, figure 1.

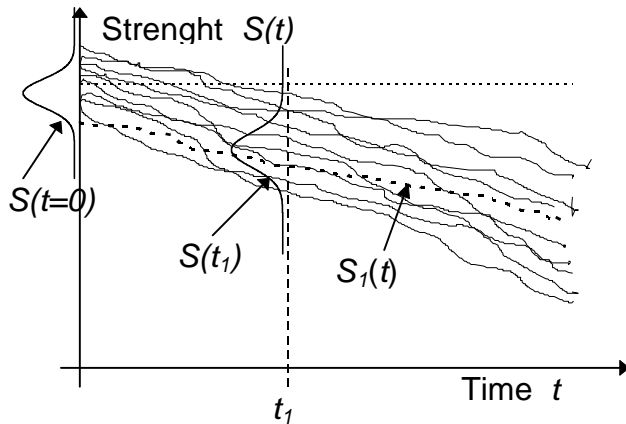


Figure 1. Strength degradation process

For any given time $t=t_1$, from the strength measurement data of each unite, strength distribution $S(t_1)$ and parameters can be estimated. In a way, random strength distribution in time $S(t_1)$ represent boundary surface (strength and time domain) under which time history strength degradation of each unit flows.

In reality, just a small measurements n are to be performed, out of all possible unites N . So, confidence level might be considered to obtain upper and lower interval limits for estimated distribution parameters.

3. STRESS REPRESENTATION

As far as load (or stress) is concern, two dominant aspects might be regarded.

1. Loading force as static random variable

The loading force measurements of k units, figure 1., gives data for distribution and parameters estimations.

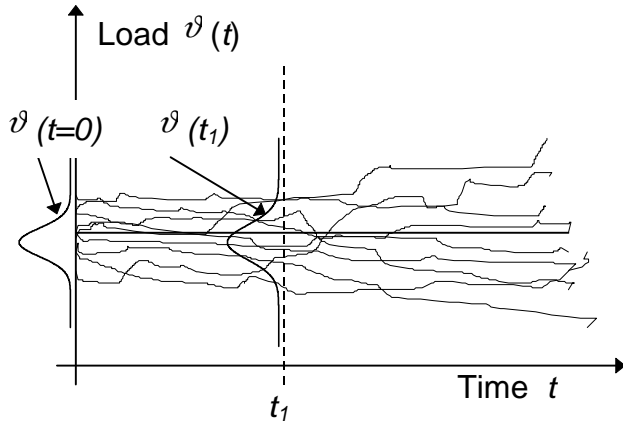


Figure 2. Loads measurements

The loads distribution and parameters estimation for certain time points $t=t_i$ can be estimated. But, for practical application (i.g. structural calculation), complete load distribution (for all unites over the time) is more important. So, complete load distribution and parameters estimation is to be described, and applied as static.

2. Loading force as Poisson random process

Real systems might be under (unpredicted) overloads appearing et certain time points. Such overload is due to shock, impact, sadden system shutdown, and many other irregularities. These loads can be represented by Poisson process, figure 3.

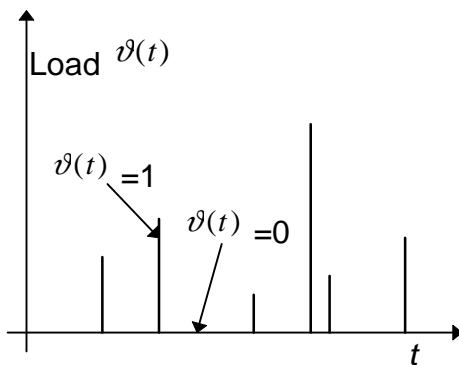


Figure 3. Loading as Poisson process

The probability of load to appear [5] is

$$P\{N[t, t + \Delta t] = 1\} = \lambda \cdot \Delta t \quad (4)$$

where λ - parameter of Poisson distribution.

The load might have different distributions, usually normal. In [2], Loll indicate possibility of electronic components failure due to random overload, while stress and strength distributions are Weibull.

4. STRESS-STRENGTH INTERFERENCE

At time $t=\tau$, strength and stress distributions are $S(\tau)$ and $v(\tau)$, respectively, figure 4.

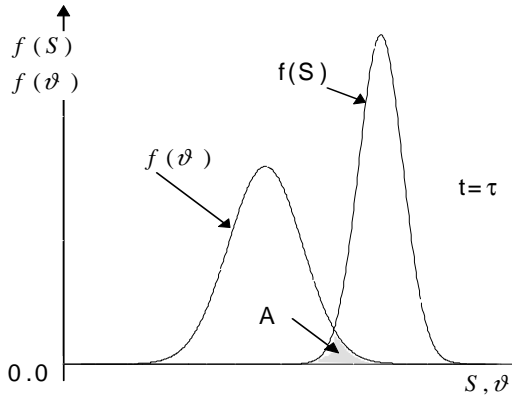


Figure 4. Strength and stress distributions $S(\tau)$ and $v(\tau)$ at time $t = \tau$

The overlapping area indicates the possibility of failure, but it is not equal to, nor proportional to the probability of failure. The failure happens whenever the load is larger than strength

$$P_f(\tau) = P_f\{S(\tau) < v(\tau)\} = 1 - P\{S(\tau) > v(\tau)\} \quad (5)$$

The general formula for stress-strength interference and probability of failure is [3]

$$P_f(t = \tau) = \int_{-\infty}^{+\infty} f(S) \left[\int_S^{+\infty} f(v) dv \right] dS \quad (6)$$

Solving (numerically in general case) equation (6) gives the probability of failure $P_f(t)$ at any time $t = \tau$. When considering the strength and the stress as static random functions, the probability of failure $P_f(t)$ would be constant (in time). Since, the strength is time degrading process, the probability of failure $P_f(t)$ will be continually increasing function.

Taking into calculation upper and lower parameters limits for stress and strength distributions, gives upper and lower bounds for probability of failure at given time $t = \tau$.

5. RELIABILITY

The reliability is probability that the strength is larger than load in time interval $[0, T]$

$$R(T) = P\{S(t) > v(t): t \in [0, T]\} \quad (7)$$

For small time increase (Δt), reliability becomes

$$R(T + \Delta t) = P\{S(t) > v(t): t \in [0, T + \Delta t]\} \quad (8)$$

Or

$$\begin{aligned} R(T + \Delta t) &= P\{S(t) > v(t): t \in [0, T]\} \cdot P\{S(t) > v(t): t \in [T, T + \Delta t] / S(t) > v(t): t \in [0, T]\} \\ &= P\{S(t) > v(t): t \in [0, T]\} \cdot (1 - P\{S(t) < v(t): t \in [T, T + \Delta t] / S(t) > v(t): t \in [0, T]\}) \end{aligned} \quad (9)$$

Substituting (7) and (5) into (9) gives

$$R(T + \Delta t) = R(T) \cdot \{1 - P_f(t) \cdot \Delta t\} \quad (10)$$

and reliability is $\frac{d[\ln R(T)]}{dt} = -P_f(t)$

$$R(T) = \exp\left[-\int_0^T P_f(t)dt\right] \quad (11)$$

The probability of failure $P_f(t)$, (6), is determined at time point $t=\tau$, while reliability $R(t)$, (11) takes into account the time interval $[0,t]$.

Similarly, when considering load appearance as Poisson process, the reliability equation is [1]

$$R(T) = \exp\left[-\lambda \cdot \int_0^T P_f(t)dt\right] \quad (12)$$

6. NUMERICAL EXAMPLES

a) The material strength degradation is describe by tree parameters Weibull distribution with parameters b , X_0 , and θ , table 1.

Table 1. Weibull distribution parameters b , X_0 , and θ

Time /h/	b	θ /MPa/	X_0 /MPa/
0	1.855	546.9	465.9
1	1.855	546.9	465.9
10	1.855	480.7	409.5
100	1.855	422.5	360.0
1000	1.882	371.4	315.9
10000	1.880	326.4	278.1
100000	1.880	326.4	250.3

The stress is static with normal distribution $N(160\text{MPa},68.5\text{MPa})$, figure 5.

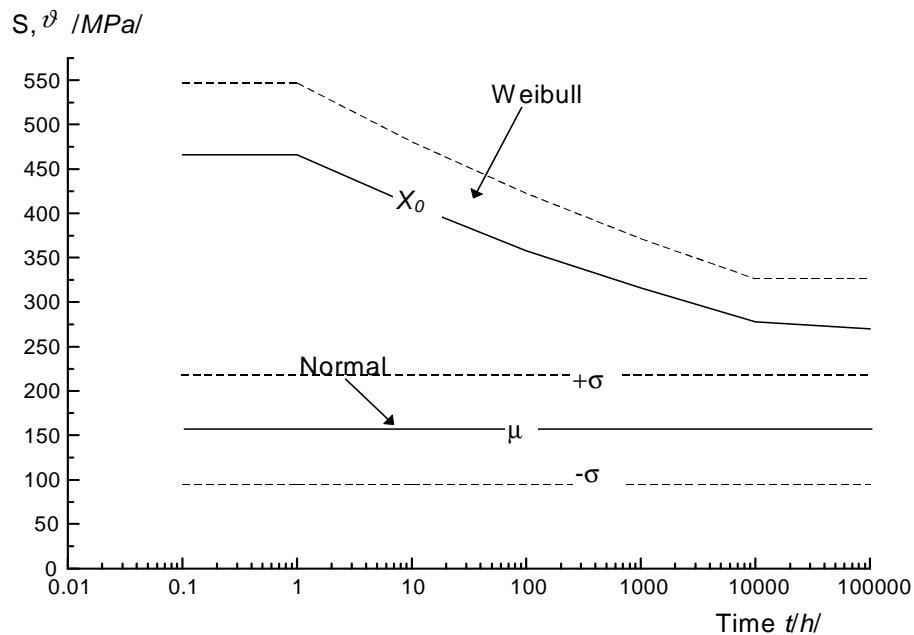


Figure 5. Random strength degradation (Weibull) and static stress (normal)

The probability of failure for time points $t=\tau$ (eq. 6) is plotted at figure 7.

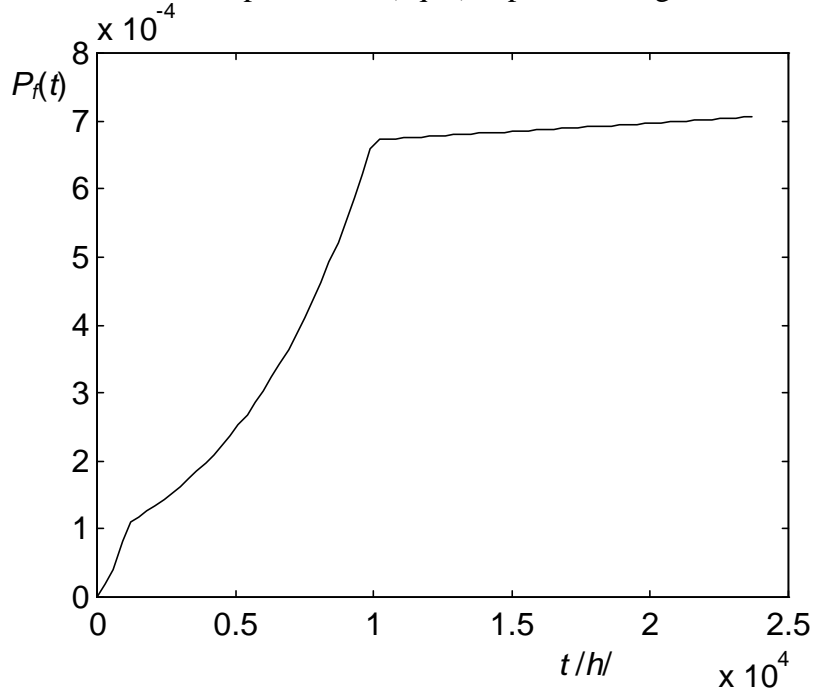


Figure 7. The probability of failure for time points $t=\tau$

The probability of failure is increasing function and for $t=24000$ h $P_f(t=24000)=0.71 \times 1.0e-004$. Reliability decrease in time, as shown in figure 8.

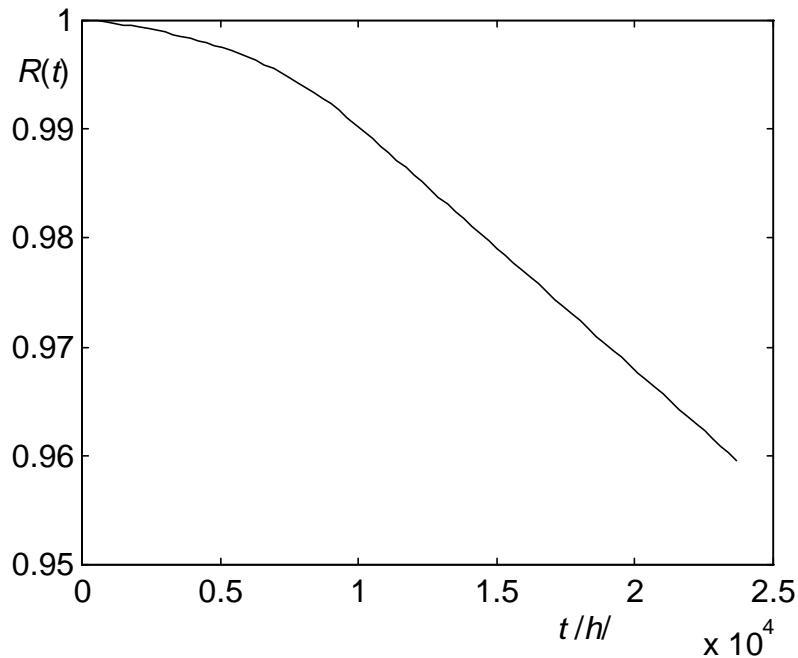


Figure 8. Reliability decrease

For working period of $t=24000$ h (almost tree years), the reliability is $R(t=24000)=0.959$, or probability to survive working period is 96%.

b) Stress as Poisson process

The strength is given by random normal increments degradation, as

$$\overline{S_U} = 538.84 - 0.02 * t_n;$$

$$\sigma_{Su} = 57.32 + 0.002 * t_n;$$

while stress is static $N(102.3; 38.5)$ MPa. The probability of failure and reliability are presented at figure 9. and 10, respectively.

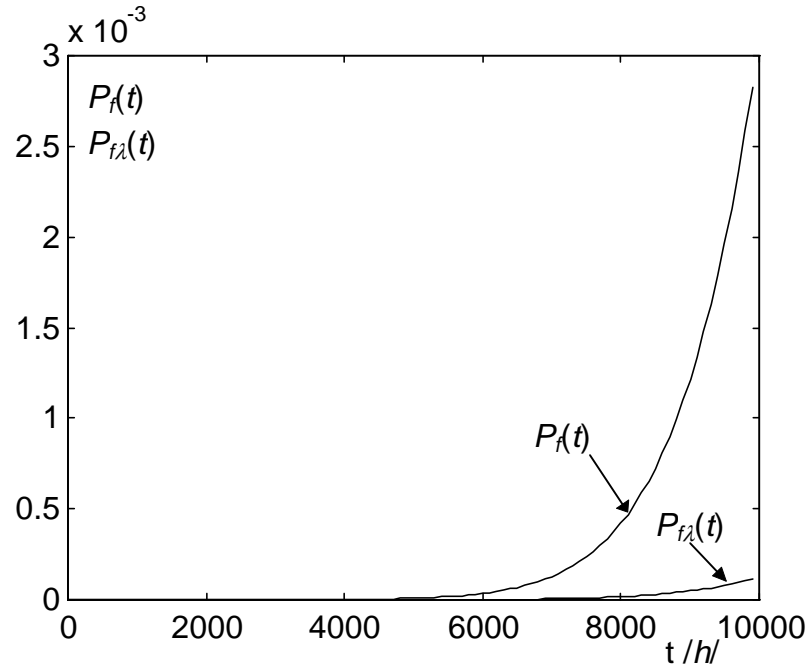


Figure 9. Probability of failure under constant and Poisson stress and strength degradation functions for time points $t = \tau$

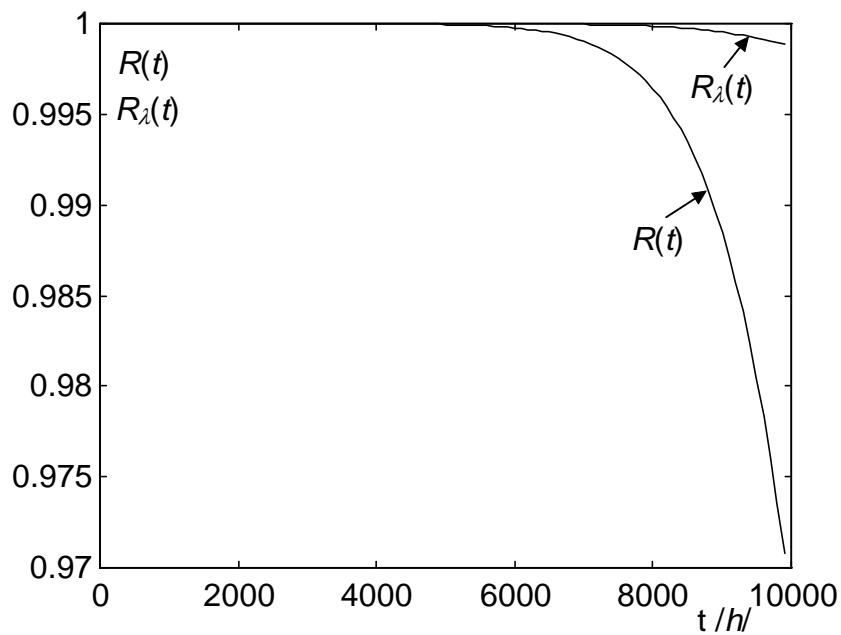


Figure 10. The reliability under constant and Poisson stress and strength degradation functions for time points $t = \tau$

At $t=1000$ h the probability of failure is $P_f(t=1000)=0.8104 \times 10^{-13}$

Considering stress (overload) as Poisson process with $\lambda=4/100$ (1/h) and $N(300,38.5)$ MPa, gives probability of failure and reliability function as shown at figure 9 and 10.

For $t=1000$ h the reliability is $R(t=1000)=0.9459$, and the probability of failure is $P_f(t=1000)=0.1142 \times 10^{-3}$

7. INSTEAD OF CONCLUSION

This paper establishes the method for prediction of probability of failure and reliability. The method might be applicable to mechanical, as well as electrical components and system. Failure comes from stress-strength interaction. Strength is time decreasing function and might be describe by continuous process. Stress is changing in time, too, and practical description might be by static random variable or Poisson process. For static stress and strength random variables, the probability of failure is constant. In reality, probability of failure is time increasing function due to, first of all, strength degradation. The reliability is nonlinear function of in time.

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Mirce-mechanics Analysis of the Flight 1549

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Abstract

The main objective of Mirce-mechanics is the understanding of mechanisms that generate positive and negative functionability events, which cause the motion of a system through corresponding functionability states. Hence, this paper addresses the mechanism of the collision between birds and flying objects, commonly known as a bird strike. This is a typical example of the overstress mechanisms where a huge amount of kinetic energy is generated by the collision of both flying objects. Consequently, the main purpose of this paper is to analyse mechanisms of the motion of the USAir A320 through functionability states caused by the kinetic energy generated by the collision with a flock of Canadian Geese during the flight 1549, on 15th January 2009, in New York. The consequences of the motion on the fuselage and engines are analysed and presented here.

1. Introduction

Aerospace Engineering is the primary branch of engineering concerned with the research, design, development, construction, testing, science and technology of aircraft and spacecraft. It deals with the design, construction, and study of the science behind the forces and physical properties of aircraft, rockets, flying craft, and spacecraft. The field also covers their aerodynamic characteristics and behaviours, airfoil, control surfaces, lift, drag, and other properties.

The main scientific body of knowledge used in aerospace engineering is aerodynamics (from Greek $\alpha\eta\rho$ aer (air) + $\delta\upsilon\nu\alpha\mu\iota\kappa\acute{\eta}$ (dynamics)). It is a branch of dynamics concerned with studying 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 functionability¹⁷ performance of maintainable systems, including aircraft. Its axioms, mathematical formulas, rules and methods enable accurate predictions of a system's measurable functionability performance characteristics like reliability, punctuality and others to be made with probabilistic regularity. [1]

¹⁷ 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 is 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 mechanisms that generate positive and negative functionability events. Hence, this paper addresses the mechanisms that cause the occurrence of NFE resulting from the collision between birds and flying objects, commonly known as a bird strike. This is a typical example of the overstress mechanisms where a huge amount of kinetic energy is generated by the collision of both flying objects. Consequently, the main purpose of this paper is to analyse the propagation of the collision generated kinetic energy through the fuselage and the engines of the aircraft and to assess the consequences of the NFE that occurred on the 15th January 2009 when a flock of Canada geese collided with a USAir Airbus A320 in New York, USA.

2. The USAir Flight 1549

On the 15th January 2009, the US Airways flight 1549, which originated from LaGuardia Airport (LGA), New York City, at 15.25 Eastern Standard Time, was en route to Charlotte Douglas International Airport, Charlotte, North Carolina. An Airbus Industrie A320-214 experienced an almost complete loss of thrust in both engines after encountering a flock of birds. At the time of the collision the aircraft was about 4.5 miles north-northwest of the approach end of runway 22 at LGA and about 9.5 miles east-northeast of the approach end of runway 24 at Teterboro Airport (TEB) New Jersey, New York.

Approximately, 60 seconds after the bird strike, it was evident to the flight crew that landing at an airport may not be an option, and, at 15.28:11, the captain reported to Air Traffic Control (ATC) that he did not think they would be able to land at LGA. Given the aircraft's airspeed, altitude, and position, Hudson River that flows through the centre of New York would be the best and safest landing option, from his point of view.

Within seconds after the ditching on the Hudson River, the crewmembers and passengers initiated evacuation of the aircraft. All of the 150 passengers, including a lap-held child, and 5 crewmembers evacuated the aircraft via the forward and over-wing exits. During that process one flight attendant and four passengers were seriously injured, and the aircraft was substantially damaged. [3]

3. Bird Strike as a Negative Functionability Event

The onset of the jet age revolutionised air travel, but magnified the bird strike problem. Early piston-powered aircraft were noisy and relatively slow. Bird strike could usually avoid these aircraft, and strikes that did occur typically resulted in little or no damage. However, modern jet aircraft are fast and relatively quiet, and their engine fan blades are often more vulnerable than propellers to bird strike damage. When turbine-powered aircraft collide with birds or other bird strike, serious structural damage and engine failure can occur.

It basically comes down to the physics equation for kinetic energy:, which is proportional to mass times velocity squared. For example, when a plane is taking off, it is going 275 km/h and accelerates to several hundred km/h. At the take off fan blades in engines are rotating around 3,000 to 4000 rotations per minute, while the tips of those turbofan blades are reaching the speed of sound or greater. When a bird hits one of those fan blades, there's a tremendous energy transfer from the bird to the engine, and that's basically why a bird can cause serious damage to an aircraft engine.

According to [4] the number of bird strikes annually reported in the USA has increased 5.8-fold from 1,851 in 1990 to a record 10,726 in 2012 (131,096 strikes for 1990–2012). Although the number of reported strikes has steadily increased, the number of reported damaging strikes has actually declined from 764 in 2000 to 606 in 2012.

From 1990–2012, about 41 percent of bird strikes with commercial aircraft occurred when the aircraft was at 0 feet above ground level (AGL), 72 percent occurred at 500 feet or less AGL, and 92 percent occurred at or below 3,500 feet AGL. Less than 1 percent of bird strikes occurred above 9,500 feet AGL. Above 500 feet AGL, the number of reported strikes declined consistently by 34 percent for each 1,000-foot gain in height. The record height for a reported bird strike involving a commercial aircraft in USA was 31,300 feet AGL. [4]

Strikes occurring above 500 feet AGL had a greater probability of causing damage to the aircraft compared to strikes at 500 feet or less. Although only 28 percent of the reported strikes were above 500 feet AGL, these strikes represented 43 percent of the damaging strikes. [4]

The aircraft components most commonly reported as struck by birds from 1990–2012 were the nose/radome, windshield, engine, wing/rotor, and fuselage. Aircraft engines were the component most frequently reported as being damaged by bird strikes (30 % of all damaged components). There were 14,322 strike events in which a total of 15,013 engines were reported as struck (13,656 events with one engine struck, 647 with two engines struck, 13 with three engines struck, and 6 with four engines struck). In 4,069 damaging bird-strike events involving engines, a total of 4,206 engines were damaged (3,935 events with one engine damaged, 132 with two engines damaged, 1 with three engines damaged, and 1 with four engines damaged). [4]

Canada Geese have already caused one major aviation accident. For example, in September 1996 a US Air Force E-3A AWACS aircraft crashed after two engines were seriously damaged by a flock of Canada Geese at take-off., killing the crew of 24.

4. Determination of Impact Force

In classical mechanics, impulse or impact refers to something that changes momentum of an object. The impulse of force acting for a given time interval is equal to the change in linear momentum produced over that interval. It is denoted as J and it is quantified through the product of a force, F , and the time, t , during which it acts. Impulse is a vector quantity since it is the result of integrating force, a vector quantity, over time. The SI unit of impulse is the Newton

second (Ns) or, in base units, the kilogram meter per second (kg·m/s). Thus, for cases where the mass is constant, the impulse is defined as:

$$J = F\Delta t = mV_f - mV_i \quad 1.$$

where: F is the resultant force applied, Δt duration of impact, m is the mass of the object, v_2 is the final velocity of the object at the end of the time interval, v_1 is the initial velocity of the object when the time interval begins.

Under the following assumptions equation 1 becomes equation 2:

- Head on collision
- Bird is riding with the aircraft after the collision
- Bird's velocity is negligible compared to that of the aircraft
- Total time taken to crush the bird (estimated impact time)
- Impulsive applied to the bird

$$F = \frac{mV_f}{\Delta t} \quad \left[\frac{kgm}{s^2} \right] \quad 2.$$

The above expression could be used for the calculation of the force generated by the collision between an aircraft. The estimated impact time, for all practical purposes, could be determined as a ratio of the length of the bird, (LB), and the speed of the aircraft, (AV), thus:

$$\Delta t = \frac{BL}{AV} \quad [s] \quad 3.$$

For example, the impact force of 101338 N (10.3 tonnes) will be generated in the collusion between an aircraft that flies 260 m/s and a bird whose length is 20 centimeters and weight 300 grams.

5. Airbus A320

The first Airbus A320, launched in March 1984, first flew on 22 February 1987, and was first delivered in 1988. The A320 family pioneered the use of digital fly-by-wire flight control systems, as well as side-stick controls, in commercial aircraft.

The Airbus A320 family are narrow-body (single-aisle) aircraft with a retractable tricycle landing gear and are powered by two wing pylon-mounted turbofan engines.

5.1 Airframe

The Airbus A320 is a low-wing cantilever monoplane with a conventional tail unit with a single vertical stabilizer and rudder. Wing swept back at 25 degrees, optimised for a maximum operating speed of 0.82. In addition, the aircraft has a cargo hold equipped with large doors to assist in expedient loading and unloading of goods.

The Airbus A320 is the first narrow body airliner to use a significant amount of structure made from composite material. Its tail assembly is made almost entirely of such material by the

Spanish company CASA, which also build the elevators, main landing gear doors, and rear fuselage parts.

5.2 Flight Deck and Avionics

The Airbus A320 is a digital fly-by-wire aircraft: whose flight control surfaces are moved by electrical and hydraulic actuators, controlled by a digital computer. The computer interprets pilot commands via input from a side-stick, making adjustments on its own to keep the plane stable and on course, which is particularly useful after engine failure by allowing the pilots to concentrate on engine restart and landing planning.

The A320's flight deck is equipped with an Electronic Flight Instrument System (EFIS) with side-stick controllers. At the time of the aircraft's introduction, the behaviour of the fly-by-wire system (equipped with full flight envelope protection) was a new experience for many pilots. The A320 features an Electronic Centralised Aircraft Monitor (ECAM) that gives the flight crew information about all the systems of the aircraft. With the exception of the very earliest A320s, most can be upgraded to the latest avionics standards, keeping the aircraft advanced even after two decades in service.

5.3 Engines

The mechanical energy generated by the two engines is the primary source of routine electrical power and hydraulic pressure for the aircraft flight control systems. The aircraft also has an auxiliary power unit (APU) which can provide backup electrical power for the aircraft, including its electrically powered hydraulic pumps; and a ram air turbine (RAT) a type of wind turbine that can be deployed into the airstream to provide backup hydraulic pressure and electrical power at certain speeds. Both the APU and the RAT were operating as the plane descended into the Hudson, although it was not clear whether the RAT had been deployed manually or automatically.

Three suppliers provide turbofan engines for the A320 series: CFM International with its CFM56, International Aero Engines, offering the V2500 and Pratt & Whitney whose PW6000 engines are only available for the A318 variant.

CFM International is a joint venture between GE Aviation, a division of General Electric of the United States and Snecma, a division of Safran of France. The joint venture was formed to build and support the CFM56 series of jet engines.

5.4 Incidents and accidents of A320

In aviation industry negative functionality events are recognised as:

- An aviation incident is defined as an occurrence, other than an accident, associated with the operation of an aircraft that affects or could affect the safety of operations.
- An accident in which the damage to the aircraft is such that it must be written off, or in which the plane is destroyed is a hull loss accident.

6. Branta Canadensis

Branta Canadensis, commonly known as Canada Geese, are well known birds that reside within the United States, Canada and Northern Europe. However, biologists recognise 11 subspecies of *Branta Canadensis*. In the mid-Atlantic region of the USA, the Giant Canada goose is most common. The Canada goose has a greyish-brown body and wings, a white breast, black feet, bill, and neck, and a characteristic white patch on each cheek. Although body size varies somewhat among the subspecies, most individuals range between 1.5-9.5 kg. Giant Canada goose, males typically reach 4.5-78.0 kg as adults, whereas females usually are slightly smaller, reaching about 4-6.7 kg at maturity. Canada geese are relatively long-lived animals-it is not unusual for an individual bird to live up to 25 years.

Today, two distinct behavioural patterns in Canada geese are recognised, those that are truly migratory and those that are non-migratory (or resident). Migratory Canada geese spend the spring and summer on the breeding grounds in the northern parts of their range and then fly south during fall to their wintering range. In contrast, resident Canada geese spend much of the year in the same general area and fly only far enough to find food or open water (especially in winter when ice has covered their ponds).

The Atlantic Flyway population of migratory Canada geese has been in decline for over a decade, whereas the population of resident geese has seen near exponential growth. Because they never leave their familiar year-round habitats, and due to this dramatic increase in population size, resident geese are responsible for most conflicts with farmers and home and business owners.

The range of migratory Canada geese along the Atlantic coast extends from north-eastern and central Canada south to South Carolina. Their summer breeding range extends throughout the southern Canadian provinces from Ontario to the Maritimes, whereas their wintering range extends from as far north as western New York, through Delaware, Pennsylvania, and Maryland, south to Virginia, North Carolina, and South Carolina.

7. Mirce-mechanics Analysis of the Aircraft N106US

The aircraft that collided with Canada geese was an Airbus A320-214, registered as N106US. It was “born” at Airbus final assembly at Aéroport de Toulouse-Blagnac in France in June 1999. It was delivered to the US Airways on August 2, 1999, but it was registered to Wells Fargo Bank Northwest, NA, as owner/lessor with AIG listed as the lead insurer. It was one of 74 A320s in service in the US Airways fleet at that time.

Maintenance records, required by USA Federal Aviation Administration, FAA, showed that up to the collision the airframe had logged 16,299 cycles (flights) totalling 25,241.08 flight hours. Total time on the engines was 19,182 hours on the left, known as number 1, and 26,466 hours on the engine number 2.

The engine number 1, serial number (S/N) 779-828, was manufactured on September 12, 2000, and installed on the airplane on January 15, 2008. At the time of installation, it had accumulated 16,233 hours and 11,897 cycles since new (CSN). At the time of the accident, the left engine had accumulated 19,182 hours, 13,125 CSN, and 2,949 flight hours since its last maintenance inspection.

The right engine, S/N 779-776, was manufactured on February 16, 2001, and installed on the airplane on May 28, 2006. At the time of installation, the right engine had accumulated 17,916

hours and 6,755 CSN. At the time of the accident, the right engine had accumulated 26,466 hours, 10,340 CSN, and 8,550 flight hours since its last maintenance inspection.

The last A Check, a maintenance check performed every 550-flight hours, was passed on December 6, 2008, whereas the annual comprehensive inspection, known as C Check, was completed on April 19, 2008.

Flight Data Recorder (FDR) extracted from the aircraft was in good condition, and the NTSB verified all of 178 parameters of aircraft flight information for the entire flight were extracted normally.

The change in functionability states of the different parts of the aircraft caused by the bird-strike event and consequential ditching into the river is briefly presented here. [6] Thus,

- The left engine was found separated from the wing, while the right engine was found attached to the wing. The horizontal and vertical stabilizers and portions of the movable control surfaces remained attached to the aircraft. The nose and main landing gear remained attached to the aircraft and were found in the up-and-locked position.
- Both the forward and aft cargo doors were open when the aircraft was lifted from the river. The forward cargo door frames, rollers, latches, and drift pins were in good condition and without any signs of deformation. The forward cargo door interlock mechanism exhibited no signs of damage and functioned properly. The aft cargo door latches and rollers were in good condition, but the door frame structure was fractured at multiple locations. The aft cargo door handle was fractured into multiple pieces.
- The cabin of the aircraft was intact, and no crew or passenger seats were dislodged. The left, forward passenger door was found open, undamaged, and in the armed mode. The right, forward passenger door was found open and in the armed mode, and it could not be closed. The door was twisted on its hinge, and two tie rods had separated. The left aft passenger door was found open and in the armed position as its slide/raft was deployed during the recovery operations. The right aft passengers door was found closed and in the armed position.
- The fuselage and wings sustained damage during the bird-strike event, ditching, and recovery efforts. The upper portion of the radome exhibited dents, a crushed honeycomb core, skin fractures, and punctures consistent with damage sustained during the ditching and recovery efforts.

Full results of the analysis performed by the National Transportation and safety Board of USA are available in [6].

8. Impact of Negative Functionability Event on Engines

Visual examinations revealed that all of the fractured surfaces on both engines were consistent with overload, and no signs of pre-existing damage or fatigue-type failures were found. Sixty ultraviolet light inspections of both engine cores revealed that foreign material consistent with bird feathers and tissue was inside the engine.

8.1 The Left Engine

The left engine was found near the initial impact location of the aircraft with the water, 8 days after the accident. Examinations revealed that the left engine had separated at the front and rear wing attachment fittings. The nacelle was fractured and deformed in several locations. No indication of engine uncontainment was found. The thrust reverser was found in the stowed position.

The left engine inlet lip was intact but exhibited crushing and had an 8- by 9-inch dent, consistent with soft-body impact, at the 4 o'clock position 56 of the lip. The outer nacelle skin aft of the inlet lip was fractured at the 3 to 9 o'clock position, and the lower portion of the skin was missing. The exhaust duct was present but crushed.

All fan blades, of the left engine, were present and intact but were bent aft about 1 to 3 inches in a predominantly skewed fan-plane pattern. All of the blade leading edge tips were curled in the direction opposite of rotation, and the curled-edge size ranged from very small to about 1/4 inch. The trailing edge of one fan blade was torn and notched with about 3/8 inch of material folded. The trailing edges of three fan blades were notched in a circular shape with about 1/4 to 3/8 inch of material folded in the direction opposite of rotation.

Foreign material consistent with bird feathers and tissue was found on the outer surface of the outer vane ring at the location of the fractured vanes. Further, five stage-1 HPC blades were found fractured, and the remaining blades were battered and bent. The stage-0 HPC variable guide vanes (VGV) were found disconnected from the VGV actuator.

The left engine combustor case was intact and appeared to be undamaged. When disassembled, examination of the combustor dome revealed crushing on the forward dome section between the 3 and 6:30 clock positions consistent with soft-body impact damage.

8.2 The Right Engine

The right engine was found still attached to the aircraft. Examinations revealed that the right engine nacelle was fractured and deformed in several locations. No indication of engine uncontainment was found. The thrust reverser was found in the stowed position. The right engine inlet lip appeared to be undamaged. The acoustical panels in the inlet duct appeared to be undamaged except for a small section between the 11 and 12 o'clock positions.

The right engine spinner was intact and undamaged. The front of the spinner cone exhibited a brown stain about 4 inches long starting about 2 inches from the tip. All of the right engine fan blades were present and intact but were bent aft about 1/2 inch. Five of the right engine fan blades exhibited a large-radius curvature 59 dents at the midspan location. A portion of a feather was found stuck between two adjacent fan blades at the midspan damper.

The right engine combustor case was intact and appeared to be undamaged. When disassembled, examination of the combustor dome revealed crushing on the forward dome section consistent with soft-body impact. About 1 cup of charred remains was found in the combustor area.

9. The "Ditch switch"

The Airbus A320 has a "ditching" button that closes valves and openings underneath the aircraft, including the outflow valve, the air inlet for the emergency RAT, the avionics inlet, the extract valve, and the flow control valve. It is meant to slow flooding in a water landing.

However, the flight crew did not activate the "ditch switch" during the incident. Captain Sullenberger later noted that it probably would not have been effective anyway, since the force of the water impact tore holes in the plane's fuselage much larger than the openings sealed by the switch. [6]

10. Mirce-mechanics Analysis of Biological Material

As Mirce-mechanics studies the life of maintainable system in its entirety no analysis could be completed without addressing the natural environment with which they continuously interact. Consequently, Mirce-mechanics analysis could not have been completed without analysing the physical properties and characteristics of the birds as a second element of the bird strike phenomena.

Investigators from the National Transportation and Safety Board of USA collected ten samples of biological material from the right engine fan, the radome, the No.3 flap track on the left wing, and various locations on the fuselage. Two additional samples were collected from the shroud from the No.3 flap track on the left wing after it was removed from the aircraft. In addition, a United States Department of Agriculture, USDA representative and General Electric (GE) personnel collected six samples from the exterior of the left engine before its disassembly at the GE facility. At the end of the disassembling process of the left engine, an additional 23 samples of biological material were found, including feathers, blood, muscle, and bone. A similar operation on the right engine disclosed another 14 samples of the same type of biological material. [6]

Samples collected from both engines were analysed by the Feather Identification Laboratory of the Smithsonian Institution, National Museum of Natural History, Division of Birds, in Washington, DC. The DNA analysis has shown that 39 of the samples matched 99 % or more, of the Barcode of Life Database for Canada goose. All 53 samples, where 50 of them were from the engines, contained feathers or feather fragments consistent with Canada geese. Analysis of the DNA shown that 16 of the 18 samples found in the left engine wing were male and female, while only male remains were found in the right engine, and only female remains were found on the No.3 flap track on the left wing.

10.1 Residential or Migrating Canadian Geese

Determining whether the geese involved in this functionality event were resident or migratory is essential to the development of management techniques that could reduce the risk of future collisions. Currently, the US civil aviation industry is not required to report bird strikes, yet information on frequency, timing, and species involved, as well as the geographic origin of the birds, is critical to reducing the number of bird strikes. Integrating this information with bird migration patterns, bird-detecting radar, and bird dispersal programs at airports can minimize the risk of such collisions in the future.

However, applied DNA sequences techniques were able to identify the species, but they could not determine if these birds were local Canada Geese from the New York area or migratory geese spending the winter in the New York region. Under the leadership of Dr Marra, the team from the Smithsonian Migratory Bird Center, National Zoological Park, Washington, DC, analysed the stable isotopes in the feathers. Isotopes are naturally occurring variants of elements, and in the case of hydrogen there is documented geographic variation associated with latitude.

Hence, the team studied the isotopes in goose feathers comparing those from the plane crash with migratory and non-migratory birds to answer the question posed. [7]

The analyses were conducted and isotopic data resulted in the determination of a non-local origin for the Canada Geese that struck the plane. Even further, stable isotope analyses of feathers recovered from the engine specifically concluded that the geese had spent their summer farther north than Labrador. These findings were significant on several fronts. First and foremost were the implications from a wildlife management perspective. Had the geese been determined to be from a local New York population, it is highly likely that the local population would have been culled or exterminated. Determining that these particular geese were migratory requires a completely different management plan to reduce, or prevent, such bird strikes in the future. The use of deuterium isotopes to effectively “source” the geese was a novel application of isotopic research.

11. Conclusion

The main objective of the paper was to present Mirce-mechanics type of analysis of the negative functionability event that occurred on 15th January 2009 during the scheduled flight of the USAir Airbus A320. Hence, this paper addresses the collision between birds and flying objects, commonly know as a bird strike. This is a typical example of the overstress failure mechanisms where a huge amount of kinetic energy is generated by the collision of both flying objects. Consequently, the paper analysed mechanisms of the motion of the USAir A320 through functionability states caused by the kinetic energy generated by the collision with a flock of Canadian Geese during the flight 1549. The consequences of the occurrence of the negative functionability event in the fuselage and engines are analysed and presented here, together with the brief analysis of biological material collected from the damaged aircraft, after it was lifted to the surface of the Hudson River.

For the completion of the Mirce-mechanics analysis it is necessary to mention that Aircraft N106US has never entered into positive functionability state again, as a flying machine. However, after changing the functionality and becoming an exhibit at the Carolinas Aviation Museum in Charlotte, North Carolina., it fulfils its functionability performance by staying in positive functionability state during the working hours.

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Life-Cycle Benefit of Repair

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Abstract

During the concept, design and development phases of a project, the role of the Logistics Support Department is to influence the product design for supportability and originate support systems optimised for life cycle benefit. The support system's task is the management of the effects of product failure. To ensure that the Logistic Support department fulfilling its role it is essential that each aspect of the support system is providing maximum life cycle benefit. This paper investigates the operation of the repair system with regard to life cycle benefit.

1. Introduction

The modular construction of contemporary military jet engines allows rapid recovery of a damaged engine at the main operating base workshop by replacement of damaged modules with serviceable ones, taken from a pool. The damaged modules are then recovered to a serviceable condition and returned to the pool of serviceable spares for use in future engine recoveries.

The recovery of damaged modules is generally accomplished by the replacement of damaged parts or assemblies with serviceable ones. This process generates a number of unserviceable parts, which are then sentenced to be discarded or repaired. The outcome of the discard or repair decision process can have a profound effect on the engines' cost of ownership and the operational effectiveness of the weapon platform.

Some individual repairs generate only trivial costs and clearly deliver huge benefits. At the other extreme, an individual repair may require huge investment with only a meagre return. However, the majority of repairs lie somewhere between these two extremes and the cost/benefit comparison is far from obvious.

2. What is "repair"?

The Oxford dictionary defines repair as "To restore to good condition after damage or wear". For the purposes of this paper the meaning of the words "good condition" is of prime importance. The repair may restore full functionality to the item under repair, but is it "as new"? The repaired item may not last as long as a new item. The repaired item may fail in a different way from a new item. The repair may address the obvious failure mode but leave the deterioration due to other failure modes unaffected. For example a turbine blade may be repaired by the replacement of the thermal barrier coating. The blade will pass all visual and functional tests and be reinstalled in an engine. The blade with the replaced thermal barrier coating may be installed alongside a brand new blade. However, the replacement of the thermal barrier coating has done nothing to address "hidden" deterioration due to failure mechanisms such as thermal fatigue or

creep. The next failure of the blade may manifest itself as a “half height” fracture, rather than the graceful degradation expected in cases of coating erosion. The half height fracture failure will probably impact adjacent components causing expensive secondary damage throughout the system.

If the item under consideration is the whole system rather than a component similar implications can be experienced. For example a car’s performance is restored by regular maintenance; worn or corroded items are replaced at the service intervals. However some items show no obvious signs of wear. If the cam drive belt is not replaced in a timely fashion failure may occur. This has the effect of a loss of synchronisation between inlet/exhaust valves and pistons. There is then a distinct possibility that moving pistons will strike inlet/exhaust valves as the engine continues to turn due to the car’s inertia, causing expensive engine damage.

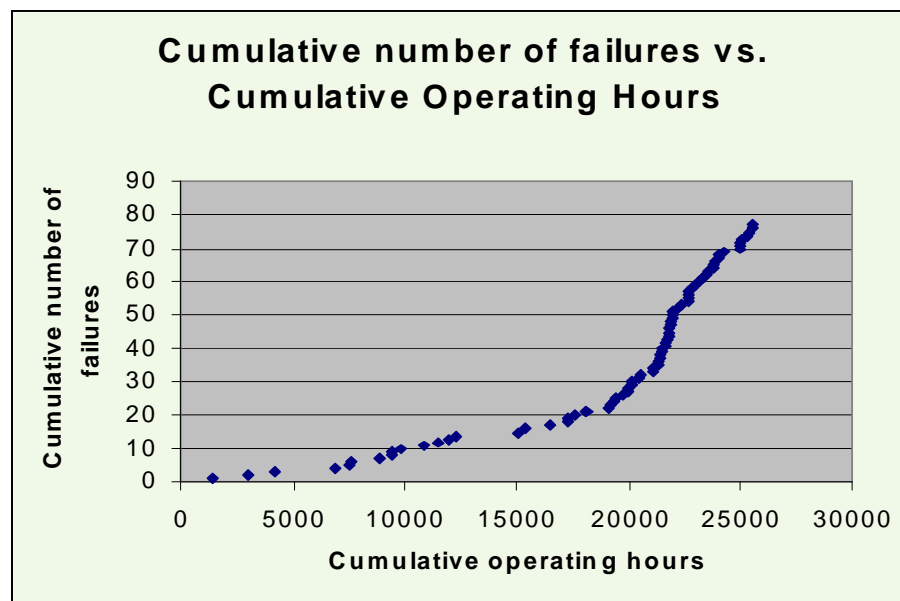


Fig 1

The chart above (fig 1) shows cumulative number of failures vs. Cumulative Operating Hours for a submarine’s main propulsion Diesel engine. USS Halfbeak (data from Ascher & Feingold, 1969). It can be seen that despite intermediate repairs, the number of failures per unit time increases with the age of the engine. This demonstrates that repair does not necessarily return the repaired system to an “as new” condition.

If then repair is an activity performed on a component or system which restores functionality but does not necessarily return the component or system to an “as new” condition, how is it then possible to determine the benefit of the repair activity?

3. Contribution of repair to cost of support

The cost of repair is often considered as the cost of materials, and man-hours required to achieve the repair. Some other cost elements associated with the repair can be identified, such as:

- Facilities and Tooling (acquisition & maintenance)
- Training of operators
- Technical Publications

- Packaging, Handling, Storage and Transportation
- Increased spares pools required to support required availability due to increased TRT

In the chart below (fig 2) the cost of repair is compared with other support costs, these costs cover a 25-year period. The data was produced using the MEAROS simulation model, and represents total support costs of £1.6 Billion.

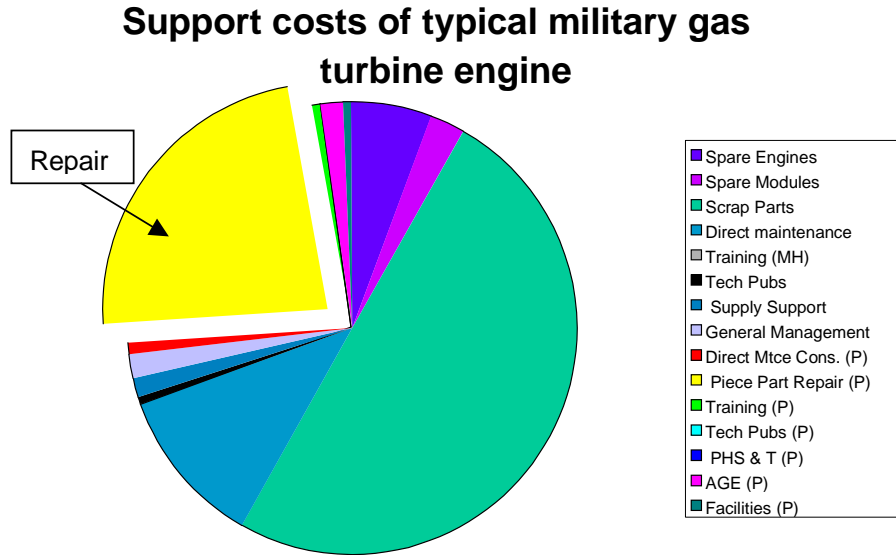


Fig2

It is clear that even by considering only the above elements that repair costs contribute significantly to the support costs over the life cycle of the system under consideration.

It could be said that if repair is so expensive then why not discard and replace with new parts. The strategy adopted with regard to repair or replace has significant implications for life cycle cost. This is not a question that should be taken lightly. To always repair or to always replace, even for an individual component, will not produce an optimum (i.e. minimum) contribution to the cost of ownership of the system under consideration. The optimum strategy lies somewhere between “always replace” and “always repair” This is illustrated in the chart (fig3) below:

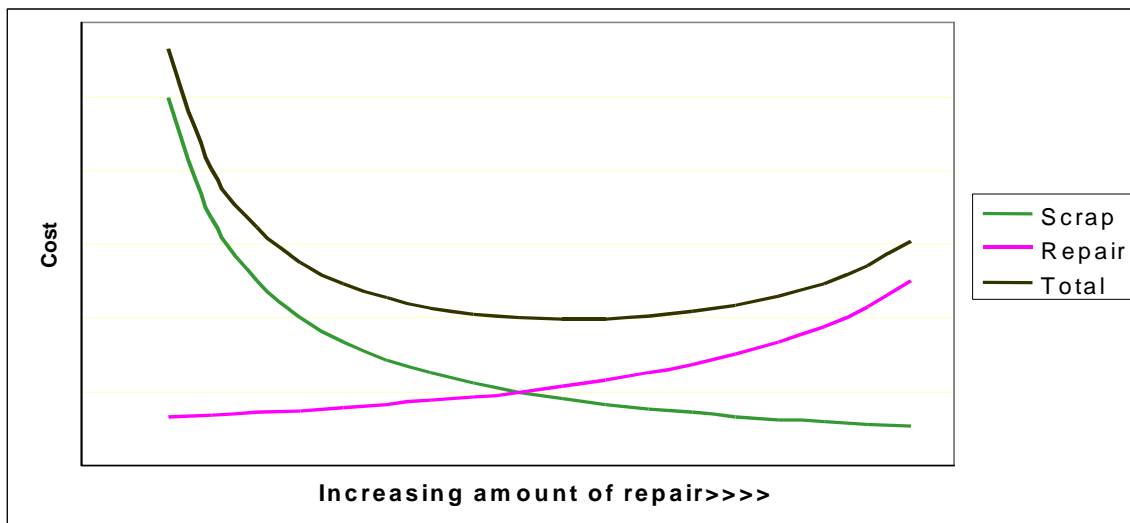


Fig 3

The chart shows life cycle cost for replacement of scrap, repair and the total of scrap and repair on the y-axis. The x-axis represents changing repair strategy from (nearly) always replace with new on the left to (nearly) always repair on the right. The data for the chart was generated with the MEAROS simulation model.

So how close is current practice to achieving the optimum repair strategy?

4. Current Practice

Research in Industry has shown that the decision to repair or replace a part is generally approached in the following way. If the cost of repair is more than some arbitrary proportion (68% has been quoted by several sources) of the new cost then a replacement part is fitted, if the cost of repair is less than this arbitrary proportion the repair is carried out.

A more detailed approach is proposed by James V Jones in “Integrated Logistics Support Handbook (second edition)” This approach takes more factors into account when deciding to repair or discard.

It may be more economical to discard an item when it fails rather than repair it. This decision is based on a comparison of the cost of repairing an item with the relative cost of buying a replacement. This method compares the relative value of a repaired item with the cost of buying a new [replacement] one. The factor “N” is a predetermined acceptance level, either supplied by the customer or set by the contractor, that is used to establish a criterion for derating the value of a repaired item. Basically it creates an acceptance criteria for a discard decision that states that if the cost of repair exceeds a given percentage of the cost of a new item, the decision should be to discard the failed item.

– if $(MTBF_2/MTBF_1) N < (L + M) / P$ then discard

– *Where:*

- $MTBF_1$ = MTTF of new Item
- $MTBF_2$ = MTTF of repaired item
- N = “Predetermined acceptance level”
- L = Labour required to repair item
- M = Material to repair item
- P = Unit price of new item

Examples:	A	B	C
MTBF1	1000	1000	1000
MTBF2	1000	800	600
L	100	20	40
M	100	40	80
P	200	500	200
N	60%	60%	50%
Decision	Discard	Repair	Discard

This approach is better than the “general percentage rule” approach, as it embodies consideration of the possibility that a repaired component or system is less durable than a new one. Notwithstanding this fact it does not consider several important factors. Additional “life-cycle” factors that should be considered as part of the “repair or replace” decision process are discussed below.

5. The life cycle approach

The cost and benefit of repair should be considered in the context of the whole system life cycle. The questions that should be asked before any repair is developed are:

What is the cost of repair development?

What is the ongoing cost change due to repair (over scrap)?

What are the failure characteristics of a repaired component vs. new component?

How many times will the repair be carried out in total?

How many times can each component be repaired?

This is not aligned with current practice which tends to concentrate on the cost of a repaired vs. new component. However the UK government has in place a process called COEIA (combined operational effectiveness and investment appraisal). This process is used, *inter alia*, to decide if and when to replace major defence systems. A scaled down version of COEIA could be applied to repair or replace decisions. Some additional considerations to be included in the analysis are:

5.1. The cost of repair development.

Evaluation of the full cost of repair development will require the following questions to be addressed:

How many man hours in repair design? This can be estimated from the development of similar repairs on other projects. However the use of new technology can pose problems, as there are no previous data for comparison.

What is the cost of repair verification? Expensive components may have to be scrapped (cut up) to verify the expected result of the repair. Also many man-hours may be consumed in the metallurgy laboratory

What additional capital plant/facilities are required? Some repairs may require the use of specialised and possibly expensive facilities and machines. The extended cost of such facilities and machines need to be considered. The cost of maintenance and possible replacement over the product life cycle of this equipment will have to be considered as contributing to the cost of repair.

What tooling changes are required? Some repairs may require the use of specialised and possibly expensive tooling. The extended cost of such tooling needs to be considered. The cost of maintenance and possible replacement over the product life cycle of this equipment will have to be considered as contributing to the cost of repair.

What technical publications changes are required? The technical publications will need to include a description of the repair technique and in what circumstances it can be applied.

5.2. Ongoing cost of repair

Evaluation of the ongoing cost of repair will require consideration of the following topics.

Distributions other than (negative) exponential

Repaired components or systems, as shown above may well have differing mean times to failure (MTTF) and differing failure distribution parameters. For example, in the case of a gas turbine blade a “new” blade time to failure may be distributed with Weibull parameters $W(\text{Characteristic life, Shape})$, $W(800,2.5)$ representing failures due to thermal barrier coating erosion and a repaired blade time to failure may be distributed $W(1300,3.5)$ representing failure due to creep.

Changed failure characteristics of repaired components

Again, taking the example of the turbine blade. If a decision was taken to always repair the blades by replacement of eroded thermal barrier coating rather than replace with new, as the fleet aged more and more blades would fail in the “creep” mode. Due to the changed secondary damage characteristics this “repair” policy could well be more expensive than blade replacement over the system life cycle. Crocker explores this aspect in some detail in his paper “Age related maintenance” 1998

Increased costs due to configuration control/parts tracking for repaired components

For example: in the aero gas turbine industry fracture critical components, such as turbine disks are serialised and individually tracked, due to the fact that failure of such components may cause loss of the aircraft, because failure of such components may cause an uncontained failure of the engine. Repairs to disks can not address the failure mode for which safety restrictions are imposed (low cycle fatigue). A repaired component may not be suitable for use in all marks or applications of the parent assembly or have other restrictions placed upon its use, whereas the new or non repaired component may have wider applicability, although outwardly similar to the repaired component. The additional overhead of managing the logistics system containing both repaired and non-repaired components could add significantly to the cost of operation.

More than one repair per component.

To assess the life cycle benefit of a particular repair it is necessary to subtract the “cost of repair development and the cost of all repairs over the life cycle” from the savings produced by all repairs over the life cycle. This means at least you have to know how many such repairs are likely to be performed over the life cycle. In addition, knowledge of the reliability of components following repair will be necessary for a full evaluation of the ongoing cost.

The effects of increased turn round time (TRT)

If turn round time increases the spares pool size (for a given confidence level of availability) will increase, hence reduced availability or increased cost. For example: In the past, an assembly had normally been repaired by replacing damaged components with new. There is now a proposal to repair the damaged components, instead of discarding them. Here comes a choice: wait for component repair to be completed and re-install the repaired component in the parent assembly

or maintain a pool of repaired components to support the repair activity. In either case extra cost is incurred. In the first instance due to a higher spares requirement for the assembly to support the longer turn round time caused by waiting for repaired components. In the second instance the cost of maintaining the pool of repaired components. This extra cost has to be counted as part of the cost of implementing the repair policy. This effect may be more pronounced when repairs are “batched”, such as for operational or other reasons component repair has to wait until a sufficiently large batch of damaged items can be repaired together as a “batch”.

Sales margins and repair

Often high tech. goods, for example aero gas turbines, are sold at a very low margin or even at a slight loss to gain entry to a particular market, this in the hope that the majority of revenue will come from the sale of the support system. When considering the whole life cycle most of this revenue will come from the sale of spare parts. If large numbers of component repairs or salvage schemes are published the volume of turnover from spares sales will decrease. When considering the margins on spare parts, due consideration should be given to the effect that repair will have on the volume of spares business. The amount of repairs carried out may thus be driven by the profit margin on spares sales. The operator may be driven to a non-optimal combination of repair and replacement by this mechanism, possibly leading to the selection of a different manufacturer for the next generation of engines.

5.3. Other Considerations

The cost of repair can not always be expressed directly in financial terms. Due to some of the considerations in the above paragraph, that is huge margins on new replacement parts, particularly found in the civil airline business an operator may decide to have components repaired by some third party. This repair may well comply with all relevant regulatory bodies (FAA, CAA) rules but a result might be that the performance of engines containing such third party repaired items may be degraded in some subtle way such as an increase in specific fuel consumption. Such aspects of performance are often part of the contract in airline operations. The resultant dispute may result in lengthy legal proceedings, from which the legal profession is the main beneficiary

Due to a variety of reasons such as: wars, bad planning or change in operational regime an operator may run out of a particular spare. The manufacturing leadtime for this spare may be (much) longer than the time taken to repair the part. It can happen therefore that the manufacturer receives a request to develop a repair scheme for this part to enable operation to continue in the absence of replacement spares. Once established, the operator may continue to carry out the repair and in future order a reduced level of replacement spares, without due regard to the effect that this may be having on life cycle cost and the more subtle aspects of functionality.

6. Conclusions

Repair costs are a significant contributor to support costs. This is clearly demonstrated in fig 2. Repair costs, in this example, are demonstrated to be around 20 percent of the total support costs over a 25-year period

There is a relationship between the amount of repair carried out and total support costs (fig 3). Up to some point increased repair reduces life cycle cost. Beyond this point life cycle cost

increases. The relationship between the amount of repair and the life cycle cost is not fully understood but certainly not linear.

Current methods used to make the “repair or replace” decision do not adequately consider the costs and benefits of repair in the context of system life cycle

There is very little work currently underway that addresses the life cycle benefit of repair. Ascher and Feingold make the point that although reliability (of repaired systems) is a very important issue, very little work had been done on systems, which had been repaired rather than renewed. Most of the literature is concerned with time to first failure or is based on the assumption that failures are not age-related.



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When “if it ain’t broke, don’t fix it may not be the best policy

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Abstract

It is the fate of almost every system made by man to eventually wear out or outlive its usefulness. Most high-value systems are designed to be repairable such that if parts of the system cease to perform their designated function adequately, they can either be returned to a state of functioning or replaced without having to discard the whole system. For these systems, waiting until they fail is seldom the most cost-effective policy. Unfortunately, few failures can be predicted with very much confidence or precision. This paper proposes an opportunistic maintenance policy that attempts to reach a compromise between the conflicting desires to maximise the times between maintenance actions whilst minimising the in-service support costs.

Introduction

It is a sad fact of life that although we all know we will die one day, none of us can predict exactly when this event will happen. The same is also true for manmade systems. The time to first failure or between subsequent failures is impossible to predict accurately. The best we can usually hope for is that we can state that there is a given probability the next failure will occur before time T_2 but after time T_1 . It is also a fact that as we close the gap between these two times so the probability will decrease to the point when $T_1 = T_2$ this probability is infinitesimally small. For those who have read the novels of Nevil Shute [Norway], (from my recollection of some 40 years ago) the ability to predict that the tail of a given aircraft would fail catastrophically through metal fatigue as it was approaching Gander in Newfoundland (after crossing the Atlantic from Shannon on the west coast of Ireland) was pure fiction. What is perhaps most remarkable about “No Highway” is that it was written by an aeronautics engineer before the De Havilland Comet disasters which were caused by metal fatigue, although in their case it emanated from around the corners of the poorly designed cabin windows.

Tyre wear is reasonably linearly related to mileage given the vehicle is driven in a similar fashion throughout the life of the tyre. The rate of wear may increase slightly as the tyre ages and its diameter decreases (through wear), as the wheel has to rotate more times and at a higher speed to cover the same distance at the same [road] speed. On most vehicles, the tyres are particularly easy to inspect which is why imposing legal limits on the minimum depth of tread has been relatively successful. Compare this to trying to impose a limit on CO emissions to no more than x ppm. Not only is carbon monoxide invisible (under most normal conditions) it is also impossible to measure without specialised (and hence expensive) equipment. It also varies considerably with the temperature of the engine, the ambient conditions and the way the car is driven as well as the state of the engine.

Oil debris monitoring using electron-scanning microscopes and spectroscopy (such as a JetSCAN®) can tell us not only how much metal is being worn away but even from which

particular components. Unfortunately such a process is not yet continuous and is rather expensive. It also relies on sufficient oil washing over the wearing parts to collect the debris which means that it will not work for sealed joints or bearings. Taking these apart to inspect them for wear will almost certainly cause damage to the joint/bearing and accelerate its rate of wear – a true case of when the adage in the title is perhaps the best policy.

In the following, we will explore some of the ways probability theory and statistics can be used to help us make better decisions. To do this we will also make use of a very powerful technique which was first used on the Manhattan Project during WWII and given the name “Monte Carlo” simulation. It is effectively the mathematical equivalent of tossing coins, throwing dice or shuffling decks of cards, hence its name. This will then lead into an even more powerful method for modelling actual system behaviour known as “discrete event” simulation.

We will apply these methods to a case study and investigate some of the different maintenance policies which we could adopt. From this, we attempt to draw some useful conclusions about how we might manage a fleet of complex, high-value, repairable assets to ensure they have a reasonable level of availability at an affordable price.

A Probabilistic Approach

Since design engineers cannot predict when components will fail we must resort to less certain methods. Typically, we have to use statistics. Unfortunately, engineers are also not very good at calculating with any accuracy what the parameters of the times-to-failure (TTF) distributions will be. There is a fair amount of circumstantial evidence to support the hypothesis that most failure modes can be best modelled using a 2-parameter (or in a few cases a 3-parameter) Weibull distribution. This evidence also supports the hypothesis that the shape or slope parameter (β) is a constant for a given failure mode although the scale, characteristic life (η) will vary according to types of usage, materials used and operating conditions. As in-service data accumulates, so this can be used to gain better estimates for the scale and check the shape.

Once we “know” the parameters of the TTF distributions for all of the components in our system that are likely to cause a system failure if and when they fail, we can start to look at how best we can manage these failures. We can calculate the mean time to first failure and the expected number of failures over the life of the system assuming that each component that fails is replaced with a new one and that no other components are replaced. These however give the best and worst cases. We know that the mean time between failures will decrease with the age of the system so the mean time to first failure is only meaningful if the whole system is replaced every time. At the same time, if we assume only the failed item is replaced and that we therefore perform no opportunistic maintenance then there will, almost certainly be more failures and hence a lower overall MTBF. Actually, this is not the worst case, bad though it may be, because that honour is reserved for when components are repaired to the same-as-old condition. If no limit is imposed on how many times a component be repaired or on the age after which it should be replaced then the times between failures of the given component is a reducing function and for the system, it will eventually reach an age when it can be expected to fail immediately after being put back in service. An example of this is seen with old cars that have started to rust. As each patch of rust is cut out and replaced with a new piece of metal (or filled with glass fibre) so another patch of rust will show up somewhere else. Bicycle inner tubes are another, such that eventually one is forced to try sticking a patch over another one.

The difficult decision is to decide what to replace and when. There will often be occasions when it is more cost-effective to repair a component than replace it. If you have just fitted a new tyre on your car and it picks up a small nail or screw causing a puncture, it will certainly be cheaper to have it plugged rather than to replace the tyre. The only problem here is one of safety; a plugged tyre is not as safe and is not recommended if the car is going to be driven at high speed. In the case of a set of turbine blades, if one is damaged by a foreign object but the remainder are still in good condition then it may be sensible to only replace the one blade because the cause of the damage was not age-related so there is no reason to suppose the other blades are about to be similarly damaged. In fact, even if there was reason, it still would not be sensible to replace them as the new ones would be at exactly the same risk as the replaced ones would have been had they been left in. If a stretch of road has been resurfaced, we know there is an increased probability of suffering a broken windscreen but replacing it would not reduce the probability. The only sensible action is to leave plenty of room behind the car in front and to keep ones speed down.

Not for the squeamish

Before considering a specific case, it is perhaps worth reminding ourselves of what the various TTF functions are and what they mean. The first which defines the distribution is known as the probability density function (pdf) usually denoted by $f(t)$. For the [2-parameter] Weibull distribution this is given by:

$$f(t) = \frac{\beta}{\eta} \left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^\beta} \quad \text{where } \beta, \eta > 0 \text{ and } t \geq 0$$

The cumulative density function (cdf) $F(t)$ is simply the integral of $f(t)$:-

$$F(t) = \int_0^t f(x) dx = 1 - e^{-\left(\frac{t}{\eta}\right)^\beta}$$

This gives the probability a failure will occur before time t . The opposite, the reliability function $R(t)$ gives the probability that no failure will have occurred by time t and is given by:-

$$R(t) = 1 - F(t) = e^{-\left(\frac{t}{\eta}\right)^\beta}$$

Now, $f(t)$ effectively gives the probability that a failure will occur at exactly time t given we know nothing about the actual age of the item. If we know its age is t , then we can determine its conditional probability of failure or its [instantaneous] failure rate also called the hazard function $h(t)$ which is given by:-

$$h(t) = \frac{f(t)}{R(t)} = \frac{\beta}{\eta} \left(\frac{t}{\eta} \right)^{\beta-1}$$

If we substitute $\beta=1$ then $h(t)=1/\eta$ (i.e. a constant independent of t). Thus for the exponential distribution ($\beta=1$), the hazard function is a constant so we can talk about the failure rate (since it is the same for all values of $t \geq 0$).

The cumulative hazard function ($H(t)$) gives the expected number of failures for a system that is recovered to the same-as-old after each failure.

$$H(t) = \left(\frac{t}{\eta} \right)^\beta$$

It can also be shown that the mean time to [first] failure from new is given by:-

$$\mu = \int_0^\infty R(t)dt = \eta\Gamma(1 + 1/\beta)$$

A function that we will have particular need for in the following is the mean residual time to failure $\rho(T)$ (i.e. the expected life remaining given the item has attained an age T) given by:-

$$\rho(T) = \int_0^\infty \frac{R(T+t)}{R(T)}dt = \frac{1}{R(T)} \int_T^\infty R(t)dt$$

Now, for a system consisting n components that can be considered as in “series” regarding the reliability block diagram (RBD), the reliability function is given by:-

$$R_s(t) = \prod_{i=1}^n R_i(t)$$

If the ages of the components are T_i (for $i = 1, n$) when the “age” of the system is T then the mean residual time to failure of the system is given by:-

$$\rho_s(T) = \frac{1}{\prod_{i=1}^n R(T_i)} \int_0^\infty \prod_{i=1}^n R_i(T_i + t)dt$$

For a more in-depth treatise of the mathematics, see Kumar et al 2000

You can open your eyes now

In the above, we defined the mean residual time to failure (MRTF) – the expected life remaining – in terms of the reliability functions of each of the components within the system. If we replace one of the components with a new one then its MRTF will be same as its mean time to [first] failure (MTTF). Now, it can be proved that for a Weibull distribution with shape greater than 1, the MTTF is always greater than the MRTF if the age of the component is greater than zero. It can also be proved that expected age of failure ($T + MRTF$) is always greater than MTTF for $T >$

0. At the system level, provided none of the TTF distributions are negatively age-related (i.e. none of the shape parameters are less than 1) then the MRTF(system) is never greater than the MTTF(system).

This means, very simply, that if we replace a component whose times to failure are positively age-related then we can expect the system to last longer than if we do nothing or simply recover the system to a same-as-old condition. Clearly, if we replaced all such components with new ones then we would have effectively restored the system to an as-good-as-new condition. In practice, the former means that the system can be expected to fail increasingly more often so the availability will decline whereas, the latter will maintain the availability but is usually too expensive.

To overcome the declining availability, we could simply buy more systems. As to whether this would be affordable would depend on how long the system is likely to be out of service following each failure. For commercial systems, it would also depend on how much revenue we might expect to lose as a result of the failure and the time it was unavailable. For military systems, the “costs” are a little more difficult to calculate. If the system is a vehicle and the forces are advancing then the lack of the support/fire power lost could be decisive in winning the battle on the other hand if the forces are retreating then vehicle will either have to be abandoned or a large support force will need to be deployed until it can be recovered. Either way, the losses could be significantly more than the cost of the vehicle. Deploying a larger force might be an option but for every additional vehicle deployed there is a corresponding need to increase the operational forces (vehicle crew) plus security forces (guards) plus support forces (logistics – food, shelter, ammunition, etc). Appleton and Hockley (1997) suggested that in order to support a squadron of 8 aircraft on deployment, it required a force of 150 personnel and daily flights of 3 Hercules transport aircraft. They also pointed out that for the aircraft and missions concerned, the 8 aircraft were needed to ensure there was always 2 aircraft ready and able to fly together.

In many cases, neither of the two extremes will give the most cost-effective solutions. Few would expect a garage to replace one sparkplug, one HT lead or one piston ring if the reason for replacing them was that they were “worn-out”. If they were broken due to carelessness in trying to unscrew the plug, or had melted because the lead had come in contact with the cylinder head or the ring was damaged due to some external contaminate then replacing just the failed item might be a sensible option because we could expect the others to be unaffected although even then it would depend on their ages, their relative conditions and the costs of replacing them now against the inconvenience of having to do it later.

For a complex system, there could be many components whose failure would require immediate invasive maintenance. If each of these has positively age-related TTFs, then the replacement of any one of them may be cost-effective. However, we could expect some to give a better return on investment than others. If we ignore the costs then the best component to replace must be the one which has the biggest impact on the system MRTF, i.e. the one which increases the expected time to next failure by the largest margin. To determine which this is, it is necessary to calculate the new system MRTF resulting from replacing each of components, one at a time. Unfortunately, it is not sufficient to consider the increase in the individual component MRTFs. Having found the best one to replace, we may wish to consider the second, third and n^{th} best depending how much additional benefit each of these may be expected to provide.

In the absence of any cost data, we may choose to try to maintain the system MRTF at a level that does not fall below a certain percentage of the [system] MTTF. This would give a higher

probability of achieving a desired level of availability. Alternatively, we might decide a better criterion would be to set the percentage at the level which minimises the number of component replacements over the life of the system. Here we must recognise that every system failure will require at least one component replacement.

The actual costs involved are rather complicated. Obviously there is the cost of the new parts but in addition there is the labour cost of performing the additional work. Because it may be necessary to take more components off the system to access the ones being replaced, there could be additional labour costs. At the same time, because this takes longer so the system will be unavailable for longer so there could be additional losses of revenue or the need for spares or possibly the temporary hire of additional systems to cover the period of unavailability. If we buy more spare/redundant systems and use them then these will tend to dilute the fleet so that there will be that many more times to first failure. This will tend to reduce the overall number of failures and hence reduce the number of spares required for a given level of availability. In practice, it is likely that we can achieve very reasonable cost savings whilst maintaining an acceptable level of availability (or mean time between maintenance actions) by choosing a target system MRTF. To decide what the target should be, we may need to simulate the fleet over its life and evaluate the in-service support costs for a range of values.

Case Study

To show that the above can have some practical value, we will look at a particular case. In the following we consider a system comprising just 18 components each with its own TTF distribution. It is assumed that the failure of anyone of these components will require immediate invasive maintenance but has no effect on any of the other components. To make the mathematics relatively simple it has been assumed there will be no secondary rejections, i.e. no caused or found damage, no benign failures or minimum issue lives.

In this case study, the operation of a single system was simulated over a period of 10,000 hours. The times to failure for each of the 18 components were sampled from their respective distributions using pseudo-random numbers generated by the Excel™ Rand function. This resulted in 60 failures with {9,0,5,1,3,2,0,4,4,4,1,3,2,3,0,3,10,6} failures of each of the 18 components, respectively against an expectation of {8,1,2,1,3,2,1,5,4,4,3,4,3,4,1,4,10,6} rounded to nearest integer and a total of expectation of 63. Note that whenever a component failed, it and only it was immediately replaced with a new one of exactly the same type. Had the components only been repaired (to a same-as-old condition) we might have expected {8,1,2,1,10,4,1,176,64,117,10,64,10,64,0,64,1993,15} giving a total of 2604 failures. Note that the first 4 numbers are the same for both repair and replace because these correspond to the components with exponential times to failure.

Figure 1 shows how the failures occurred with time for each of the 18 components and, under “Y = 0” for the system. Most of these display the typical bunching (“bad news comes in threes”). An exception is Component 17 which appears to have relatively evenly spaced events in keeping with its relatively high value of the shape parameter ($\beta = 3.5$).

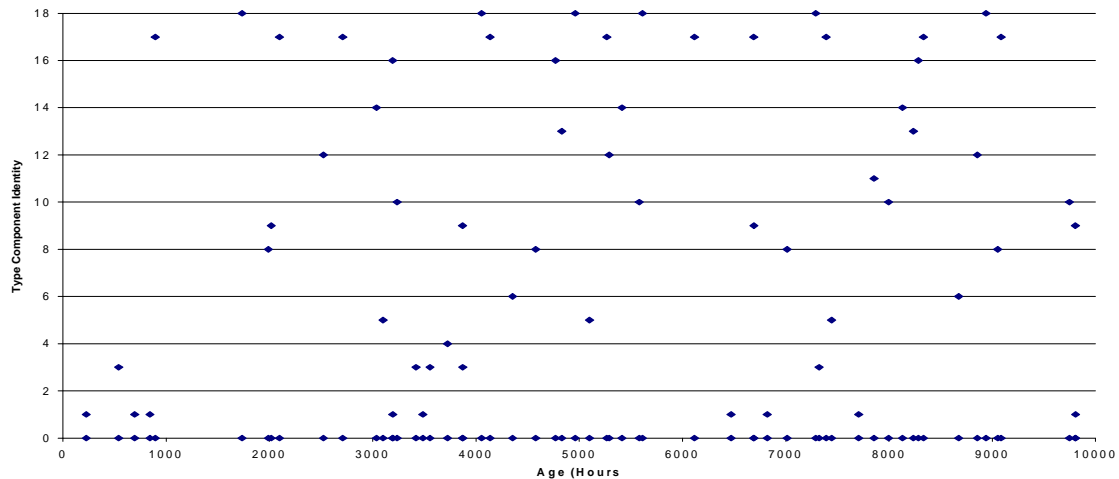


Figure 1 Graph showing the times and types of component which failed

Figure 2 shows how the instantaneous failure rate (IFR) (or hazard function – $h(t)$) changes through the life of the system. Having replaced the failed component with a new one, we can then calculate the new IFR from knowing the ages of each of the components and their respective TTF distributions. Essentially, the system IFR is an increasing function of time because for 14 components it is increasing and for the other 4 it is constant. In the graph, we can see that it increases quite steeply until one of the 14 components fails when it drops down only to start rising again until another of the 14 fails.

Although the IFR gives a good indication of how likely a failure will occur within the next increment of time (in this case an hour), a possibly more useful statistic is the MRTF since this gives us an indication of how long we can expect the system to last (on average) given the current status. Figure 3 gives an estimate of the MRTF given the current status (ages of the components) after each system recovery. The values were calculated using the trapezoidal rule for numerical integration with a constant width $h = 10$ (Noble 1966).

In Figure 4, we can see how much improvement on the MRTF can be gained by replacing the most influential component, in addition to the one which caused the failure. The difference between the averages of these MRTFs over the 60 events suggests that a policy of removing one component opportunistically could reduce the number of failures by approximately 25%. Unfortunately, we would need to perform a large number of passes with and without replacing an extra part to determine how confident we could be in achieving an actual benefit of this proportion or, indeed, what the expected benefit might be.

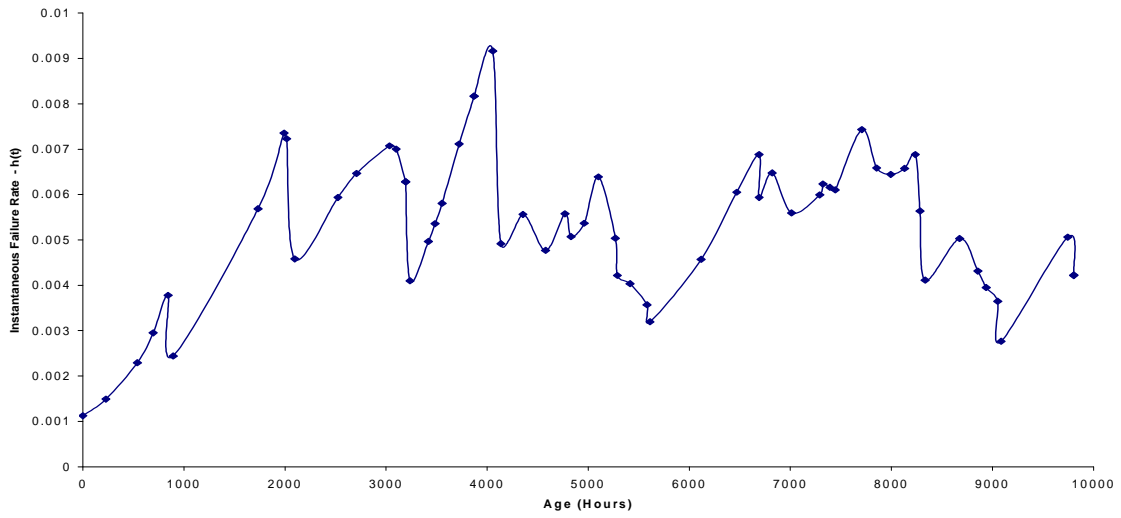


Figure 2 Graph showing how the instantaneous failure rate varies through the life of the system.

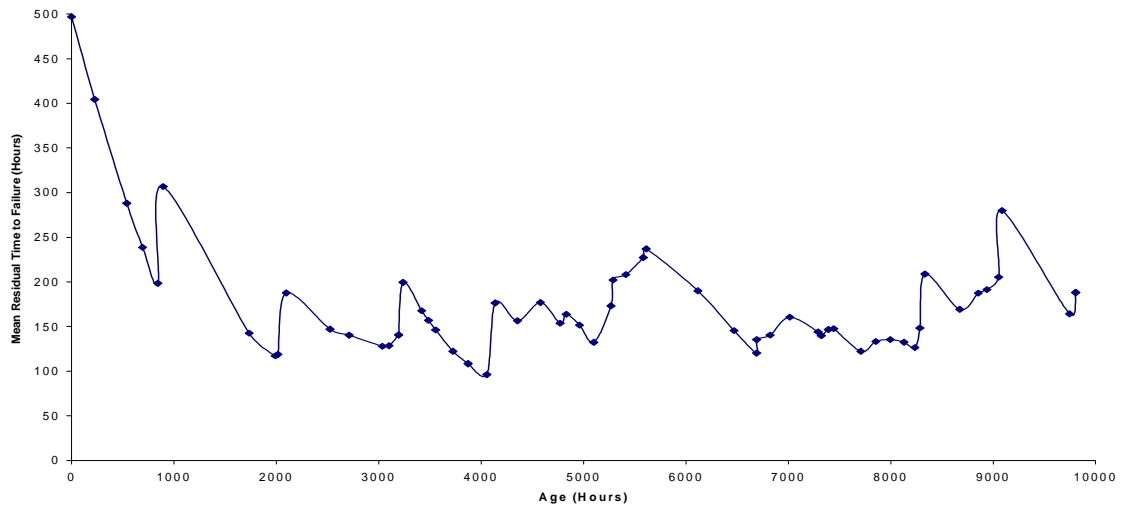


Figure 3 Graph showing the mean residual time to failure (MRTF) at the time of each system recovery

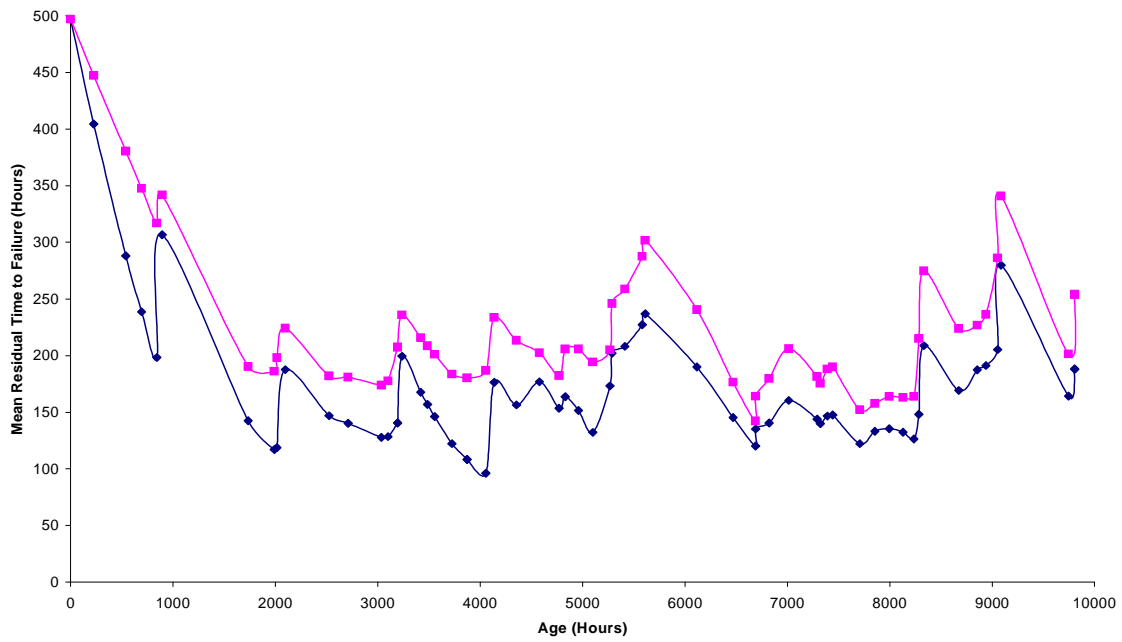


Figure 4 Graph showing the revised MRTF after replacing the most influential component during each system recovery

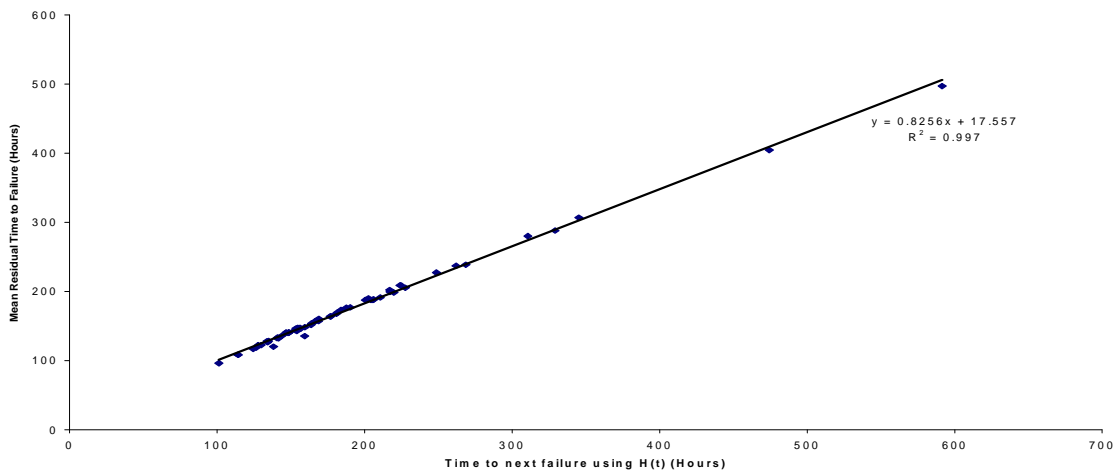


Figure 5 Graph showing the relationship between the MRTF and the expected time to next failure using the cumulative hazard function.

Calculating the MRTF is a time-consuming process as it involves evaluating a complex exponential expression many thousands of times for each system recovery. If we then wanted to determine which components we should replace opportunistically, as well, then this increases the number of calculations by another 1-2 orders of magnitude (for the system in question). An alternative approach might be to use the cumulative hazard function in the way described in section 3, above. This function (H(t)) is relatively easy to calculate, unfortunately it is not

possible to rearrange the expression to isolate the time t so it is necessary to resort to some form of linear search algorithm (such as binary or Fibonacci – see Noble 1964).

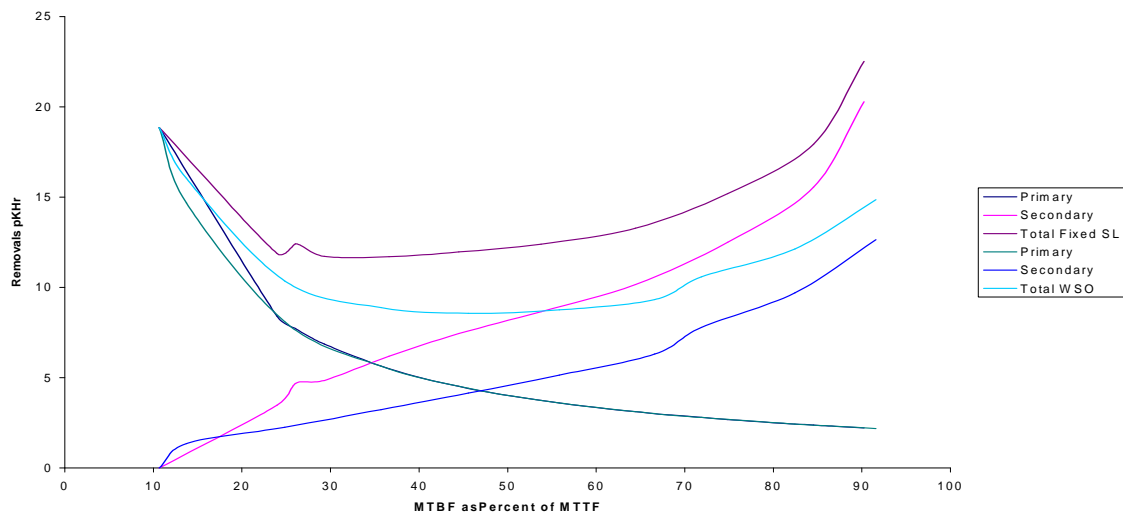


Figure 6 Comparison between conventional soft lifing and using MRTF

Finally, in Figure 6, we can see how for the same number of primary system rejections, using the MRTF to decide which components to replace opportunistically gives a very much lower (up to 30%) number of component replacements than using a fixed soft life policy. Obviously, it will depend on the relative costs of a system failure versus the that of replacing components within the constraints of desired availability as to which of these policies would be chosen.

Conclusions

Although there is still a lot more work to do on this technique to determine the best algorithms, nonetheless there is considerable evidence to suggest that using the system mean residual time to failure has a lot of potential. If the case study is representative then it would also suggest that the old engineering adage may certainly not always be the best policy. However, in this example we did make the underlying assumption that there would be no maintenance induced failures, that there were no “no fault founds” and that every replacement part was devoid of any quality/manufacturing/handling problems.

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System Engineering - Can reality prediction be made as accurate as in Physics?

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Abstract

System Engineering involves, basically, prediction of the future behaviour of systems. One wishes to answer questions such as: What would the reliability, availability and other performance measures of the system be? How many spare parts, repair teams, Inspections, Maintenance operations of all kinds and other resources be allocated for the system so as to guarantee a required performance level at a minimal cost? etc. The purpose of this paper is to discuss the framework under which such predictions can be made. It will be demonstrated that a general system transport equation exists which governs the system behaviour. The prediction process can be most effectively performed using the Monte Carlo method for the solution of the transport equation.

1. Introduction

In the spectrum of human predictions two extremes can be observed. At one edge one may find social sciences or political predictions. At this extreme, very little can be done. On the other extreme one has physics where very accurate predictions can be made. Why is it then that very accurate predictions can be made in physics while so little can be done on the other edge? The reason, most probably, lies in the fact that the questions asked in physics are extremely simple.

The hydrogen atom contains a single electron and a single proton holding each other in an electrostatic grip - This simple structure has inspired the whole of quantum physics. At the same time a single human being contains roughly 480000 cubic centimeters of living matter each containing about 10^{23} atoms, all of them interacting via physical and chemical processes, molecules, DNA, cells, emotions, brain... and social sciences involve millions of such creatures. The complexity level is so high that even the variables involved are not clear. When problems become that complex no scientific prediction can be done. Instead, one may have an opinion. One would not have an opinion as to the potential energy of a cluster of charges in an electrostatic field. Or the size of concrete shield needed to attenuate a flux of neutrons. One either knows how to calculate it or not. Yet, every one has an opinion as to the correct social system to be maintained. This brings about an interesting observation "The more complex the problem is, the less one needs to study in order to have an opinion".

Where does system Engineering stand along the above mentioned spectrum? Is it a matter of opinion, "experience", Engineering insight, "Intuition" or is it a matter of calculation?

One of the characteristics of physics is that it is based on the basic laws of nature. These are clear, unambiguous, simple laws. In the basis of every subject in physics there is a law, presented as a basic equation or set of equations. Such are the Schrödinger equation in quantum physics,

Maxwell equations in Electromagnetism or Hamilton and Newton equations of dynamics. In particular one should note the Boltzmann transport equation which governs the behavior of neutral particles in matter. This equation, which provides the basis for all nuclear engineering is of particular importance because as will be shortly shown it bears some resemblance to the behavior of systems. A neutron entering a nuclear reaction is characterized by \vec{r} the spatial position of the event, $\vec{\Omega}$, the direction with which the neutron enters the reaction and E, the energy of the particle. These are presented as $\vec{P} = (\vec{r}, \vec{\Omega}, E)$, the phase space point of the event(collison). The collision rate $\psi(\vec{P})$ is defined as the number density of events at a given point \vec{P} (per unit volume, unit direction and unit energy). The collision rate fulfills the Boltzmann transport equation [1,2]:

$$\psi(\vec{P}) = S(\vec{P}) + \int_{\Gamma} \psi(\vec{r}', \vec{\Omega}', E') K(\vec{r}', \vec{\Omega}', E' \Rightarrow \vec{r}, \vec{\Omega}, E) d\vec{P}' \quad 1.1$$

where the kernel $K(\vec{P}' \Rightarrow \vec{P})$, called the transport kernel, describes the probability density that a particle entering an event at \vec{P}' will enter the next event at \vec{P} . $S(\vec{P})$ is a source term describing the rate of first collisions and Γ is the phase space (location, direction and energy).

Consider next the behavior of a system. Let b_i be an indicator of the possible states of component i in a system. The vector $\vec{B} = (b_1, b_2, \dots, b_n)$, the state vector, describes the state of every component in the system. Let also τ_i denote the time point at which the i^{th} component entered its respective state and let $\vec{\tau} = (\tau_1, \tau_2, \dots, \tau_n)$, be the entry time vector. The time of entry of the system into a given state is t such that $t = \text{Max}\{\tau_j\}_{j=1, \dots, n}$. Thus, the system enters into a new state when the last component enters into its respective state. A general phase space vector of the system now takes the form: $\vec{P} = (\vec{B}, \vec{\tau}, t)$ indicating that at time, t , the system entered state \vec{B} . The event density $\psi(\vec{P})$ is now the number density of entries of the system into state $\vec{P} = (\vec{B}, \vec{\tau}, t)$ and its knowledge means that all aspects related to the future behavior of the system are known. All it really takes is to calculate $\psi(\vec{P})$.

The transport kernel for systems is conceptually identical to that of neutral particles. It describes the transfer in time and state space, of the system, from one state to another. Define the ‘free flight’ kernel, $T(\vec{B}', \vec{\tau}'; t' \Rightarrow t)$, as the Probability density that a system that entered state $\vec{P}' = (\vec{B}', \vec{\tau}', t')$ at time t' will exit that state at time t (per unit time). Define also the collision, or event, kernel, $C(t; \vec{B}', \vec{\tau}' \Rightarrow \vec{B}, \vec{\tau})$, as the probability that a system that is known to exit state $\vec{P}' = (\vec{B}', \vec{\tau}', t')$ at time t will transfer into state $\vec{P} = (\vec{B}, \vec{\tau}, t)$. The transport kernel can then be written as $K(\vec{P}' \Rightarrow \vec{P}) = T(\vec{B}', \vec{\tau}'; t' \Rightarrow t) C(t; \vec{B}', \vec{\tau}' \Rightarrow \vec{B}, \vec{\tau})$. The system transport equation is obtained by arguments similar to those leading to equation 1.1 [3] and takes the general form:

$$\psi(\vec{P}) = S(\vec{P}) + \sum_{\vec{B}', \vec{\tau}'} \int \psi(\vec{B}', \vec{\tau}', t') K(\vec{B}', \vec{\tau}', t' \Rightarrow \vec{B}, \vec{\tau}, t) d\vec{\tau}' \quad 1.2$$

It is worth noting that the “free flight” kernel in the case of systems describes the transfer of the system through time, with its state unchanged until any state change takes place. Similarly, for neutral particles, that kernel describes the ‘flight’ of the particle through space with its direction

and energy unchanged until it encounters a collision with a nuclei. The collision kernel contains the information on the dynamics of the change. i.e. given that an event has occurred in the system it provides the probabilities that the state transfer will occur into any specific new state. Equation 1.2 applies to Non-Markovian systems and any system model that can be thought of. In the case of Markovian or even semi Markovian systems (where only the elapsed time since entry point into the last state is of importance) the entry time vector $\bar{\tau}$ can be omitted. In Markovian systems it is easy to see [4] that equation 1.2 reduces into the well-known Markov equation which is, thus, a special case of 1.2. The transport equation includes aging and partial repair [5,6] and models in which the order of entry of the components into their respective states are of importance. These elements are, in fact, part of many realistic models of industrial systems. Knowledge of $\psi(\bar{P})$ and functionals of it, provides all the information one may seek regarding every aspect of the system behavior including, availability, reliability, any other performance measure such as throughput, resources, maintenance inspections etc. Admittedly, the explicit construction of the equation is not simple to establish and once established it is, in most cases, prohibitively difficult to obtain an analytic or deterministic numerical solutions.

2. The Explicit Form of the Transport Kernel

The general form of the free flight kernel can be written in the form:

$$T(\bar{B}', \bar{\tau}'; t' \Rightarrow t) = \left\{ \prod_{j=1}^n \left[\frac{1 - H_j(b'_j, t - \tau'_j)}{1 - H_j(b'_j, t' - \tau'_j)} \right] \right\} \times \left[\sum_{j=1}^n z_j(b'_j, t - \tau'_j) \right] \quad 2.1$$

The term in the curly brackets is the probability that no event will occur up to time t . $H_j(b'_j, t - \tau'_j)$ is the cumulative distribution (Cdf) of component j in state b'_j with elapsed time being measured from the point of entry, τ'_j , of the component into the state. $z_j(b'_j, t - \tau'_j)$ is the hazard function of component j in state b'_j and the sum of the hazard functions yields the hazard function of the system, namely

$$Z_s(\bar{B}', \bar{\tau}'; t', t) = \left[\sum_{j=1}^n z_j(b'_j, t - \tau'_j) \right] \quad 2.2$$

The collision kernel for a change to incur in the i^{th} component takes the general form:

$$C(t; \bar{B}', \bar{\tau}' \Rightarrow \bar{B}, \bar{\tau}) = \frac{z_i(b'_i \rightarrow b_i, t - \tau'_i)}{Z_s(\bar{B}', \bar{\tau}', t', t)} \left[\prod_{j \in K_c} \delta(\tau_j - \tau'_j) \right] \left[\prod_{j \in K_e} \delta(\tau_j - t) \right] \quad 2.3$$

$z_i(b'_i \rightarrow b_i, t - \tau'_i)$ is the partial hazard of going into a particular state b_i . The product of the Dirac delta functions is used to specify any changes occurring in the entry points of components into their states. K_c is a group of components (including at least component i) which will have an immediate change in their state if the trigger change in the i^{th} component occurs and K_e is the complementary group. Thus, for the components in K_c the entry time is set to be t while for the unchanged components the entry time remains unchanged.

Substituting 2.3 and 2.1 into equation 1.2 yields a set of integral equations. If the number of possible states of component j is K_j then the number of different state vectors is $\prod_{j=1}^n K_j$. This is also the minimal number of equations. Furthermore, if the order in which components enter their respective states is of importance, each vector state is further divided into $n!$ combinations and the overall number of states is of the order of $n! \times \prod_{j=1}^n K_j$. This means that the number of states increases exponentially \times factorial with the number of components. For example, a system composed of 54 components, each having 3 possible states (active passive and failed), which is a moderate situation for realistic systems, will have (assuming no combinations of entry times) 5.81×10^{25} states. This imaginary number of states is a fair reflection of the complexity of reality and renders any attempt to obtain deterministic solutions (or even writing down the equations) an hopeless task.

It was already mentioned that any quantity of interest may be obtained once the event densities are known. For example, the probability of being in state \bar{B} at time t is given by:

$$P(\bar{B}, t) = \int_{\tau_1} \dots \int_{\tau_n} \psi(\bar{B}, \tau_1, \dots, \tau_n, t') R(\bar{B}, \bar{\tau}, t - t') d\tau_1 \dots d\tau_n \quad 2.4$$

where $R(\bar{B}, \bar{\tau}, t - t')$ is the state reliability i.e. the probability that the system will remain in state \bar{B} up to time t while t' is the time of entry into the state given as $t' = \text{Max}\{\tau_j\} \quad j=1, \dots, n$.

Similarly, the number of system failures up to time T is given by:

$$M(T) = \sum_{\bar{B} \in \Gamma_f} \int_{\tau_1} \dots \int_{\tau_n} \psi(\bar{B}, \tau_1, \dots, \tau_n, t') d\tau_1 \dots d\tau_n \quad 2.5$$

Where Γ_f is the set of all failed system states.

3. A Simple Example

Consider a system composed of 3 components named Pump, Valve and Protection (referred shortly as P, V and R respectively). Component P has two modes of operation. Mode 1 is the normal operational mode, the failure time distribution in this mode is denoted by $f_p(1; t)$ this mode is also referred to as the ‘slow’ mode. A failure in this mode does not result in a failure of the component but, rather, a transfer into a state (mode 2) in which a full severe failure is fast developing. This second mode is referred to as the ‘fast’ mode with failure probability $f_p(2; t)$. The mean time to failure of the first mode is of the order of 8000-16000 hours while that of the fast mode is 700-1400 hours. Models of this nature are useful in describing mechanisms in which a threshold situation is slowly developing such as in the appearance of small cracks in turbine blades, metal bodies or corrosive material containment. A failure in the fast mode has severe consequences on the system, repair time is considerably longer and costly and also an immediate failure may be caused to the V component. The protection unit is intended to detect a failure in Mode 1. Thus, if the R unit is operational at the time of a slow mode failure in P, the system is set passive and the P component is repaired without going into the fast mode. If the R unit is failed, then there will be no intervention and the fast mode commences. A failure in the R unit is not detected when it happens, a special inspection process is required. Inspection is modelled

using a clock (fourth component) which has two states. In state 1 the clock counts time up to inspection. This, with distribution $N_C(1; t, \mu, \sigma)$ which is a sharp normal distribution where μ is the average interval between inspections and $\sigma \ll \mu$. An event in state 1 means the beginning of inspection and the inspection state is denoted by (0). In this state the R component is inspected with 100% failure detection capability. The duration of the inspection has a distribution $g_R(0; t)$. Table 1 summarizes the components involved in this model, their states and the distributions attached to these states.

The total number of state vectors for this model 84. However, the time of entry is of importance since, for example component P can not enter state (-3) if the former entry is that of component C into any of its states. An indication of a state must include the entry time vector as indicated

$$\begin{matrix} 1, -2, 1, 1 \\ (\tau_1, \tau_3, \tau_4) < \tau_2 = t \end{matrix}$$

by the phase space vector $\vec{P} = (\vec{B}, \vec{\tau}, t)$. For example, the state indicates that components 1,3 and 4 entered state 1 in the past (with any order of entries) and component 2 (the protection) has failed (undetected) at time $\tau_2 = t$. Figure 1 displays a possible sequence of events in the system. Initially all the components are in state (1), component R fails into an undetected state (-2), then component P fails and the fast mode is activated and then it fails in the fast mode resulting in detection of the R failure and an immediate induced failure in component V.

Component	State indication	Meaning	Pdf
Pump	1	Operational Slow mode	$f_p(1; t)$
	2	Fast mode	$f_p(2; t)$
	0	Regular detected failure in slow mode	$g_p(0; t)$
	-3	Severe failure in fast mode	$g_p(-3; t)$
Protection	1	Operational	$f_R(1; t)$
	-2	Failed undetected	No event
	0	Failed detected under repair	$g_R(0; t)$
Valve	1	Operational	$f_V(1; t)$
	0	Regular failure	$g_V(0; t)$
	-3	Severe failure induced by fast failure of Pump	$f_V(-3; t)$
Inspection Clock	1	Counting time to inspection	$N_C(1; t, \mu, \sigma)$
	0	Inspection in effect	$g_R(0; t)$

Table 1: States and Data for the model.

Figure 1 is a partial presentation of all the possible states and transitions in the system. In this sense it is equivalent to a Markov diagram except that the entry times and their order is essential here. Such diagrams may be referred to as Non-Markovian diagrams and additional full examples of them can be found in [3,4,6].

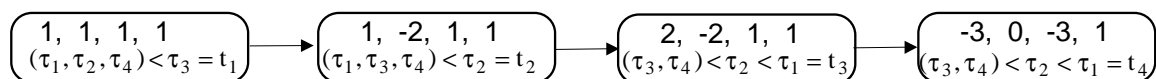


Figure 1: A set of events

The transitions indicated in figure 1 are also shown in figure 2 on the time axis.

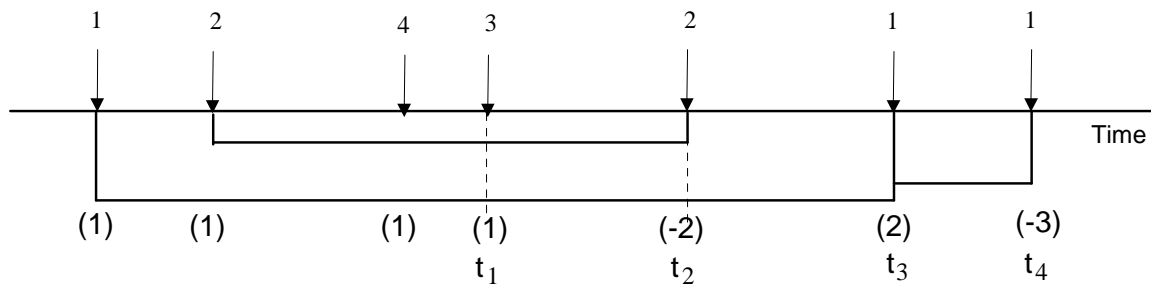


Figure 2: The set of transitions on the time axis.

The transport kernel for the transfer of the last two states in figure 1 is obtained using equations 2.1 and 2.3 in the form:

$$K(\bar{B}', \bar{\tau}', t' \Rightarrow \bar{B}, \bar{\tau}, t) = \frac{1 - H_4(1, t - \tau'_4)}{1 - H_4(1, \tau'_1 - \tau'_4)} \frac{1 - H_3(1, t - \tau'_3)}{1 - H_3(1, \tau'_1 - \tau'_3)} \frac{1 - H_2(-2, t - \tau'_2)}{1 - H_2(-2, \tau'_1 - \tau'_2)} [1 - H_1(2, t - \tau'_1)] \delta(\tau'_4 - \tau_4) \delta(\tau'_3 - t) \delta(\tau_2 - t) \delta(\tau_1 - t) z_1(2, t - \tau'_1) p_3 \quad 3.1$$

p_3 is a constant probability that a fast mode failure of component P will induce a failure onto component V. Substituting this transport Kernel into the transport equation yields for the related state:

$$\psi(-3, 0, -3, 1, \tau_4 < \tau_3 = \tau_2 = \tau_1 = t) = \int_{\tau'_2}^t d\tau'_1 \int_{\tau'_4}^t d\tau'_2 \int_0^{\tau'_1} d\tau'_3 \int_0^{\tau'_1} d\tau'_4 \psi(2, -2, 1, 1, \tau'_4, < \tau'_2 < \tau'_1; \tau'_3 < \tau'_1 = t')$$

$$K(\bar{B}', \bar{\tau}', t' \Rightarrow \bar{B}, \bar{\tau}, t) = \int_{\tau'_2}^t d\tau'_1 \int_{\tau'_4}^t d\tau'_2 \int_0^{\tau'_1} d\tau'_3 \int_0^{\tau'_1} d\tau'_4 \psi(2, -2, 1, 1, \tau'_4, < \tau'_2 < \tau'_1; \tau'_3 < \tau'_1 = t') \delta(\tau_1 - t) \delta(\tau_2 - t) \delta(\tau_3 - t) \delta(\tau_4 - \tau'_4) \frac{1 - H_4(1, t - \tau'_4)}{1 - H_4(1, \tau'_1 - \tau'_4)} \frac{1 - H_3(1, t - \tau'_3)}{1 - H_3(1, \tau'_1 - \tau'_3)} \frac{1 - H_2(-2, t - \tau'_2)}{1 - H_2(-2, \tau'_1 - \tau'_2)} [1 - H_1(2, t - \tau'_1)] z_1(2, t - \tau'_1) p_3 =$$

and using the Dirac delta function it is easy to integrate over τ'_4 yielding, finally, the equation:

$$\psi(-3, 0, -3, 1, \tau_4 < \tau_2 = \tau_3 = \tau_1 = t) = \delta(\tau_1 - t) \delta(\tau_2 - t) \delta(\tau_3 - t) \times \int_{\tau'_2}^t d\tau'_1 \int_{\tau'_4}^t d\tau'_2 \int_0^{\tau'_1} d\tau'_3 \int_0^{\tau'_1} d\tau'_4 \psi(2, -2, 1, 1, \tau_4 < \tau'_2 < \tau'_1; \tau'_3 < \tau'_1 = t') \frac{1 - H_4(1, t - \tau_4)}{1 - H_4(1, \tau'_1 - \tau_4)} \frac{1 - H_3(1, t - \tau'_3)}{1 - H_3(1, \tau'_1 - \tau'_3)} \frac{1 - H_2(-2, t - \tau'_2)}{1 - H_2(-2, \tau'_1 - \tau'_2)} [1 - H_1(2, t - \tau'_1)] z_1(2, t - \tau'_1) p_3 \quad 3.2$$

Equation 3.2 is one part of the transport equation. A similar equation should be explicitly written for each possible state of the system. Except for a number of rather trivial cases [3,6] the

obtained set of equations is prohibitively difficult to address. It should be noted that for the transport equation of neutral particles there is only a single case, that of a monoenergetic isotropic point source in an infinite homogeneous medium [7], that has an analytic solution. In all other cases one and two-dimensional cases have numerical solution methods [8] while full six dimensional transport problems require the application of the Monte Carlo method. The systems transport equations is by far more complex than that of neutral particles. First, the dimension of the equation is $n \times n$, where n is the number of components. This is the product space of the states of the components and n entry times. Furthermore, whereas the free flight of a neutron through space (the free flight kernel) is always Markovian, i.e. follows an exponential distribution, the free flight kernel of realistic, aging, systems is often non exponential. Also, Nuclear reaction laws are finite, accurate, universal and relatively easy to measure. The dynamics of the collision kernel in the case of systems is partially of a physical nature and very often based on men made rules which are not finite, complex and not always coherent.

Two basic difficulties are thus identified in obtaining realistic models and solutions. First, the dimension of the space in which system's transport takes place and second, as is demonstrated in equation 3.2, the complexity of the equations involved.

The Monte Carlo method is specifically suited for the type of difficulties described above. It is insensitive to the dimension of the space (courtesy of the central limit theorem) and it overcomes the difficulty in solving the equation by sampling, term by term the Neumann series expansion of the solution of the equation [2,6,9]. In the Monte Carlo method, Histories of the system are sampled using the free flight kernel to sample the next event point and the collision kernel to sample the type of the event that occurs. Having a sufficient sample of system's random histories, unbiased estimators are used to estimate any quantity of interest. The accuracy of the estimates is limited only by the computer time invested in the calculation.

3.1 Monte Carlo Solution of the Slow -Fast Modes Example

The above-described model was analyzed using the Monte Carlo method. The specific distributions data used is shown in table 2 along with various cost values assumed in the system. The target of the analysis is the systems availability and the time dependent total cost of repairs and down time. The general Monte Carlo code SPAR [10] was used for this example. As was noted above no finite set of closed rules can be stored to describe all possible eventualities in a system. SPAR contains a set of default rules (Such as all component start in an active state, all failures are immediately detected and repair is commenced according to the given repair distributions etc.) additional rules are entered with the aid of a special, menu driven, language. For example, some rules relevant to the current example are:

1. If {Component P fails in slow mode} then:
 - If {The protection unit is operational} then:
 - repair the slow mode (Default)
 - else
 - Activate the fast mode
 End of if
2. If {Component P failed in fast mode} then:
 - With probability p_3 :
 - induce immediate failure on component V
 - Change the repair distribution of V from $f_V(0; t)$ to $f_V(-3; t)$.

End of if.

A set of such operation rules guides the system to stochastically transport between all its possible states along the time axis with the appropriate probability of entering and residing in each state.

Cost	Pdf
Cost of slow mode failure -800	$f_p(1;t)$ - Exponent (8000)
Cost of Fast mode failure - 8000	$f_p(2;t)$ - Normal (860,60)
Cost of Inspection - 1200	$g_p(0;t)$ - Normal (24,8)
Cost of Induced Valve failure - 3060	$g_p(-3;t)$ - Normal (336,48)
Cost of Regular Valve failure - 460	$f_R(1;t)$ - Weibull(9.3E-06,1.35)
Cost of 1 hour Down time - 456	No event
p_3 - Probability of induced failure to V upon fast failure of P - 0.18	$g_R(0;t)$ Normal (8,2)
	$f_V(1;t)$ Weibull(1.63e-5,1.6)
	$g_V(0;t)$ Normal(16,5)
	$f_V(-3;t)$ Normal (168,48)
	$N_C(1;t,\mu,\sigma)$ Normal(4000,2)
	$g_R(0;t)$ Normal (8,2)

Table 2: Data and costs for the slow / fast model.

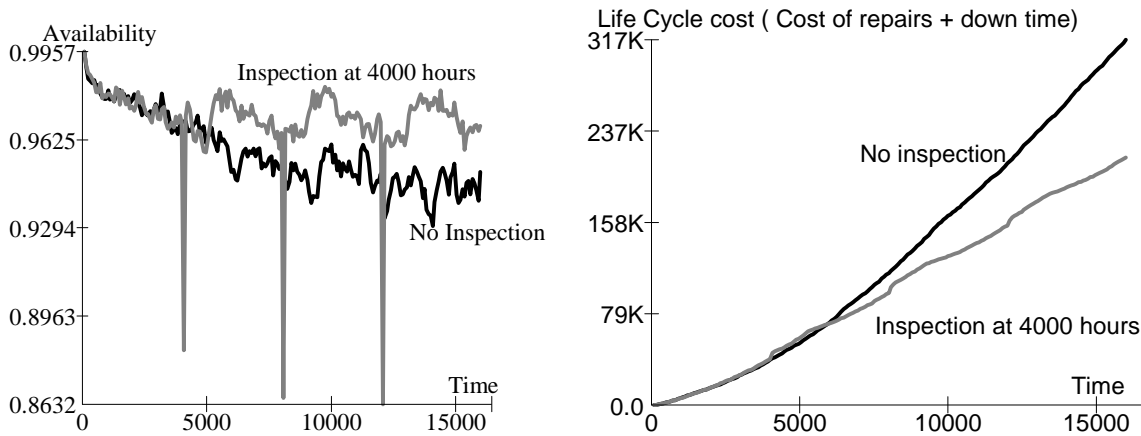


Figure 3a: Time dependent availability

3b: Time dependent cost of operation

Figure 3 (a&b) display the time dependent availability's and total cost for two cases. When no inspection is performed on the protection unit i.e. Upon failure it remains failed and undetected until a fast mode failure occurs and when inspection is applied every 4000 hours. The service time considered is 16000 hours.

4. Conclusions

System Engineering was, for many years an art composed of an eclectic collection of methods and procedures. A vast array of excuses ranging from lack of data to excessive unnecessary complexity was used to justify semi heuristic solutions based on uncontrolled approximations. In almost all cases of reliability and availability analysis exponential distributions are assumed, detaching the problem from aging and maintenance issues. In cases of maintenance, immediate repair is assumed. In spare part models homogeneous Poisson processes are assumed and no relation is established between resources (such as spare parts) and system performance. Most categories of system engineering are treated as independent subjects, such that Availability analysis is done as if no spare part problem exists. Maintenance analysis is executed with no relation to resources and performance and non-Markovian analysis is almost unheard of. These procedures are routed even in the structure of industries and organizations. One would find a Reliability department, detached from the spare parts department, detached from the maintenance department, Detached from the operations research department. The existence a single equation that unifies all aspects of system engineering may support the unification of the treatment of systems. It is claimed that such an equation does exist and is represented by the general Transport equation examples of which were brought above. Although this equation is prohibitively difficult, in most realistic cases, for an analytic or numerical solution it lands itself naturally in the range of Monte Carlo methods. It is, thus, suggested that the use of Monte Carlo methods may provide a meaningful step in the accurate unified and realistic analysis of all aspects of system Engineering. The last 15 years of experience indicate that many millions of Dollars along with improved and more reliable performance can be achieved with this approach.

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Opportunistic Maintenance in Aircraft using Relevant Condition Parameter based Approach

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Abstract

Opportunistic maintenance has been an essential part of all systems-maintenance, implicitly if not explicitly. However, as systems become more expensive and complex, the decisions involving opportunistic maintenance activities become more challenging. In this paper, we discuss a few issues that arise while carrying out the opportunistic maintenance and try to resolve them with the help of a popular optimisation technique called Genetic Algorithms. We also present a few results concerning relevant condition parameter based maintenance, as it has a high potential to be an opportunistic maintenance in complex systems. A systematic methodology is designed to enable the maintenance crew in deciding which items to be maintained when an opportunity arose. The cost of premature replacement is compared with the cost of down time, in the optimisation process using Genetic Algorithms.

Keywords: Opportunistic Maintenance, Condition based Maintenance, Relevant Condition Parameters, Condition Monitoring, and Genetic Algorithms

1. Introduction

Opportunistic maintenance plays a crucial role in systems that are maintained under both time-based as well as condition-based maintenance policies. In opportunistic maintenance, when a system or module is grounded for corrective or preventive maintenance, that opportunity is utilized to do maintenance on other parts of the module, which are found to be damaged or have started to deteriorate. On one hand, this improves the safety and reliability of the system, and on the other hand it reduces the downtime by avoiding un-scheduled maintenance. This in turn reduces the cost of maintenance, loss of revenue due to extra groundings, customer goodwill and so on. But, what is the criterion used to decide which parts to be considered for opportunistic maintenance and how far does one go? There is the engineering maxim, which says that, "unless it's broken, don't fix it!" Therefore, there are numerous factors that need to be considered before going ahead with opportunistic maintenance of a particular part. A detailed description of various situations that demand an in-depth analysis of advantages and disadvantages of carrying out the opportunistic maintenance is given below.

Maintenance cost has always been the most unappealing and at the same time the most unavoidable cost of a systems Life Cycle Cost (LCC). Especially in an airline industry, maintenance of an aircraft, commercial or defence, contributes a substantial amount of expenditure to the LCC. For example, the routine maintenance program of an aircraft itself is very extensive, and consists of maintenance checks like pre-flight before each flight, A and B

checks, which are performed on a regular basis, once in every 150 and 750 flight hours respectively. In addition to these checks, major inspection and reconditioning are done through C and D checks, which come under heavy maintenance, every 3,000 and 20,000 flight hours respectively. The annual demand for heavy maintenance of a narrow body aircraft is 11,000 labor hours and for a wide body aircraft, it is 17,150 labour hours approximately [3]. In spite of this major inspection and maintenance schedules, aircraft still requires condition-based maintenance for most part of the engine and corrective maintenance in some cases. Although, most part of the engine comes under condition-based maintenance, in practice, it is very difficult to estimate the condition of the items with 'boroscopes' and 'intrasopes' [1], as only a part of the surface is visible and that too at a very oblique angle. Thus, most of this on-condition maintenance is carried out as an opportunistic maintenance; when the engine or any module of the engine is stripped down to part level during the shop visits and performance restorations. In such situations, if some safety significant items seem to have been damaged, then they are obviously repaired or replaced. But the difficulty arises, when some potential failures of non-safety significant items are detected. These failures, if and when they occur, would only cause small increase in vibration, reduction in thrust or specific fuel consumption etc., which may result in engine being run hotter to achieve the required performance. However, if there was no actual failure and these secondary damages do not measure up to the cost of the remaining life of the component, the maintenance crew is in an ambiguity as to carry out a premature replacement or not.

Another important factor that puts the maintenance crew in a dilemma during opportunistic maintenance is features like *hard life (hard time)* and *soft life (soft time)*. *Hard life* is the age of the component at or by which the component has to be replaced. For example, at least 10% of parts in an aircraft engine consist of *Life Limited Parts (LLPs)*, which are replaced at pre-determined time intervals, irrespective of their condition. Safety critical parts like discs and shafts are given *hard times* and come under LLPs, as they can cause the loss of aircraft if they burst. These parts are usually very expensive and any wastage of life remaining in a LLP will significantly add to the maintenance costs. But at the same time, an unscheduled grounding of the aircraft or removal of the engine, just to replace a few LLP's would cost the operators huge sums of money. A trade off would be to replace the LLP's during the regular shop visits for performance restorations or full overhaul [4]. However, since all the LLP's may not have same "hard times", it is always not feasible to wait until the complete useful life of an LLP is exhausted and hence at least few LLP's are replaced prematurely during an opportunistic maintenance.

On the other hand, *soft times* are life thresholds for certain hot components of an engine, and usually determine the absolute limits for a performance restoration and full overhaul. Soft times are in fact the basis of on-condition engine maintenance. While some components may have reached their life thresholds, others may not and may also be in good working condition, so do not have to be repaired or replaced. Now the thousand-dollar question would be, how to decide whether to replace them now or not to avoid another engine removal in near future, when the soft times would have reached their thresholds. Another important aspect, which adds to the complexity of opportunistic maintenance, is the level of workscope required by the airline operators. Depending on their requirements, the airline may wish to have the engine overhauled either so that it remains on the wing for maximum time possible, or just the minimum work done to keep the engine serviceable for a shorter period at lower cost. This latter practice is typical when an airline expects to keep the aircraft or engine in service for only a short time or it can acquire used engines on the market for a price lower than the cost of overhaul [3].

Condition based maintenance is replacing time based maintenance in modern aircraft, especially in case of mechanical components, which undergo degradation failure mechanisms like crack growth, corrosion etc. As mentioned earlier, 90% of the parts in aircraft engine undergo condition-based maintenance, which is carried out during scheduled shop visits. Now the question arises, when some expensive parts are found to be deteriorating, and there may be a potential failure in future. These parts are not always necessarily repaired or replaced, immediately after the deterioration is detected. For example, fracture critical hardware such as rotors and disks are assigned service limits for crack growth, where cracks are allowed to grow to a specified size before the hardware item is repaired or replaced [12]. Therefore, items that fall under this category also need to be analyzed for cost of premature replacement against the cost of down time in future. Also, there is a possibility that there may be enough components with more or less equal useful lives left, which will collectively compensate the cost of down time for a future grounding. This is another factor that if optimized would result in a significant saving to the airline operators.

Thus, in the present paper, we mainly concentrate on two key issues. Firstly, as mentioned in the previous paragraph, condition-based maintenance is slowly but steadily taking over the traditional maintenance strategies like time-based maintenance (hard life). Hence, there is a need to develop various tools and techniques that not only monitor the condition of various components and subsystems, but also enable the maintenance crew to predict various reliability characteristics. Presently, many modern aircraft engines are equipped with Health and Usage Monitoring Systems (HUMS) to monitor various maintenance significant items. Strategies like Relevant Condition Parameter (RCP) based maintenance [8&9], which were developed mainly to model the degradation failure mechanisms, can be integrated into on-condition maintenance to predict the failures depending on the original condition of the components. RCP-based strategy is an effective way of condition based maintenance, which not only reduces the number of inspections and hence downtime [10], but also lends itself to opportunistic maintenance gracefully. The latter part can be attributed to the unique features of RCP-approach, like prior information and lead-time available to the maintenance crew regarding the eminent and potential failures of the components under observation.

Secondly, we develop a procedure to decide what components to be included in an opportunistic maintenance activity, using a popular optimization technique called Genetic Algorithms. In the following section we give a brief description of RCP-based maintenance.

2. Description of RCP based Maintenance

RCP-based maintenance is carried out in two parts. The first part is a systematic approach, with each step addressing a sequenced set of questions for each individual item of the system. The answers to these questions lead to the type of maintenance strategy that is most suitable to the corresponding item. The second part is a mathematical model, which is the implementation of RCP-based approach to maintenance planning. These are the four steps involved in the first part [2]:

Identification of the maintenance significant items (SSI's)

Determination of all condition parameters

Identification of Relevant Condition Predictors (RCP's)

Selection of condition monitoring techniques

Once the above steps are carried out, the next step is the implementation of RCP-based maintenance. The fundamental idea behind RCP-based approach is to integrate reliability of an

item or a system into maintenance planning and to be able to predict the reliability of the system with the help of condition monitoring devices. In order to achieve this, an RCP for each maintenance significant item, which is at a risk of degrading, is being monitored with a suitable condition monitoring technique. For an item to be able to function satisfactorily its RCP should lie between certain prescribed limits, denoted by RCP^{in} and RCP^{lim} set by the manufacturers. Once the numerical value of RCP crosses these limits, the item is qualified as a failure. Therefore, in RCP-based approach, the reliability of an item or system at time t is defined as *the probability that the RCP lying between the prescribed limits RCP^{in} and RCP^{li} at time t* , which can be given by the following expression [7].

$$R(t) = P(RCP^{in} < RCP(t) < RCP^{lim}) \quad (1)$$

Depending on the nature of these limits, RCP may be divided into the following four categories

- Fixed RCP^{in} and fixed RCP^{lim}
- Fixed RCP^{in} and distributed RCP^{lim}
- Distributed RCP^{in} and Fixed RCP^{lim}
- Distributed RCP^{in} and distributed RCP^{lim}

The reliability functions for each of the above mentioned categories and the cases involved within them are derived in Knezevic (1987), El-Haram (1995) and Saranga (2000) [8,9,2&10]. Once the reliability functions have been obtained for each maintenance significant item, depending on the nature of the limits, the next step is to plan the inspection intervals. In RCP-based approach, required reliability is considered as optimization criterion to maintain each significant item. Therefore, as soon as the reliability of an item reduces to its required level of reliability, maintenance actions needs to be carried out to restore the item to its original condition.

In order to achieve this, the time to the first examination of each item i , denoted by T_i^1 is calculated using the following expression [Knezevic (1987b)] ,

$$R_i(T_i^1) = P(RCP_i^{in} < RCP_i(T_i^1) < RCP_i^{lim}) = R_i^r \quad (2)$$

Where, R_i^r is the required reliability level for i^{th} item and $R_i(T_i^1)$ is the reliability of item i , at time T_i^1 . Now, we measure the reliability of each maintenance significant item at time to the first examination, T_i^1 to see if the measured value M_{RCP_i} , is less than the critical value RCP_i^{cr} ,

where RCP_i^{cr} may be obtained from the manufacturers. For all the items, whose

$M_{RCP_i} < RCP_i^{cr}$, the item is allowed to operate until the next time to the examination. And for

all the items, whose $M_{RCP_i} \geq RCP_i^{cr}$, required maintenance actions be carried out to restore the items to their original condition. The next subsequent times to the examinations depend on the difference between the measured value of RCP at the previous time to the examination and critical value of RCP, and can be obtained using the expression [2],

$$\int_{T_i^{(j-1)}}^{T_i^j} f_{M_{RCP_i}(T_i^{(j-1)})}(\tau) d\tau = \int_{M_{RCP_i}}^{RCP_i^{cr}} f_{RCP_i(T_i^j)}(c) dc \quad (3)$$

Where T_i^j is time to the j^{th} examination, T_i^{j-1} is time to the $(j-1)^{\text{th}}$ examination, $f_{M_{RCP_i}(t)}(\tau)$ is the probability density function of M_{RCP_i} at time t and $f_{RCP_i(T_i^j)}(c)$ is the probability density function of RCP_i at time T_i^j .

Thus, for all those items, which did not need maintenance at the time of examination $T_i^{(j-1)}$, $j=2,3,\dots$ the time to the next examination will be T_i^j , where one of the above two decisions are made depending on their measured value $M_{RCP_i}(T_i^{(j-1)})$. For the items that have undergone maintenance at $T_i^{(j-1)}$, the time to the next examination will be T_i^1 , as they are treated *as good as new* and the entire process starts all over again. An important point to note here related to opportunistic maintenance is that, although we know that the condition of RCP_i is critical once it exceeds RCP_i^{cr} , we still do not know exactly how much time it takes for RCP_i to reach RCP_i^{lim} i.e., to fail, from RCP_i^{cr} . And hence we do not know the time available for the maintenance crew in order to decide whether to ground it immediately or to wait until the system is available for maintenance in the immediate future. In such situations, it is helpful to know the *Residual Life* of the item, which is the mean remaining lifetime of the item that has survived up to time T_0 and can be obtained from,

$$\begin{aligned}
 MTTF(T_0) &= \frac{1}{R(T_0)} \int_{T_0}^{\infty} R(t') dt' & (4) \\
 &= \frac{1}{R(T_0)} (MTTF - \int_0^{T_0} R(t) dt)
 \end{aligned}$$

Where $t' = t + T_0$. Thus, once the item reaches RCP_i^{cr} , we can calculate the residual life of the item in order to know as to how long the item will survive.

Thus the question that arises here, with regard to opportunistic maintenance is that whether the inspections or the maintenance activities can be carried out as a part of scheduled maintenance whenever there is an opportunity. The lead time and the prior information available to the maintenance crew regarding the nature of the potential or eminent failures enables them to plan the required preventive or corrective maintenance activities according to their convenience. But again, the comparison between the cost of grounding and the cost of premature replacement needs to be made even in this case.

3. Genetic Algorithms

In order to incorporate all the above-mentioned factors and like into the decision making process of opportunistic maintenance, one needs to come up with an efficient optimization tool that is robust enough. One such rapidly expanding optimization tool, recently being used for opportunistic maintenance strategies is Genetic Algorithms (GAs). Genetic algorithms are a subclass of Evolution Programs (EPs), which imitate natural selection process in searching for an optimum solution for an objective function called the fitness function. GAs were first proposed by Holland (1975)[7] and were further developed by his student, Goldberg and others in the 1980s. The GAs differs from most optimization techniques, due to their nature of searching a

population of solutions, rather than a single solution. Savic *et al* (1995)[11&12] used genetic algorithms for optimum group replacement problem during opportunistic maintenance.

Following key features of Genetic Algorithms [6] lend themselves to use GAs as an optimization tool in the current context.

- Optimizes highly complex cost functions
- Optimizes with continuous or discrete parameters
- Simultaneously searches from a wide sampling of cost surface
- Deals with a large number of parameters
- Provides a list of optimum parameters, not just a single solution
- Works with numerically generated data, experimental data or analytical functions

Since, while talking about aircraft maintenance, we are dealing with thousands of unique parts, which involve numerous factors to be considered to be included in the opportunistic maintenance, GAs, being the best technique to model highly complex cost functions, will suite the present situation very well. The objective here is to be able to decide, whether the item under consideration should be replaced under opportunistic maintenance or not, purely depending on the basis of whether it is cost-effective to replace it now or not. Those items, whose hard or soft lives have been expired, are replaced without ambiguity. Question arises, only for items with useful life left in them, which most of the time are expensive, as otherwise are replaced prematurely whenever an opportunity arises, instead of grounding the system. The choice of replacing it now should be weighed between the cost of premature replacement and the cost of grounding the system in future, purely for the purpose of replacement.

Thus, with each item under question, we attach a cost or fitness function, and use Genetic Algorithms, to decide which ones to be replaced. We formulate the fitness function as follows:

$$\begin{aligned} & \text{Maximize} \\ & Z_{ij} [D_i * C_d - j * C_i] \end{aligned} \quad (5)$$

Where,

$$Z_{i,j} = \begin{cases} 1 & \text{If the item is replaced } j \text{ hours before the scheduled time} \\ 0 & \text{Otherwise} \end{cases}$$

D_i = Downtime due to replacement

C_d = Cost of Downtime per hour

C_i = Cost per hour for item i

At this point, it is important to note that, we have only considered the simplest case, just as an example, and the fitness function may be extended to incorporate various factors that play a crucial role in deciding whether an item should be replaced prematurely or not.

In the present paper, we discuss a step-by-step procedure to decide whether a particular component should be included in the opportunistic maintenance and suggest a method to decide when GAs can be used. To start with, we need to identify the points at which opportunistic maintenance can be performed. In general, for any complex system, the below mentioned timings provide an appropriate means to carryout opportunistic maintenance.

Scheduled maintenance intervals: these are predetermined times, at which scheduled tasks like overhauling, checks like A, B, C and D etc. are carried out.

Corrective maintenance: when a module is grounded to repair or replace a failed item.

Progressive inspection: if an inspection or examination of a condition monitoring device needs to be carried out.

Once the opportunity arises, the next problem is to identify which components to be considered for repair or replacement amongst the components that are accessible and are at a risk of potential failure. At this point, one needs to divide the potential failures into age related and non-age related, and focuses only on age related failures. And also, we concentrate only on maintenance significant items, as the failure of non-significant items should not affect the system performance directly. The following flow chart diagram will be of great help in describing the procedure.

Notation:

MSI --- Maintenance Significant Item

TBM --- Time Based Maintenance

RCPBM --- Relevant Condition Parameter Based Maintenance

HT --- Hard Time

ST --- Soft Time

t --- time of opportunistic maintenance

t^1 --- time of next scheduled maintenance

RCP --- Relevant Condition Parameter

RCP_i^{cr} --- Critical Value of RCP, for item i

$RCP_i(t)$ --- Value of RCP for item i at time t

GA --- Genetic Algorithm

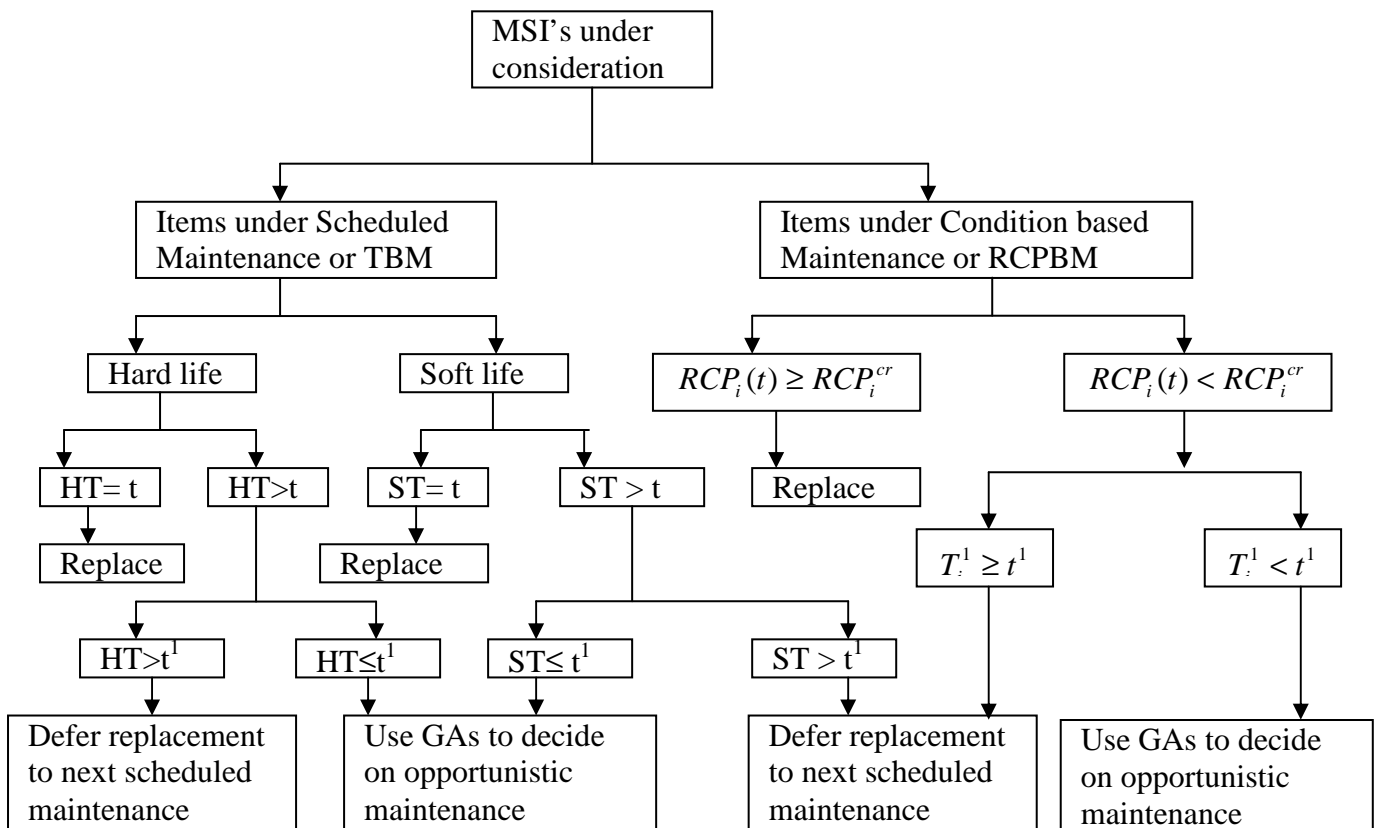


Figure 1. Flow Chart Description of the procedure to decide on opportunistic maintenance

As one can see from the flow chart, the MSI's accessible for opportunistic maintenance have been divided between time-based maintenance and condition-based maintenance, depending on how they are being maintained. For all the items that fall under TBM, we have to further divide them into hard life and soft life, depending on what times are allotted to them. At the time of opportunistic maintenance, all those items, whose hard life or soft life has elapsed, would any way be replaced. For those items, whose hard life or soft life is remaining, depending on how much life is remaining, the decision to defer the replacement to the next scheduled maintenance, t^1 or to replace now has to be taken. If the life remaining is more than t^1 , then obviously, the replacement is deferred to t^1 . If the life remaining is less than t^1 , then the decision of whether to replace now, or ground the system when it is required, is taken using Genetic Algorithms.

Similarly, for items under condition-based maintenance, especially, in case of relevant condition parameter based maintenance, the decision to replace now or not, is taken depending on the value of RCP^{cr} . If the value of RCP for item i , at the time of opportunistic maintenance, t is equal to the critical value, then the item is replaced. If $RCP_i(t)$ is less than the critical value, and if the time to the next examination, T^1 is greater than the time to the next scheduled maintenance, t^1 , then the replacement can be deferred to t^1 . And if the time to the next examination, T^1 is less than the time to the next scheduled maintenance, t^1 , then Genetic Algorithms is used to decide whether to replace now or to ground the system whenever the requirement arises.

4. Conclusions and Limitations

The significance of opportunistic maintenance in fields like aircraft engine maintenance, where complex systems are involved has been emphasized. There are numerous factors to be considered, while deciding on whether a particular component should be replaced or repaired when an opportunity arises. An effective condition-based maintenance, called relevant condition parameter based maintenance, has a great potential to be integrated into aircraft engine maintenance and adopts gracefully for opportunistic maintenance with its unique features. Genetic Algorithms is introduced, as an optimization tool, to compare the cost of premature replacement with the cost of downtime if grounded for the sole purpose of replacement.

This paper was an initial attempt to use Genetic Algorithms for opportunistic maintenance in complex systems. Much work needs to be done in this area, and numerous other relevant factors needs to be incorporated for a comprehensive study. A case study involving a practical application of Genetic Algorithms to real life data, would bring about the practical difficulties involved, but was not carried out here. This was just a preliminary research done to integrate the two areas of opportunistic maintenance and relevant condition parameter based maintenance and to explore the scope of Genetic Algorithms as an optimization tool in this respect.

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MAINTENANCE EFFECTIVENESS – THE HIDDEN COSTS

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Abstract

Maintenance managers like to think that they are both efficient and effective and that their organisation is performing at its best. Initiatives come and go and some may help but some are often merely window dressing. Managers may be proactive in reducing waste in their organisations whether it is waste of resources, waste of time or waste of effort. However, to be the most successful organisation in any field requires an admission that there is always room for improvement and that there is probably still waste that remains to be identified; sometimes depending on the type of waste identified or perceived to remain, many middle managers will be reluctant to admit there are still problems to tackle. Admitting where the waste is and what needs to be done requires many things to come together. Identification of the waste and the hidden costs that result must be done though and a major area of waste that many organisations either do not recognise, or are unwilling to tackle, is the problem of No Fault Found (NFF). Using a benchmarking tool developed by the EPSRC TES Centre, is a vital first step that allows the organisation to focus on the hidden costs of NFF.

Introduction

Availability is a key requirement for most organisations in whatever industrial sector they operate within. Providing enough assets at the right time and in the right condition is vital whether you provide aeroplanes, trains or plant machinery. If those assets are suffering unexpected faults that need diagnosis and corrective action, then they are not available and faults that cannot be diagnosed successfully waste more time and consume extra effort. Such faults are termed No Fault Found (NFF), Can Not Duplicate (CND) or ReTest OK (RTOK) among many other similar terms. In certain circumstances these unresolved faults may also affect safety but will certainly have a detrimental effect on availability. Research undertaken by the EPSRC Centre for Innovative Manufacturing in Through-Life Engineering Services at Cranfield University, has investigated the NFF issue within the Royal Air Force to establish the cost of NFF across a representative number of aircraft fleets. Maintenance data analysis and interviews with maintenance and diagnostic technicians have been used to inform the development of a benchmarking tool that assesses an organisation's ability to deal with NFF. Following trials, the tool is intended to be widened in its application to a diverse range of industries that would benefit from assessing their capability to reduce NFF.

The RAF Study

Initial results showed some general conclusions that need to be addressed in any development of a benchmarking tool. Procedures for some maintenance actions were either overly complicated or overly simplified and in some cases for particular faults, a procedure did not even exist. Diagnosis on modern aircraft often now relies too heavily on Built-in-Test (BIT)

and test equipment to provide results and solutions; if such test routines have not been designed well enough, faults can be masked or never identified. A common problem identified for aircraft and in the RAF study was that testing invariably fails to replicate the usage and operational environment that was being experienced when the fault occurred. Another problem identified and one that is prevalent in most large organisations is the lack or under-utilisation of data; for example fault and repair data is often not shared between users, workshops and suppliers, meaning that the relevant fault history is not easily available. Where there are databases in use, such as that used by the RAF, the data is perceived as too unwieldy and there is no consensus or funding available to make the changes needed.

In the RAF study a major finding has been that there is a lack of understanding that there is a significant cost involved from NFF. Maintenance personnel indicated during the interviews that they believe there is a significant occurrence of NFF and there must therefore be a significant cost, yet there is no real awareness of the cost among higher management. There is often a belief that availability is the key parameter so the quick fix is preferred regardless of whether this causes costs further down the support chain. For example, three boxes would be changed when only one is going to be at fault and this will cause two of them to be NFF on test in the workshop bay. Finally, there was little recognition that NFF could possibly be a safety issue yet there was anecdotal evidence of situations that had either been experienced or that could happen where safety and NFF were inextricably linked.

Data Anomalies

One clear conclusion that demonstrated the need for a benchmarking tool was the different attitudes among maintenance personnel that were evidenced by how the maintenance data was recorded. It is an aspect of human nature that people do not like to admit defeat. In the maintenance environment there are many other factors also at work such as team working, management pressure, environment and stress to name but a few. On top of that there is an individual's training, experience and most importantly their own personality and character. All these elements and their personal attributes will form how the individual deals with a diagnostic task and more importantly how he reports what has been done. In analysing the RAF maintenance data, there were a certain number of tasks that would indicate that no fault had been found and would thus be recorded in the database as NFF. In many other cases, the work done was recorded in many diverse ways which should have been correctly identified as NFF, but were not, when entered into the database. Examples are:

- Fault cleared itself during investigation
- Tested satisfactorily.
- No fault indications found.
- No fault codes evident.
- No fault symptoms apparent.
- No damage found.
- Unable to replicate fault or symptom.

These sorts of descriptions show a certain reluctance to declare that a positive outcome has been achieved in identifying a real fault. Either it is deliberate or perhaps it is a symptom of hiding the fact that more work needs to be done as the work so far has in fact been a failure? In some instances, and quite understandably, it is perhaps a reluctance to disbelieve the originator of the fault. It is also perhaps a resignation that the particular fault will never be replicated on the ground as the environment and usage can never be accurately replicated. Some or all of these

attitudes though are symptomatic of the organisation's overall view of the NFF issue. The use of a benchmarking tool that identifies these attitudes and produces appropriate mitigation strategies was thus recognised as a useful development and so the NFF Impact Avoidance Benchmarking Toolset was born.

The NFF Impact Avoidance Benchmarking Toolset

Following the research into NFF including as much published work as possible, the EPSRC Centre established some key aspects of the knowledge and understanding that existed. These fundamental issues included the acknowledgement that NFF is a collection of complex related issues rather than merely a single issue. The issues relate to a breakdown in the processes of identification, localization, root cause identification and effective diagnosis of faults. But there are also complex organizational issues and human factors issues that are just as prevalent in the causes that produce the high levels of NFF as there are purely technical causes; these organizational, process and human factors issues are generally often easier to solve providing they can be identified and recognised. Perhaps the main conclusion though was that to address the NFF issues you have to impact the effectiveness with which the underlying process steps are performed.

In order to address the relevant organisational issues and the underlying process issues though, it is vital to first know the organisation's policies, culture and applicable processes that should deal with levels of NFF. These all need to be identified honestly and openly with nothing hidden. Clearly the right people have to be involved and it is likely that some startling revelations might be learnt on the way! Benchmarking provides a structured way of doing this assessment and one where the results are most likely to be accepted and the identified mitigation strategies adopted. Benchmarking also can identify the areas most sensitive to attention and improvements.

For the NFF benchmarking tool development, the purpose to be achieved was first defined as:

Achieve a minimum level of non-value added activity in the timely diagnosis and resolution of complex system fault indications with the minimum amount of time and other resources expended to:

- *Confidently restore the customers operation,*
- *Robustly isolate and remove the cause of the fault indication,*
- *Learn lessons and prevent future impacts,*

The process also had to be identified and consisted of two areas for diagnosis; these were maintenance on-board and the process for diagnosis for those items when removed. Figure 1 shows the process diagram that was used.

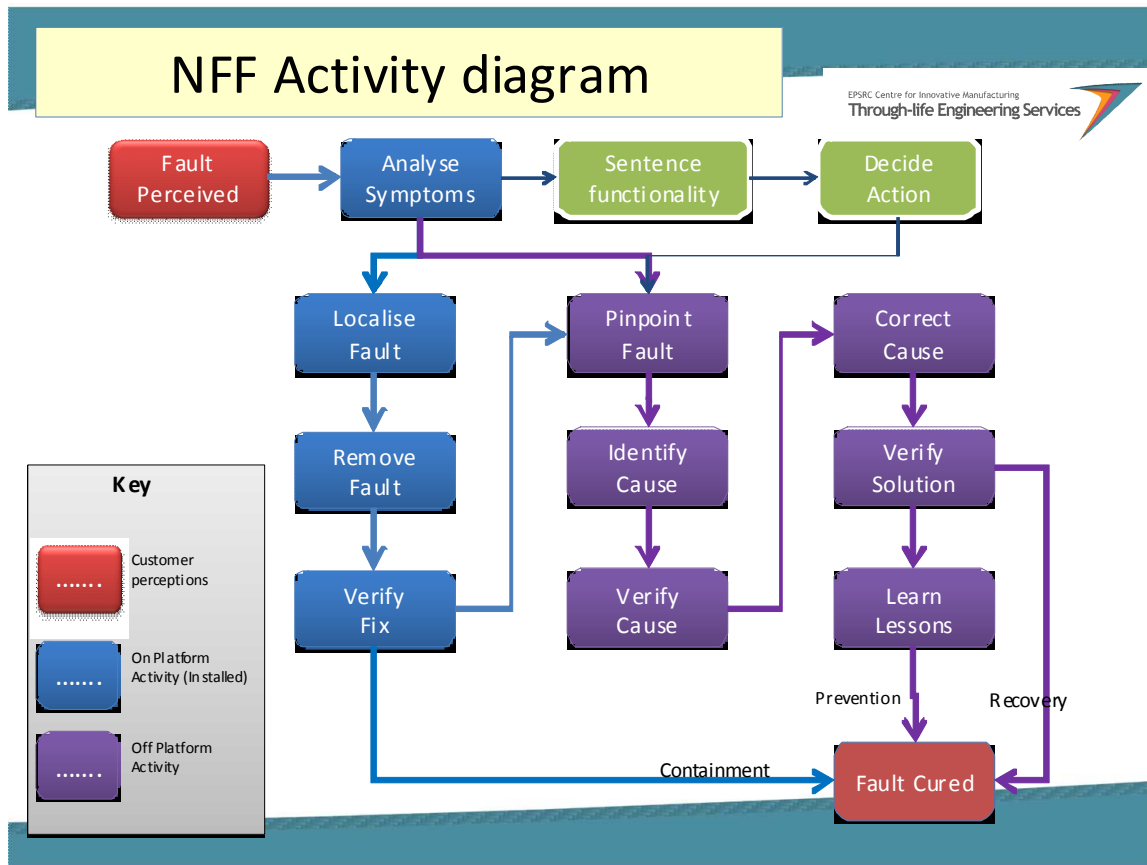


Figure 1. The NFF Activity Process Diagram

Part of the rigour of defining the NFF activity process was to define verb-noun pairs for each step of the activity. Once agreed, the key success indicators for each activity had to be defined followed by the definition of world class, competitive and basic capability for each activity. The benchmarking tool is then developed further into an improvement opportunity toolset by linking key improvement activities to each activity and indicator. The toolset was then developed on an Excel spreadsheet in order to inter-link the assessment values at each activity to a score showing where the low scores exist. These low score areas then allow the team to identify first where the organisation is weak and to focus on solutions and options for mitigation.

Future Development

The benchmarking tool has now been piloted in one large organization and during 2015 will be proved and developed in both aerospace and other transport industries with the aim of making it able to be customized to a specific organization and to an industry. Early evaluation shows this approach to be feasible and highly beneficial to those taking part and to the industry concerned.

Conclusion

The research done by the EPSRC Centre for Engineering Through-Life Services and those who have sought to tackle the NFF problem in the past have identified that a problem still exists with the costs of NFF; the effort and resources expended are far in excess of what is either apparent or believed to be involved by management. Many of the problems, mitigations and solutions are organizational, process driven or lie in the field of human factors. All these issues

need to be identified yet there is a reluctance to face up to them in many organizations. Yet most are responsive to change once they are identified. A clear and honest appraisal by those closely associated with the maintenance process and its management are best positioned to make the assessment. The most effective way to do this assessment is with a structured benchmarking tool which now exists for organizations to trial and customize to their own industry and organization.

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