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Maintenance Challenge: Troubleshooting Broken Computer Chips

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Abstract

Computer chips are essential providers of functionality of today's advanced digital systems. However, digital systems are different from traditional electromechanical systems, as they are an integrated, tangle of electrical, mechanical and electronic parts. Nevertheless, they do fail and need to be maintained. Unfortunately, it is impossible to troubleshoot a computer chip by looking for physical evidence of failure. A broken chip neither looks any different from a healthy one, nor, leaks, vibrates or makes a noise. Faulty software within them doesn't leave puddles or stains as evidence of its failure. Even more, it is physically impossible to see 1s and 0s falling off the end of a connector pin. Thus, the main objective of this paper is to address the challenges and possible solutions related to the troubleshooting broken computer chips and associated digital systems. Challenges are shared between the system designers who conceive their complexity in the design office, on one hand, and system maintainers whose corrective maintenance actions are initiated by detecting and understanding failure causes, locations and determining appropriate maintenance actions on the other. Regretfully they do not work together and it is safe to conclude that they do not even meet, as they work for different companies. Hence, a closer collaboration between them, at the learning stages of their lives, is the obvious way forward. However, current educational and training institutions, world-wide, do not facilitate that integration. Even further, the situation is very much the same with corresponding professional organisations and societies.

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1. Introduction

Axiom 4: The probability of occurrence of in-service failure at any instant of time is greater than zero. [2]

Human needs for transporting, communicating, defending, producing, heating, information, cooling, entertaining and many other functions are being satisfied by making ships, airplanes, tractors, computers, factories, radios and other functional systems. However, experience teaches us that while satisfying felt needs, human created systems are frequently beset by failures resulting from many causes. In order to continue satisfying expected function(s) it is necessary to perform appropriate maintenance actions. They are defined as, “the flow of predetermined maintenance tasks, starting with troubleshooting and finishing with a final testing, performed by trained maintainers, using predetermined resources, like materials, equipment, tools, facilities and so forth”. [3]

Recent developments of digital technologies have made fundamental changes to the way humans live their lives. Among others, digital technology is a driving force behind almost all modern systems, from passenger cars to spacecraft, on one hand, and from manufacturing plants to nuclear power stations, on the other.

Computer chips are essential providers of functionality of today's digital technology based systems, from computers to Internet devices and countless other electronic systems. However, these digital systems are different from traditional electromechanical systems. Digital systems are integrated and consequently more complex. Subtle, tangled and sometimes abstract relationships exist between their electrical, mechanical and electronic parts, as well as their related systems. However, contemporary digital systems, like earlier technical systems, experience in-service failures and they must be maintained.

Unfortunately, it is impossible to troubleshoot a computer chip by looking for physical evidence of failure. A broken chip doesn’t look any different from a healthy one. Although it can be argued that broken chips occasionally make smoke, evidence of malfunction is seldom readily apparent. Broken chips don’t leak, vibrate or make noise. Faulty software within them doesn’t leave puddles or stains as evidence of its misbehaviour. Even more it is physically impossible to see 1s and 0s falling off the end of a connector pin. [2]

The main objective of this paper is to address the challenges and possible solutions related to the troubleshooting of digital electrical systems. Challenges are for the system designers who conceive their complexity in design office, on one hand, and for system maintainers whose corrective maintenance actions are initiated by detecting and understanding failure causes, locations and determining appropriate maintenance actions on the other. Solutions are a closer collaboration between them. However, existing educational and training institutions, all over the world, have not yet found a mechanism to facilitate the collaboration process.

2. Digital Systems

Digital systems are designed to store, process, and communicate information in digital form. They are found in a wide range of applications, including process control, communication systems, digital instruments, and consumer products.

A computer is an example of a typical digital system. It uses information in digital, or more precisely, binary form. A binary number has only two discrete values, zero or one, both of these discrete values are represented by the OFF and ON status of an electronic switch called a transistor. Thus, computers understand binary numbers only. The basic blocks of a computer are the central processing unit (CPU), the memory, and the input/output (I/O). The CPU to the computer is basically the same as the brain to a human. Computer memory is conceptually similar to human memory. A question asked to a human is analogous, while to entering a program into the computer requires an input device such as the keyboard. Answering the question by the human is similar in concept to presentation of the result required by the program to a computer output device such as a screen or the printer. However, the main difference between them is the fact that human beings can think independently, whereas computers can only answer questions that they are programmed for.

Digital electrical systems are different from traditional electromechanical devices. Digital systems are integrated and consequently more complex. Subtle, tangled and sometimes abstract relationships exist between their electrical, mechanical and electronic parts, as well as their related systems. Thus, troubleshooting process requires a maintainer with an intuitive sense and judgment, coupled with a detailed knowledge of:

- Systems and their component parts.
- The role each of them plays
- Their distinctive behaviour and inherent design limits
- The impact of their mutual interactions

Good troubleshooting is nothing more than good deductive reasoning. At the centre of that reasoning is a careful collection and evaluation of physical evidence. Many of today’s devices use computer chips to provide a function previously performed by substantial mechanical parts of subsystems. Consequently, troubleshooting, in the traditional sense of searching out physical evidence of failure became out of the question.

3. Role of troubleshooting in Maintenance

Troubleshooting is a systematic approach to problem solving that is often used to find and correct failures of complex digital systems. The first step in troubleshooting is gathering information on the issue, such as an undesired behaviour or a lack of expected functionality.

Troubleshooting may be extremely simple or quite complex. For example, if a hydraulic leak is detected, the source of the leak is often quite easily traced. On the other hand, the failure of a small component in radar or computer equipment is not readily identified. In this instance, the maintainer must accomplish a series of steps in a logical manner, which will lead him or her directly to the faulty item. However, at times, these steps are not adequately defined and the maintainer is forced into a trial-anderror approach to maintenance. A good example is when the maintainer starts replacing parts on a mass basis (without analysing cause-and-effect relationships) hoping that the problem will disappear in the process. This of course, affects maintenance downtime and spare/repair part needs, as the maintainer may replace many parts when only one of them is actually faulty.

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

4. Built In Test Equipment Based Maintenance

Built in test equipment (BITE) based maintenance systems have the advantage of permitting effective monitoring of the deterioration of economic features and managing the scheduling of their repair while assuring functionality and economic viability of systems.

Digital BITE permits many parameters within a Line Replaceable Unit (LRU) to be monitored. These monitors generate fault reports, via maintenance messages, whenever one of the relevant condition parameters is out of acceptable limits. In turn, individual LRU reports can be consolidated with reports from associated LRUs and systems thus permitting:

- accurate isolation of the root cause of a malfunction within LRUs or systems,
- assessment of the health of individual LRUs as well as interrelated systems.

However, BITE could be affected by environmental disturbances and design limitations that may cause it to generate incorrect fault reports, namely:

- limited fault consolidation logic,
- inadequate delays in fault-setting logic circuit,
- voltage transients (bad power)

All of the above listed factors contribute to BITE's ineffectiveness. Although these factors may be controlled, but will never be eliminated. Consequently, maintenance messages may either mislead the mechanic or, more frequently, be unable to clearly pinpoint a single faulty component within a system. [11]

At the same time, there are intrinsic limitations of any BITE-based system. They are pivotal to understanding the role the maintenance messages play in maintenance processes, especially in troubleshooting. It is necessary to grasp these limitations in order to understand why BITE can be "misleading" and, further, how these limitations affect the interpretation of BITE data during maintenance. Thus, BITE-based systems only indicate the integrity of the portion of a system they monitor and as such are also limited by:

- The amount of fault logic and the degree of fault consolidation logic included.
- The parameters to be monitored (the number and kind of sensors).
- The budget allocated to it during the design of a component.

It is necessary to stress that the BITE itself could become a source of failure. After all, the primary function of any given component is to perform its intended design function, not to check upon itself for failure. Thus, BITE is often unable to absolutely identify a single faulty component within a system. The solution can be more sensors with more fault logic. This permits better isolation of discrepant LRUs. At the same time it also leads to more wire, more weight and more fault messages: this in turn means more chances for logic errors. There is a finite limit to the amount of sensing and logic, and thus a limit to the fault intelligence that may be derived from any BITE-based system. Consequently, BITE results will always contain some ambiguity.

5. Fault Logic and Consolidation

Frequently, elusive relationships exist between the subsystems/modules of a system. For example, if one component within a system fails and it is unable to provide necessary data to another downstream LRU. Thus, if BITE logic does not take this into account, the consequence is multiple fault reports: the upstream truly failed component, and he downstream units dependent upon the first's information. This is called a cascaded fault, and they challenge the mechanic with a dilemma: what to do to fix it?

Fault logic in any system must effectively consolidate fault reports from many components within a system and eliminate or at least control cascade effects. The number of fault monitors dealt with design and the consolidation logic drives the success of this process.

The inherent limitations of sensor and logic design frequently make it impossible to consolidate faults and identify a single component or system as the root cause of a failure. In most instances, the solution is carried to a group of components that are the possible causes. This is known as an ambiguity group.

In many designs, ambiguity groups are not given to the maintainers. In these situations, the designers have made a decision based on their own knowledge of the system, its components, individual reliability, and his perception of how mechanics troubleshoot. The result can be a BITE that does support troubleshooting decisions, as ambiguity is not presented to the mechanic. Thus, there is a difference between imaging troubleshooting in the design office and physically doing troubleshooting in an operational environment.

6. Power Sensitivity

In same cases the efficiency of BITEs can be affected by issues related to digital circuits, as the sensitivity to power interruptions, voltage transients, timing delays, electrical bus power up sequences, and the like, which are commonly know as a dirty power. The most obvious example is power cars that provide electrical energy to aircraft at the gates.

Fault monitoring circuits with insufficient time delays and consolidation logic will incorrectly set maintenance faults when these conditions arise. These are tagged as nuisance faults, an annoying cause of delays most evident when the system is first powered or when it encounters a power transfer. These in-service anomalies of BITEs must be estimated and dealt with in the design office. Hence, there is a difference between perceiving troubleshooting in the design office and physically doing troubleshooting in an operational environment.

7. Troubleshooting Digital Systems: The Boeing 777 Solution

Troubleshooting is the process of identifying problems in operational systems and application of corrective actions to return them to their optimal operation. Maintainers achieve this by testing the various components, either individually or collectively, to isolate faults that occur while using the system considered.

A great place to start troubleshooting faulty systems is by determining what the most likely causes of the failure are. System failures can be classified in several ways, such as functional failures and failures due to operating conditions. There are numerous examples of both related to a huge spectrum of systems in all industries.

In the remaining part of the paper author will address the practical application of troubleshooting challenges addressed by the Boeing commercial aircraft, namely, B777, as the author is the most familiar with this system. However, troubleshooting challenges are present in almost every industry today, as the number of systems that operate today without digital technology is extremely small. [7]

7.1. Fly-By-Wire Primary Flight Controls

Fly-By-Wire (FBW) has been used in military applications such as fighter airplanes for a number of years. The B777 is the first commercial transport manufactured by Boeing which employees a FBW Primary Flight Control System. It is necessary to stress that this is only a single example of what is currently in service in the airline industry. There are several other airplanes in commercial service made by other manufacturers that employ a different architecture for their FBW flight control system than described here. [8, 9, 14]

Irrespective of the architecture used by a FBW flight control system it has several advantages over a mechanical system, namely:

- Overall reduction in airframe weight
- Integration of several federated systems into a single system
- Superior airplane handling characteristics
- Ease of maintenance
- Ease of manufacture
- Greater flexibility for including new functionality

Conventional primary flight controls systems employ hydraulic actuators and control valves controlled by cables that are driven by the pilot controls. These cables run the length of the airframe from the cockpit area to the surfaces to be controlled. This type of system, while providing full airplane control over the entire flight regime, does have some distinct drawbacks. The cable-controlled system comes with a weight penalty due to the long cable runs, pulleys, brackets, and supports needed. The system requires periodic maintenance, such as lubrication and adjustments due to cable stretch over time. In addition, systems such as the yaw damper that provide enhanced control of the flight control surfaces require dedicated actuation, wiring, and electronic controllers. This adds to the overall system weight and increases the number of components in the system.

In a FBW flight control system, the cable control of the primary flight control surfaces has been removed. Rather, the actuators are controlled electrically. At the heart of the FBW system are electronic computers. These computers convert electrical signals sent from position transducers attached to the pilot controls into commands that are transmitted to the actuators.

7.2. Chief Mechanic

Since, 1916 there has always been a Chief Pilot on every Boeing model. However, the 777, in recognition of the importance of the maintenance process to successful airline operation, is the first Boeing model to have a chief mechanic. Thus, 1990 the history in aircraft maintenance was made when Jack Hessburg was named as the chief mechanic new airplanes, Boeing Commercial Airplane Group, and became the first person in commercial aviation history to hold this position.

The major efforts of the chief mechanic were concentrated on making the airplane as "mechanic friendly" as possible. Consequently, the chief-mechanic was proud to say that: "777 was built first for the line mechanic because he's the guy who signs the logbook and has to work in this tremendously time-driven environment". [11]

The rest of the paper describes that impact of the Chief Mechanic on the design of the aircraft from the maintenance point of view, which has provided an extremely high level of the inherent availability.

7.3. Central Maintenance Computer

With the increasing complexity of aircraft systems, an important consideration adopted in a new aircraft design is the incorporation of maintainers to assist the of the aircraft. For that purpose the Boeing Corporation introduced the first Central Maintenance Computer on the 747-400 that had a maiden flight in 1988. It was able to collect, process and store maintenance data for approximately 87systems and components on board of the aircraft. Based on the positive experience with CMC on board of B747-400 and rapid development of digital technology the Boeing Corporation significantly improved the troubleshooting processes. [12]

A Central Maintenance Computer (CMC) collects and stores maintenance data for aircraft systems. Primary functions include fault processing, testing, fault history and reporting. The CMC monitors aircraft systems for faults, processes fault information and supplies maintenance messages. Thus, it provides airline mechanics with an electronic maintenance terminal display that shows real time data screens and gives the mechanic the ability to access the troubleshooting procedure via an internal software hot link between the CMC fault code and the fault isolation manual (FIM) for troubleshooting procedure. The mechanic selects via a cursor control device on the Maintenance Terminal (MT), a real time highlighted CMC fault or flight deck effect (FDE) being displayed on the maintenance terminal and obtains an immediate display of the aircraft maintenance manual. Once the FIM troubleshooting procedure is displayed, the mechanic has the choice of working from the display, sending the troubleshooting procedure to an onboard printer for a paper copy, or access additional maintenance information and procedures from the Parts Manufacturer Approval (PMA) data.

7.4. The Chief Mechanic Requirements for CMC Designers

With an understanding of the inherent characteristics of BITE and an awareness of lessons learned from previous designs, Boeing designed the B777 system architecture and CMC to:

- Meet the needs of a specific user, be easy to use, and be an effective troubleshooting tool.
- Accommodate itself to the inherent limitations of BITE-based systems and not "lie".
- Provide the "eyes" into the digital functions of the design necessary to effectively troubleshoot.
- Clearly separate airworthiness-related failure from economic-related failure.
- Permit effective management and planning for maintenance of economic failures.
- Not be a part of the basic certification of the airplane. The CMC is neither required to determine airworthiness nor to maintain the 777.
- Minimise BITE ambiguity.

7.5. The Chief Mechanic Recommendations to CMC Designers

During the development of the B777, under the close scrutiny of the 777 Chief Mechanic, Boeing developed simple design recommendations to meet line mechanics' needs, some of which are listed and described below [6]:

- Design from the mechanic's perspective and environment. This means a consistent use of syntax in messages, simple language, and one "look and feel" across all member systems' BITE.

- Understand that the CMC will be used by personnel from many nationalities. There are cultural and linguistic differences that may affect how a mechanic will use the device.
- Be consistent in the design. It should have a common look and feel.
- Optimise the mechanic's performance. Liberate the mechanic as much as possible from the burden of operating the computer and memorising control symbols and cascading screens.
- Remember that mechanics are not normally dedicated to working on the B777. They work on several models of airplanes. They may not be computer oriented, hence, operation of the CMC should be intuitive.
- Automation of the maintenance function should be mechanic-centred. That is, the mechanic must be in control of the airplane and its systems, as well as the CMC.
- Allow the mechanic to look at or do what he wants when he wants, which is not exactly the way a computer programmer or design engineer thinks it ought to be.
- If ambiguity exists after fault consolidation, show the mechanic what it is. Don't presume to make decisions for him. If fault consolidation results in a large ambiguity group. Don't waste time listing all probable causes, as it just confuses mechanics. The limits of BITE have been reached in this instance, so admit it and offer a better strategy. A more effective approach is to direct the mechanic to the Fault Isolation Manual, which provides more detailed fault analysis.
- Design the Fault Isolation and Maintenance Manuals to be integrated and complementary to the CMC strategies.
- Design the Maintenance Training program to familiarise and develop proficiency in the integrated use of the CMC, manuals and good trouble-shooting practices.
- The CMC is only a diagnostic tool providing evidence upon which the mechanic will base decisions.

It is necessary to stress that the CMC is not the determinant of airworthiness or corrective action to be taken, but an appropriately certified mechanic is. The mechanic, not the CMC, has the license. S/he is aware of evidence not available to the BITE: non-monitored faults which may be relevant, the peculiarities of the airplane and the design, experience with fault history, the restraints of a Minimum Equipment List, time available to meet schedule, parts availability, etc. S/he must sign the logbook. S/he has candour, intuitive ability, experience and most importantly, deductive reasoning ability.

The 777 CMC's biggest advantage is as a diagnostic tool in the maintainers' tool box. It is not a magic device. The CMC makes the job easier and in many cases quicker, but it can not replace a knowledgeable, skilled technician. It provides the necessary "eyes" to the mechanic to see inside the abstraction of digital systems. [13]

7.6. The Interface Between Flight Control System and Line Mechanics

The main interface to the Primary Flight Control System for the line mechanic is the Central Maintenance Computer (CMC) function of AIMS[1]. The CMC uses the Maintenance Access Terminal (MAT) as its primary display and control. The role of the CMC in the maintenance of the Primary Flight Control System is to identify failures present in the system and to assist in their rectification. The two features utilised by the CMC that accomplish these tasks are maintenance messages and ground maintenance tests.

Maintenance messages describe to the mechanic, in simplified English, what failures are present in the system and the components possibly at fault. The ground maintenance tests exercise the system, test for active and latent failures, and confirm any repair action taken. They are also used to unlatch any EICAS and Maintenance Messages that may have become latched due to failures.

All the major components of the system are Line Replaceable Units (LRU). This includes all electronics modules, ARINC 629[2] data bus couplers, hydraulic and electrical actuators, and all position, force, and pressure transducers. The installation of each LRU has been designed such that a mechanic has ample

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[1] The Airplane Information Management System (AIMS) is the "brains" of Boeing 777 aircraft. It uses four ARINC 629 buses to transfer information. There are 2 cabinets on each plane (left and right).

[2] ARINC 629 has the ability to accommodate up to a total of 128 terminals on a data bus and supports a data rate of 2 Mbit/s. The ARINC 629 data bus was developed by the Airlines Electronic Engineering Committee (AEEC) to replace the ARINC 429 bus. The ARINC 629 data bus was based on the Boeing DATAC bus.

space for component removal and replacement, as well as space for the manipulation of any required tools. [11]

8. Education and Training: Integration of Designers and Maintainers

This paper highlighted non-existing professional relationship between system designers and system maintainers. In the author's view, their "segregation" starts at the early age, as:

- Designers are those who are good in physics, mathematics and chemistry go to study engineering and spend their whole working career in the design office.
- Maintainers are those who are not so enthusiastic about those academic subjects go to acquire practical skills and trades, equally necessary for the successful, safe and economical operation of technical systems.

From the age of 18 both groups follow their own career paths, which take them to different: educational and training organisations, sports (to watch and play) pubs, hotels and restaurants, wives, holidays and different housing locations (within same cities). Of course, there is nothing wrong with that, but it is so clear to the author that they never had an opportunity to meet, exchange experiences, concerns and worries, regarding maintenance issues in general, and troubleshooting in particular. Consequently, in this paper the troubleshooting process of electrical systems is addressed from both perspectives as both are driving forces for the in-service reliability, cost and effectiveness.

To the best of the author's knowledge the design and the development of B777 is the first, and only example, where maintainers and designers worked closely together from the outset. As result, their documented design changes that are initiated or requested by maintainers from several airlines were a part of working together concept adopted by Boeing.

To the best of author's knowledge the first attempt to integrate the education of designers and maintainers, at the postgraduate level, was implemented at Exeter University in 1991. [16,17]

9. Conclusions

The main objective of this paper was to address the challenges and possible solutions related to the troubleshooting broken computer chips and associated digital systems. Computer chips are essential providers of the functionality of today's advanced digital systems. However, digital systems are different from traditional electromechanical systems, as they are an integrated, tangle of electrical, mechanical and electronic parts. Nevertheless, they do fail and need to be maintained. Unfortunately, it is impossible to troubleshoot a computer chip by looking for physical evidence of failure. A broken chip neither looks any different from a healthy one, nor, leaks, vibrates or makes noise. Faulty software within them doesn't leave puddles or stains as evidence of its failure. Even more it is physically impossible to see 1s and 0s falling off the end of a connector pin.

Troubleshooting failed computer chips is a daily maintenance challenge. However, any improvement in this process is a joint responsibility of designers and maintainers. Namely, system designers who conceive the complexity of digital systems in design office, on one hand, and system maintainers who perform corrective maintenance actions on the other. Thus, both are involved with detection and understanding failure causes, locations and consequential maintenance actions, but regretfully they never meet, even less, collaborate in decision making process. For that very reason the Boeing Corporation has created the position of Chief Mechanic during the development of the 777 aircraft. His significant contribution to the design process, facilitated by a working together mantra, has been presented in the paper, as this is one of the very rear exceptions. The closing conclusion of this paper is that the closer collaboration between designers and maintainers has to be facilitated through their educational and training processes, on one hand, and through their professional organisations and societies, on the other.

Finally, as sign of respect and gratitude to the person who significantly contributed to the integration and mutual understanding between designers and maintainers, in author's experience, this paper should be concluded with the words of the world first chief mechanic in the design office. Thus, Jack Hessburg firmly believed that, "the best troubleshooting tool in the world is still between the ears of a thinking human mechanic." [2].

10. Acknowledgement

The paper is commemorating the 10th anniversary of the death of Jack Hessburg (1934-2013), the first Chief Mechanic of Boeing New Airplanes and the Grand Fellow of MIRCE Akademy. His genius helped me to understand that the word maintenance has two meanings, the common one that is "fixing broken stuff" and his, which is the "management of failures". [1] Jack continuously inspired me to research deeper and deeper in the fascinating world of aircraft troubleshooting reality, pointing out that "Broken chips don't leak, vibrate or make noise".

11. References

[1] Knezevic, J., MIRCE Science: Maintenance is Management of Failures and provision of Work, OMAINTEC JOURNAL ISSUE 3 Arab Council of Operation and Maintenance, pp. 22-32, 2 January 2023

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

[3] Knezevic, J., Systems Maintainability, Analysis, Engineering and Management, Chapman & Hall, pp 400, 1997, UK. ISBN 0-412-80270-8

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

[5] Knezevic, J., Reliability, Maintainability and Supportability Engineering - A probabilistic Approach, pp.292, plus software PROBCHAR, McGraw Hill, London, 1993.

[6] Hessburg, J., 777 Onboard Maintenance System, pp 1-9, Airliner, Jan-Mar, 1995

[7] Knezevic, J., “Jack Hessburg: The World First Chief Mechanic” , Proceedings of Maintenance 2016, pp.34-41, 22nd HDO International Conference, 16-18 May, 2016, Sibenik, Croatia,

[8] Berner, P., Big B’s Hessburg, pp 28-33, Aviation Equipment Maintenance, May, 1994.

[9] Sabbagh, C., 21st Century Jet, pp 406, Pan Books, London, UK, 1996

[10] Hopkins, H., Gentle Giant, pp. 26-30, Flight International, 26 April-2 May, 1995

[11] Hessburg, J., The Evolution of Regulations in a Digital World, pp 42-50, Avionics Magazine, September, 1998

[12] Nicholson, R.K. Whitfield, K.W., Onboard Maintenance System Testing: The Boeing 747-400 Central Maintenance Computer, AIAA-90-1303-CP, American Institute of Aeronautics and Astronautics, 1992. https://doi.org/10.2514/6.1990-1303

[13] Harvey, D., The Boeing 777, a brief outline of M.I.R.C.E. Industrial Lecture by Jack Hessburg, pp 226-227, Ten years of Achievement 1988-1998, M.I.R.C.E., University of Exeter, UK, 1998

[14] Johnson, M., Boeing 777 Airplane Information Management System - Philosophy and Display, Royal Aeronautical Conference Proceedings, Advanced Avionics on the Airbus A330/A340 and the Boeing 777 Aircraft., 1993

[15] Hessburg, J., the Evolution of Regulations in a Digital World, pp 42-50, Avionics Magazine, September, 1998.

[16] Knezevic, J. and Nicholas, C., “New horizons in UK Maintenance Education”, Proceedings of the 8th Maintenance Congress, Madrid, Spain, 1992.

[17] Knezevic, J., Industry Driven Postgraduate Maintenance Education: MIRCE Approach, Journal of Quality in Maintenance Engineering, Vol. 3 No. 4, 1997, pp. 302-308. © MCB University Press, 1355-2511