Maintenance Requirements in Aerospace Systems

Khan, S.

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 38 (2015) 100 – 105

www.elsevier.com/locate/procedia

The Fourth International Conference on Through-life Engineering Services

Maintenance requirements in aerospace systems

Samir Khan*

Coventry University, Aviation, Aerospace, Electrical and Electronic Engineering, Coventry, CV1 5FB

* Corresponding author. Tel.: 024 7765 5338;. *E-mail address:* Samir.khan@coventry.ac.uk

Abstract

The paper discusses the importance of granularity in maintenance requirements. This becomes significantly important when investigating false alarms that cannot be verified, nor duplicated under typical inspections. Continuing advances in electromechanical systems, such as an aircraft's fuel system, can frequently face a high number of No Fault Found (NFF) events due to design limitations associated with fault diagnosability. This work discusses such maintenance requirements whilst covering the human aspects of the design – involving stakeholders identification and presenting meaningful data identified from the requirements. Ideas to optimise system diagnostics (by using extra sensors) to recognise and reduce failure ambiguity groups are also discussed. This can help indicate how the most appropriate data can be selected to represent the aforementioned maintenance requirements, facilitate in trade-off analysis and making design decisions.

Peer-review under responsibility of the Programme Chair of the Fourth International Conference on Through-life Engineering Services.

Keywords: Health management; testability; false alarms; ambiguity groups; system diagnostics

1. Introduction

For a physical system to be effective it has to be coherent. This indicates looking at the system as a "whole", including its operating environment, behaviour and dependencies. The diffusion of availability based contracting within many industry sections has seen significant changes in how policy makers look at a "whole" system [1]. For example, with military aircrafts, regulatory authorities are modifying the way in which the defence industry operates due to the raising total cost of ownership. Consequently, the Ministry of Defence (MoD) had published a strategy (called the Defence Industrial Strategy) – which highlighted defence requirements on third party partnerships and availability based contracting/package. [2]. Such contractual agreements help transfer risk in the total cost of ownership found within the supply chain – from the operator of the system, on to the Original Equipment Manufacturer (OEM). Such practices continue to drive requirements to support a cultural shift towards servitization, or in other words, availability based contracts. With such changing needs, a system that was originally designed to be coherent, may cease to be. Therefore, any such change must harmonize both the user of the system and OEM organization(s). This will further extend to include adjustments within the management of the transfer-of-responsibility and supply chain. Even through notable advances have taken place, further adjustments continue, and hence delivering a service (maintaining system effectiveness) has become more important than the quality of service (system optimisation/efficiency).

The aerospace industry needs to drive such changes in order to maintain availability expectations and to maximize a return on such agreements [3]. Some organisations have capitalized on this emerging cultural shift by investing to develop their global maintenance setup for their gas turbine solutions [4]. Their "whole" understanding of their systems has allowed them to make adjustments from system user training up to the sensors design for their products to capture system condition data. The aspirations are to enhance system reliability of the subsystem while facilitate the move towards condition based maintenance instead of opting for a reactive support regime. As a result, investment and research in health and usage monitoring systems has risen – to capture health information from various operating platforms. Traditionally, health management was not considered during the design

Peer-review under responsibility of the Programme Chair of the Fourth International Conference on Through-life Engineering Services.
doi:10.1016/j.procir.2015.07.078

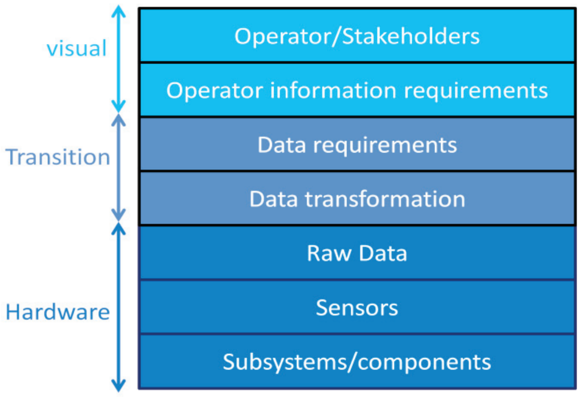

Figure 1: The three layers for a maintenance requirement

stages of electrical and mechanical systems. Systems were first developed and then the health monitoring strategies were considered by adding new sensors and/or tests as required. As both phases were done separately, addition of new sensors proved to be difficult due to design limitations. As the industry became aware of this gap, techniques that integrate the two design phases started to become more prominent. Here, the key factor to reduce maintenance overheads is the capture and analytics of the collected information for diagnostics (detection and isolation) and even prognostics (predicting failures). As a consequence to the apparent risk of bad sensor design and location, processing the wrong information (that is difficult to evaluate due to lack of resource), the challenge is in identifying and implementing a health management system for safety critical applications.

The aim of this paper is to discuss the importance of organising relevant information according to maintenance requirements. This can help in improving system designs by keeping in mind the maintenance and availability aspirations of an organisation. The rest of the paper is structured as follows: the next section elaborates on the role of maintenance and why it is important to add granularity in its requirements. Section 3 makes use of a fuel system to add clarity to preceding discussion. Finally, some conclusions are summarised in Section 4.

2. Maintenance Requirements

Considering the increase in product-service type industry, the market for software tools (and related standards) to help with the design and specification of Health Management Systems (HMS) is growing. Khella et al. (2009) discussed a core gap whereby the principal health monitoring technology does not always meet the requirements of the maintenance specifications that would utilise the health information [5]. In order to address the issue, this paper makes use of an example fuel system to discuss the concept. While this study only considered a fuel system, there can be a range of interacting stakeholders (such as the system user, the operator, their maintenance technicians and engineers) that can provide a number of complex system requirements. For simplicity, the author only considers the maintenance engineer requirement i.e., to reduce the needless changes of Line Replaceable Units (LRU)*, referred to as the NFF phenomena [6,7,9]. This paper describes NFF as a measurable consequence of the diagnostic process, where the root cause of the reported fault was not verified. It should be noted that although this is not a complete requirement (as it does not mention the availability required, nor does it point towards any tolerance when addressing the NFF rate). Although, it does describe adequate detail to evaluate the concept. This requirement was selected due to its contradictory nature and "to show the value of the Systems Engineering approach embedded within the concept for resolving them" [6]. The contradiction (where the maintenance personnel would remove a suspected unit) manifests without additional fault investigations, in an attempt to increase availability/reliability and reduce maintenance downtime/costs. Such practice can cause many units to be sent back to the OEM as NFF – imposing a burden on reputation, maintenance costs, lost man-hours/resources, but ultimately reducing the LRU inventory available at the maintenance shop. On the other hand, to properly investigate and isolate the faulty unit (the root cause), the maintenance department may need more resources, time, cost and hence will reduce the system availability. In context to the scope of this paper, the requirement for the fuel system is to: isolate engine fuel system failures to one unit. This indicates an ambiguity group of one.

Figure 1 shows an adaptation from [5] classifying the applicable data in three groups. The first group (visual) includes the human aspects; which involve the recognition of the main stakeholders within the system and their data needs to help them operate. The second group (transitional) covers the data requirements. This layer is also concerned with the data transformation that converts raw sensor data into meaningful information according to stakeholder requirements. The third group (hardware) represents the bottom layers of the figure, which are the physical (or hardware) elements. These encompass the various data formats available for processing and the raw sensor outputs. The transitional layer represents an essential part of the concept, as it describes the analytics required to gather health usage and monitoring data to be used for "diagnostics (detecting and isolating faults) or prognostics (predicting failures)" [6]. This layer is the core and should be designed by an engineer who understands the impact of the maintenance requirement.

* An LRU is a modular component designed to be replaced quickly from on-site inventory. Thus, restoring system availability, while the unserviceable LRU is undergoing maintenance.

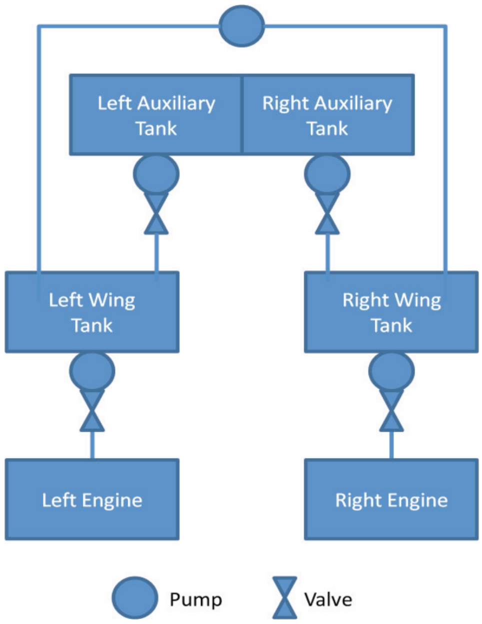

Figure 2: Top level design of a fuel system

2.1. False Alarms

At this point in the paper, it is worth discussing some literature associated with false alarms.

False alarms are major issues within maintenance for the stakeholders. Within the aerospace sector, research on such events has gained renewed interest in the past decade [6]. One significant example is the avionics components where this phenomenon reaches 85% of their failures and 90% of the total cost of maintenance [7]. Its effects are non-negligible because it impacts the system safety and dependability, so it is necessary to limit the consequences to satisfy stakeholders. This also demonstrates how an inconsequential event can build up into a strategic concern for organisations within their competitive environment. Currently, there is a drive towards a more electric aircraft, which indicates a rise in the number of false alarm reports [8]. When faults occur in a typical maintenance activity, maintenance personnel are called to find them. Procedurally, they rely on fault isolation manuals or manufacturer documents. If a component is not removed, then it is tagged serviceable. On the other hand, if the maintainer removes a component, it is sent to depth maintenance for further testing. At depth, if no fault is discovered, concerns are raised on why a serviceable component was removed from service. It is tagged as an NFF. There are three different scenarios which can explain unsuccessful fault diagnostics during the repair process:

- The fault cannot be reproduced with the real conditions. The fault is hence considered as "one off" and the system is declared serviceable. However, the fault reappears later because the origin has not been identified.
- The maintainer decides to replace a unit because he considers that it is the main fault's root. After few tests on the new unit, the system is declared serviceable. Nevertheless, the fault reappears so the root was not clearly identified.
- The same fault reoccurs, but the only difference is that the fault's root was not in the unit replaced.

The continuing evolution of electronic equipment and its increasingly dependency on built in tests (BITs) to provide health monitoring and error checking to find components (that need to be replaced), has become costly [6], "these BIT reports often result in unit replacements, recertification, or inevitable loss of availability of the equipment". The design of system tests is a non-trivial task. This means that they rely on component interaction knowledge. As a consequence, it can be difficult to identify and assign a predetermined set of tests/checks that verify system functionality – leading to log false alarms. For example, when an operator reports a fault, these may not always correlate to the test reports. Despite modern component testability procedures, the problem of removed components that were reported by the BITs to be at fault, but bench testing reveals nothing. Furthermore, other factors such as limited test coverage and inappropriate tolerances, can also contribute to NFF events [7].

3. Concept Evaluation

Evaluation of the aforementioned concept was undertaken through a case study completed in 2014 – which designed a model of an Unmanned Aerial Vehicle (UAV) Fuel System [9].

3.1. The Fuel System

The engine fuel system is a complex electromechanical system. A typical top level diagram of the fuel rig is shown in Figure 2. In addition to its main functions of storing fuel, feeding the engines with the required flow and pressure; it is used for other external applications like management of the centre of gravity of the plane and the wing loading relief. That is why the fuel flow into various different tanks (especially in the wing tanks) has to be managed efficiently and effectively. Any failure of the system has to be avoided to fulfil the safety requirements which result from a continuous feeding of the engines throughout the flight. It is usually composed of four mains types of components: the fuel tanks, pumps, sensors and valves. In the presented architecture, left/right pumps will supply fuel to their respective engines, but there is also the option to cross feed fuel in between tanks. The purpose of the auxiliary tanks is to add redundancy in the system.

Recalling the requirement presented in Section 2: isolate engine fuel system failure to one LRU. The one in this data requirement indicates a specific number of LRUs. Whether the information about the fuel system (presented above) is sufficient for determining the general health of critical functions, the requirement can be further broken down to help clarify which fault symptoms are the engineering departments and OEM interested in for their investigations. This task can be completed by carrying out a well know concept found within fault analysis strategies i.e. a Failure Modes and Effects Analysis (FMEA). Furthermore, a FMEA can be simplified by concentrating on particular areas of the system, and isolate them down to one component. For example, consider the following five failure symptoms in the system:

- No flow
- Restricted flow
- Loss of fuel
- Low pressure
- High pressure

The end result from such an analysis can depict the FMEA as in the Table below:

Table 1. FMEA example.

Component	Failure Effect	Symptom
Pump	No power	No flow
		Restricted flow
		Low pressure
Pressure	No signal	No flow
		Restricted flow
Valve	Low pressure	Low pressure
Pipe	Blocked	No flow
		Restricted flow
		High pressure
Seal	Split	No flow
		Restricted flow
		Loss of fuel
		Low pressure

A no flow and restricted fuel flow can be indicated by correlating the captured flow (by using the installed sensors and the expected fuel flow). Likewise, any loss of fuel within the system can be picked up by correlating any variations in the fuel levels against the fuel flowing. Any changes here can be used to identify a loss of fuel from the system. Such analysis makes use of existing sensors. However, the exercise reveals that the present setup can help a maintenance engineer by indicating the loss of fuel and high pressure down to one component in the event of a split seal and broken pipe, respectively, but will not be able to distinguish amongst the outstanding three components – in case any one of them fails. In maintenance terms, this is also known as ambiguity, which is a collection of failure mechanisms for which diagnostics can detect a fault and even isolate it to a group of components, yet cannot further isolate the fault to any subset of the group. Therefore, some extra work will be needed at depth maintenance to investigate and isolate the reported unit, otherwise up to three potentially serviceable units can be substituted in an effort to reduce costs, down time and maintain availability. The financial implication comes down to the fact that two of the three components (that may have

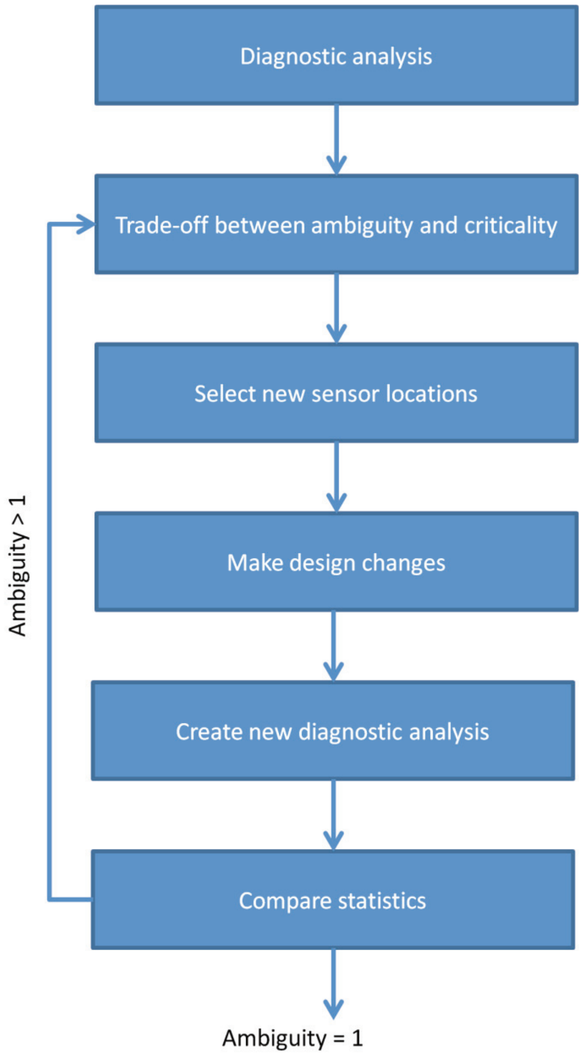

Figure 3: Strategy to decide on new sensor locations

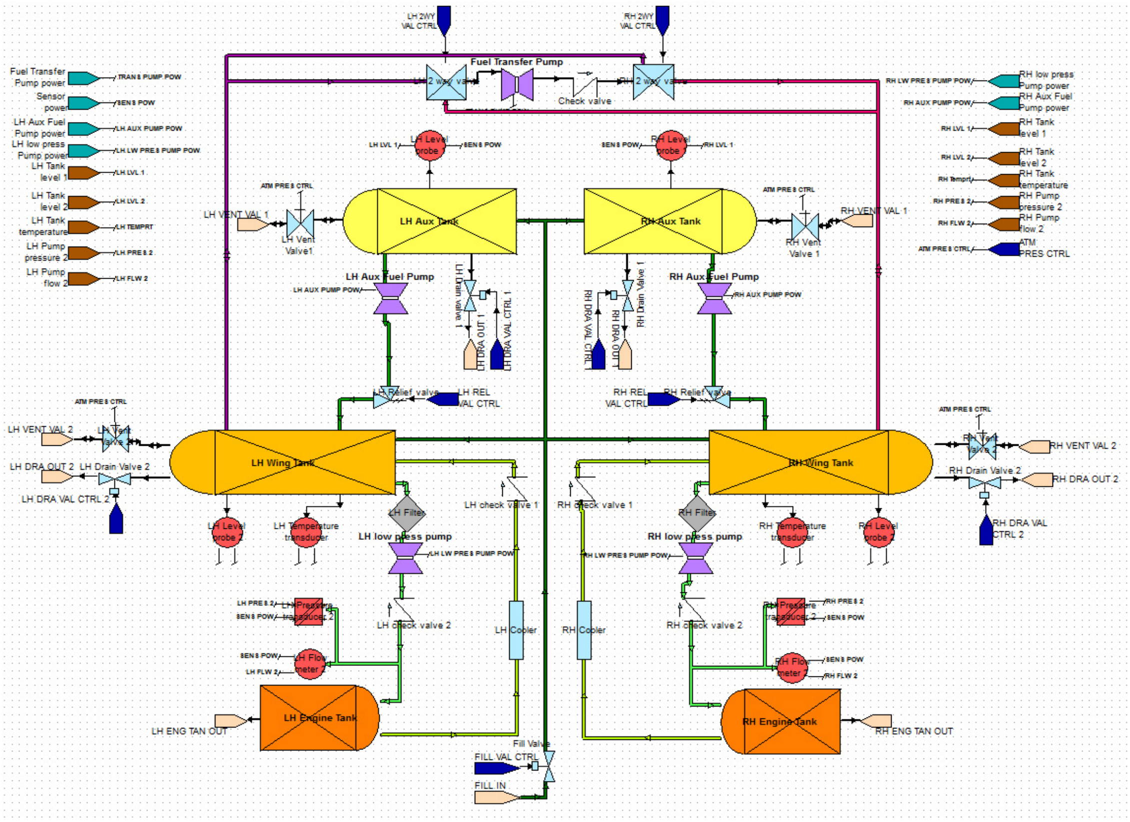

Figure 4: The fuel system model designed in eXpress™

been removed) will have no faults – the NFF phenomena. In order to increase isolation, new sensors are required. This is a simplified presentation of the problem in the real world, where the locations of the sensors seem to make all the difference in the isolation of faults. The number of NFF events can be reduced by focusing on reducing large components groups (higher ambiguities) and components that have a lower reliability. This will separate the lower reliability items out of ambiguity groups. This diagnostic study will entail a trade-off between the ambiguity and the criticality of the large component groups. Instead of reducing the fault groups with the highest ambiguity, the criticality of the groups must also influence decision-making. After identifying the essential components, new sensors are selected and added accordingly.

What are ambiguity groups?
Ambiguity groups are a collection of failure mechanisms for which diagnostics can detect a fault and can isolate the fault to that collection. However, there is no mechanism to further isolate the fault to any subset of the collection. E.g. for a system to have an ambiguity group of 10 indicated that the fault can be isolated to 10 components after which the maintainer will need to use his experience to make a judgement and conclude the most likely faulty component. In the ideal situation, ambiguity groups should be one as it indicates that a fault can be isolated to just one component – in effect, reducing NFF.

Figure 3 points towards a strategy being developed to reduce the ambiguity group size to one, by making use of new sensor locations in an existing design. The aim is for the exercise is to provide revised diagnostic statistics, which can be compared with the reference (or targeted) results.

However, the strategy has been built on the requirement of isolating system failures to one component. Component groups with highest ambiguity do not always have the highest criticality. There is still work to be completed on the strategy of the fault group selection according to the ambiguity or the criticality. For example, selecting between a fault group with an ambiguity of fifteen and a criticality smaller than the one of a fault group with an ambiguity of fourteen and thirteen is quite complex. Studying this trade-off could improve the sensors placement and decrease the average ambiguity of the design.

3.2 Use of Design Software

For Fault Identification and Isolation (FDI) during operations and maintenance, there are several software tools available for system design. Each tool is different in terms of techniques and methods for system representation and diagnostic development. In order to achieve diagnostic success, the design analysis tool should enable studying the diagnostic ambiguity and help optimise test regimes for accuracy/sensitivity. eXpress[TM] is: "a fully-featured, off-the-shelf software application providing an environment for the design, capture, integration, evaluation and optimization of System Diagnostics, Prognostics Health Management, and holistic Systems Testability engineering" [9]. Such testability software can also offer the possibility to provide a diagnostic analysis and a Failure Modes Effects and Criticality Analysis (FMECA). However, design changes can often be carried out with little information about the type of sensors and the additional effort required for sensor placement. The proposed improvements in design are by adding new sensors. Therefore, before reaching to any conclusions, it is important to take into account such costs. The obsolescence of the component and their cost inflation can be considered, and can heavily influence design decisions. An initial design of the fuel rig model is illustrated in Figure 4 (please note that component icons and their functionality is not explained in this paper due to length limitations. Please see Alexandre (2014) for more information [9]).

A note on limitations – Software simulations can help describes many metrics. Some can be based upon typical design assessment requirements while others can be more advanced design requirements for assessing future health management requirements. The graphs produced by eXpress[TM] for example, can describe the increase in risk of any failure (or the combination of failures), since the last time it was diagnosed - considering the impact of maintenance. Surprisingly, this consideration has not been found in any academic literature by the author on the embodiment of the topic. Instead, one must effectively bury the likelihood of uncertainty in the use of distributions. Yet, if that is a preference, one can even use any distribution curve of choice as an attribute assigned to any failure effect "test" used in their design. If design engineers can glance at the characteristics (or trends) presented in quick (gestalt) graphs to "visualise" the impact of design-decision modifications, then it is possible to understand their impact - originating from the same identical knowledgebase where all of the component interrelationships are captured, and in a form enabling optimisation "whole design model swapping".

4. Ongoing work and Conclusions

The concept discussed in this paper is being researched with a larger NFF related study that incorporates various stakeholders requirements. Even though the NFF research described in this paper has been limited in scope and was mentioned only to aid clarity. To paper highlights that it is useful to classify information for stakeholders and their requirements in different categories/layers. Considering the visual, transitional and hardware aspects within one design process, the idea helps with understanding the problem from a design engineer's perspective to enable more knowledgeable and integrated decisions. Also, a stakeholder's data requirement could be correlated down to feedback sensors.

The ongoing work extends to investigate trade-offs in system design attributes – factors such as cost, size and weight must be considered with designing the system for maintenance. Other characteristics, such as system reliability and data analytics, are more complex and will require software tools to evaluate the requirements. Studying this trade-off could improve the sensors placement and decrease the average ambiguity of the design.

Acknowledgments

This research was carried out at the Through-life Engineering Services Centre. The author would like to thank Professor Rajkumar Roy, Professor Ian Jennions, Mr Chris Hockley and Dr Piotr Sydor for their support and encouragement with the No Fault Found project. Also, critical comments and constructive suggestions, from the editor and the reviewers, are very much appreciated.

References

[1] R. Roy, A. Shaw, J. A. Erkoyuncu, L. Redding (2013). Through-life engineering service, Measurement and Control, 46(6), 172-175.
[2] UK MoD (2005). Defence Industrial Strategy, Defence White Paper, pp 27-28
[3] P. A. Sandborn, C. Wilkinson (2007). A maintenance planning and business case development model for the application of prognostics and health management (PHM) to electronic systems. Microelectronics Reliability, 47(12), 1889-1901.
[4] S. Blakey, L. Rye, C. W. Wilson (2011). Aviation gas turbine alternative fuels: A review, Proceedings of the combustion institute, 33(2), 2863-2885.
[5] M. Khella, R. Dixon and J. Pearson, "Designing Health management Systems: A Holistic Approach" International Conference on Systems Engineering 2009, ICSE, 2009
[6] S. Khan, P. Phillips, I. Jennions, C. Hockley (2014). No Fault Found events in maintenance engineering Part 1: Current trends, implications and organisational pratices. Reliability engineering and system safety, 123, 183-195.
[7] P. Soderholm (2006). A system view of the No Fault Found (NFF) phenomenon. Reliability Engineering and System Safety, 92(1), 1-14.
[8] J. A. Rosero, J. A. Ortega, E. Aldabas, L. A. Romeral (2007). Moving towards a more electric aircraft. Aerospace and Electronic Systems Magazine, IEEE, 22(3), 3-9.
[9] V. Alexandre (2014). Optimised Sensor Placement Strategies to Reduce False Alarms. Cranfield MSc Thesis.