Research study from industry-university collaboration on “No Fault Found” events.

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Research Study from Industry-University Collaboration on 'No Fault Found' Events

Purpose - The purpose of this article is to present the successes and barriers from an industry-university partnership on studying the impact of No Fault Found (NFF) events. As a consequence, various opportunities are explored to engage with industry to investigate the problem. A comprehensive training is also outlined to ensure that experience and troubleshooting techniques can be disseminated as guidelines across businesses.

Design/Methodology/Approach - The study was performed by Cranfield University in collaboration with industrial partners on identifying the impact of the No Fault Found (NFF) problem within engineering services. This includes discussions with maintenance engineers, outcomes from a symposium organized specifically on NFF and the authors' own experiences with the issue.

Findings - The paper discusses the continuing serious problem with NFF events found at various maintenance echelons, and suggests a need for formal postgraduate training to be taught within the field of maintenance management. This includes not just technical issues, but also encompassing organizational structures, cultures and behaviours. Since focusing only on one issue at a time does not suffice in dealing with the NFF problem, an integrated approach is required for modern maintenance services and operations.

Research - Higher education learning outcomes have been outlined for competent engineering personnel, to broaden their understanding on the subject area. This is based on discussions with industrial collaborators and recently published material.

Practical implications - This paper emphasizes the importance of the breath of interaction channels and demonstrates the opportunities for effective knowledge exchange by using the activities at Cranfield University to demonstrate their usefulness. The arguments clearly lead to the necessity of academia in this type of industrial problem. However, the presence of a university in this case is not as the sole problem solver, but the rather to act as a collaborative medium between various other outlets. Further ideas proposed, such as constructing guidelines for industries in handling NFF problems and benchmarking tools, can serve as real products that can be benefit industries. The study also aims to promote best practice in the field of maintenance management and outlines the foundations for NFF training material.

Originality/value - The originality of the paper is that it presents a structured methodology for engaging with industry. It also outlines a curriculum for NFF training. It essentially serves as a road-map for research and offers a detailed account of areas that need to be taken into account in order to reduce the likely event of NFF.

Keywords: Maintenance; No Fault Found; university-industry collaboration; Reliability; Higher Education

1. Introduction

The global interest on the topic of hidden failures is evident from the increasing number of recent publications within the area (Soderholm, 2007); James et al., 2003; Ungar and Kirkland, 2008; Hockley and Phillips (2012). Since the key enabler for their resolution is the availability of competent technicians, engineers and senior management, educational institutions have a responsibility to develop relevant high-quality modules and training material to support further progress in the field. Industry-university collaborations, particularly those involved within the manufacturing sector, are becoming increasingly important to carry out research activities and technology transfer (Hanel and St-Pierre, 2006).

Two recently published articles investigating No Fault Found (NFF) events had discussed effective approaches on troubleshooting strategies (Khan et al., 2014a; Khan et al., 2014b). They identified that currently there are no widely accepted methods for guiding or training staff on NFF occurrences, indicating the growing gap between the 'anticipated failures' captured during system design, and the 'actual failures' that appear in service. It was also reported that real-world faults are not always anticipated by design engineers, and therefore the traditional diagnostic techniques may not always be able to resolve them. In such instances, human ingenuity may solve the problem, but where does that knowledge reside after its creation? Evidently, some the knowledge makes its way back into troubleshooting manual updates, and some might be fed back to engineering to modified designs for much more reliable parts. However, most of the knowledge will only reside with experienced experts, or in personalized organizational databases, which would be consulted only after a problem has resisted several attempts at resolution. Therefore, this knowledge must be preserved and disseminated within maintenance management training courses and interactions with experts, in order to ensure that levels of expertise are retained.

Given the considerable attention, the lack of research on these factors is a concern to NFF regulation and management. In order to advance knowledge in this area, this paper examines:

1. The collaboration channels that can be explored through a university-industry partnership to investigate NFF
2. The development of an educational training curriculum to maintain competence in the subject.

Currently, there is an increase in the interactions and collaborative activities between organisations and universities. These are becoming subject to measurement and management, leading to more formal contractual exchanges between the two. There are many reasons that lead organisations to collaborate (or share knowledge) with universities (Meyer-Krahmer and Schmoch, 1998; Tether, 2002; Laursen and Salter, 2004). However, there is limited knowledge about how the perceived barriers between such collaborations could be mitigated. Bruneel et al (2010) focused on three potential mechanisms including experience, breath of interaction channels and inter-organisational trust. This paper emphasizes the importance of the breath of interaction channels and demonstrates the opportunities for effective knowledge exchange by using the activities at Cranfield University to demonstrate their usefulness.

The rest of the paper is structured as follows: Section 2 discusses why NFF events pose a serious threat to businesses. Section 3 highlights the importance of university-industry collaborations and how Cranfield University has been able to engage with several organisations to investigate the NFF issue. This is followed by Section 4 which details the data collection methodology, followed by discussions on current practice and future collaboration. Finally, some conclusions are reached from the preceding analysis.

2. NFF events in businesses

The phenomenon of NFF (also known as hidden failures) is known by a variety of names and is a problem which has plagued operators and maintainers in all technology dependent sectors from automotive to telecommunications. These events can cause unprecedented changes in the service performance, impact dependability and escalate safety concerns. Table 1 summarises some of the major causes found in literature for NFF events within businesses today.

NFF Cause	Description
Time pressures on maintenance operations	There is an overriding need to get equipment back into service quickly. Availability of the equipment for service provides an overwhelming pressure on diagnosis and maintenance actions. This means that often the quickest maintenance action is carried out, e.g. replacing several Line Replaceable Units (LRU)[1], an activity that causes NFF further down the supply chain. All too often, the pressure to return the system to service means that replacing a number of LRUs will be quicker than doing any detailed diagnostics.
Errors in fault finding isolation manuals	A fault finding guide (also known as special application document) plays significant role in detecting faults. They provide a number of causes for a fault, and outlines a list the actions that must be taken for repair. However, these documents are subjected to production resources, outsourcing and irregular updates. Other errors are caused by manuals being produced by third parties.
Organizational cultures	There may not be any cross-functionality with organisations to encourage employees to identify the root causes of reported fault events. In other words, inappropriate practices/behaviors can allow the issue to grow and take root. According to Murphy (1996), failures of complex engineered systems are often the result of management or organizational factors that influence the decisions of individuals. Thus, there could be organizational pressures affecting the work of technicians on complex systems leading to failures. Organizations often influence the state of their employees (e.g. via selection, screening, training and workload), or they may affect their situation (e.g. information, procedure, organizational structure and culture); either of which can affect an individual's action and thus have an overall effect on system risk.
Unavailability of suitable testing environment	Conducting bench tests for different systems is an important activity to investigate reported faults (or flagged events). Environmental conditions play a crucial role in such exercises – some components

[1] A Line Replaceable Unit (LRU) is a modular component designed to be replaced quickly.

	may only demonstrate the faulty behaviour under specific conditions.
Reluctance to change	Quite often, solutions that are likely to be disruptive to normal working practices are seen as unnecessary and a challenge to technical skills. An organization's culture may resist changing their working practice, because in their view, the organization is not the problem.
Not sharing information	There needs to be a culture and commitment to share knowledge between designers, manufacturers, service providers and operators. This may be easier said than done but it needs a system in place to share appropriate information between all the stakeholders to enable an effective, speedy transfer of shared knowledge. There may be a number of possible weaknesses in using manuals as a means for sharing information, including poor sequence of activities, a lack of accuracy or completeness and a lack of user-friendliness. Another issue that renders the technicians troubleshooting task even more difficult is that there can be ineffective and often ambiguous test requirements resulting from a lack of distinction between physical faults and the functional anomalies by which they are detected and isolated.
Inadequate data logging	Most often adequate data is not recorded, which is required to investigate the root cause of the NFF event. In particular, it appears that two essential factors are not being effectively recorded, i.e. environmental conditions and component history.
Ineffective Communication	This often stems from a lack of maintenance or manufacturer advice. It may be that a particular fault/event is being seen across the system (or a procedure is being improved by the manufacturer) and this information, or rather solution, is not being communicated.
Lack of experience and training	This cause of NFF relates to the human issues in the organisation. It is believed that the problem lies more at the human level as there are so many human failings related to the variety of ways that faults are reported and the way people carry out fault diagnostics (Burchell, 2007). Technicians mostly rely on their experience and instincts to carry out fault diagnostics. However, inexperienced technicians gain their fault diagnostics knowledge during early training. Lack of information and exposure for the inexperienced technicians may lead towards a wrong path in fault diagnostics and also may even cause the initiation of unwanted faults.

Table 1: The major causes of NFF events

It should be noted that effective maintenance management is paramount in the resolution and reduction of these events, where the role of senior management must be recognised in the need to:

1. Improve planning/supporting corrective actions
2. Budgeting for NFF reduction

However, organizations can often be exceedingly bureaucratic and cumbersome in their response to change and may even not recognise that they have a problem. Given the variety of NFF sources, each organisation (including the manufacturer's maintenance suppliers and operators) will approach the problem differently. This arises due to the nature of their self-interests and differing viewpoints, for example, do they take a company or a strategic view. Each of these key players therefore may not always be transparent in their approaches, and hence hinder the transference of knowledge and expertise in dealing with NFF[2]. As a result, the situation arises where internal pressure is placed upon the maintenance personnel to reduce their maintenance turnaround times. This leads to a culture where units are replaced rather than the root cause of a failure being identified and fixed.

Information regarding financial costs of NFF within many organisations is difficult to obtain, and any existing available references (within the public domain) are rather outdated. There are two main reasons for this:

1. Sensitivities within the information: critical information can provide a competitive advantage to organisations and hence they will be reluctant to release such commercial data. There is also a high culture of secrecy surrounding maintenance activities within organisations.
2. Organisations do not recognise NFF as a problem and hence do not know how much it costs: The number of elements involved in NFF events result in difficulties in stating an accurate financial figure within adequate limits.

This causes a direct impact on businesses whether that is for example passenger/ freight transportation or military operations. Without a high level of confidence that a reported event is correctly resolved in the first attempt (with a low-probability of reoccurrence) there will be negative influence on the business output[3].

3 University-industry collaboration

Collaboration activities between industries and universities incorporate considerable challenges. Whilst universities have always been driven to *create* knowledge and educate, they are now being focused to *acquire* valuable knowledge that is to be utilised to gain competitive advantage (Dasgupta and David, 1994). These do add positively in addressing market failures, and help to understand the returns of research investments (Martin and Scott, 2000; Siegel and Zervos, 2002). Such practices have been supported by an increase in joint research ventures (Hall et., 2001, Calvert and Patel, 2003), where many legislative bodies have introduced a number of policies that encourage the involvement of universities in technology transfer[4].

Evidently, the process of knowledge transfer between universities and industries can take place through various channels including personnel mobility, informal contacts, consulting relationships and joint research projects (Arundel and Geuna, 2004). This is partially due to the fact that only a handful of university-industry interactions are wholly focused by the prospect of realising business solutions. Such research is generally aimed to gather specialist knowledge and to resolve particular issues. However, this concept of knowledge creation within the private sector is dominated by efforts to increase the business value and maintain competitive advantages (Teece, 1986)[5]. The

[2] The organizational culture may dictate that, i.e. taking a machine offline, or grounding an aircraft for a period of time, should be done at an appropriate time and for a period no longer than absolute necessary.
[3] There can be other major impacts upon business costs which are not so easily quantifiable. These include the impacts on the supply chain, maintenance performance, capacity, as well as indirect impacts such as the effects on customer perception.
[4] In the UK, for example, the government has launched a range of initiatives to encourage universities to capture and exploit their research (Chapple et al., 2005)
[5] Although this private knowledge largely remains within the firm, it may be disclosed in a limited way through patents.

following section analyses related activities and highlights the methodology undertaken by Cranfield University in engaging with organisations to carry out knowledge exchange.

3.1 Activities at Cranfield University in Providing Focus

The study on NFF events was undertaken by the No Fault Found Research Group at Cranfield University, comprising the faculty within the Through-life Engineering Services Centre, the Integrated Vehicle Health Management Centre and Cranfield Defence and Security. Established in 2011, the main research goals have been focused on identifying the impact of the No Fault Found (NFF) problem in industrial engineering services, and promoting best practice. Some of the industrial collaborators include BAE Systems, Bombardier Transport, Ministry of Defence, British Standards Institute, Rolls-Royce and Siemens Limited. Since its inception, the group has been actively involved with maintenance engineering from various professional backgrounds including defence, civil aviation and land transport.

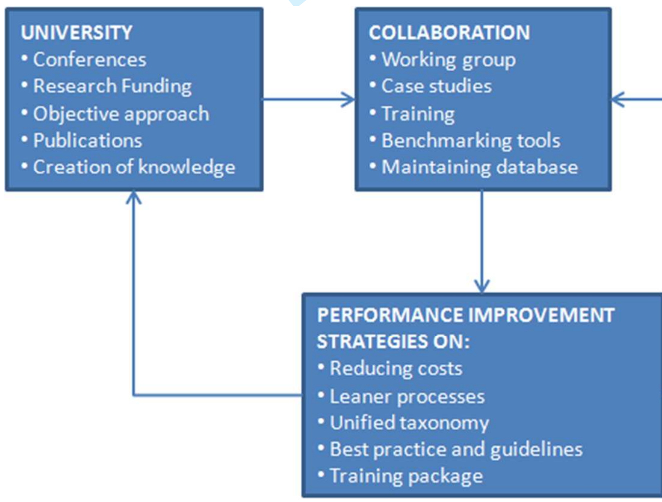

Figure 1: Industry-University collaboration with feedback

The aim was to work towards developing a community of practitioners across various domains to share experiences, best practices and ideas for future policies and strategies to address the problem. Even though the research covered a range of topics within NFF, only a hand-full have been published in open literature. This is largely due to confidential and commercially sensitive reasons (e.g. costs involved in locating the root cause or penalties due to system unavailability). Figure 1 demonstrates the arrangement to transfer the acquired research knowledge from the university to the industrial collaborators. The main goals have been to:

1. Provide in-depth training material on hidden failures and NFF events
2. Highlight the role of management including shortcomings, responsibilities and cultural impact
3. Promote inter-industrial knowledge sharing and interaction on the NFF issue
4. Identification of current best practices in dealing with NFF
5. Establish a NFF taxonomy

3.1.1 Research Methodology

A key component within the research was the application of a robust data collection phase that can effectively capture data from the targeted maintenance chain. Emphasis was primarily place of gathering information from maintenance engineers and related managers, but other personnel in technical support services were also included. The scope of participants involved covers a wide range of systems i.e. legacy/modern platforms, young/experienced maintainers and operators/supplier/Original Equipment Manufacturer (OEM). This is an important factor as several personnel adopt different practices on systems depending on their systems, experiences and business requirements. Table 2 highlights the adopted methodology to carry out the research.

Action	Objective	Method	Result
Problem definition	Industrial outlook understanding	Academic literature review, interviews	Establish scope
Data collection	Gather data required to carry out research activity	Industrial surveys, one-to-one interviews and case studies	Identification of research gaps
Critical analysis	Evaluate and discuss current practice	Annual symposium, open forum sessions	Technical reports, best practice guidance
Dissemination	Publish widely	Provide training, Author book, publish papers,	Benchmarking tools, competency development

Table 2: The adopted methodology by Cranfield University to investigate NFF events

Problem definition: This provides an in-depth review in order to understand the impact of the NFF phenomena and the state-of-the-art in academic related research. It highlights the current technology, processes and methodologies which are used in practice or have been proposed for the mitigation of the NFF problem. This phase captures information captures through a series of industrial interviews carried out amongst industry partners.

Data collection: An essential part of the research effort has been applied to establish cross-discipline features and design solutions that can be applied to any engineering design. This involved carrying out several industrial surveys, interviews and individual case studies. This approach has led to the basic understanding of how NFF manifests itself within a diagnostic process.

Critical analysis: This phase enabled the discussion of poor, competitive and world-class practices with organisations to address the NFF issue.

Dissemination: The aim is to disseminate widely amongst top international academic journals, influence industry practice and establish NFF training.

3.1.2 Research Assumptions and Limitations

Before continuing any further, the authors would like to outline the assumptions associated with the research:

1. The research work is carried out by competent personnel
2. All participating maintenance personnel provided their understandings based on their individual experiences and were not influenced by any pressure.
3. All participant are familiar with the NFF phenomenon and the challenges it presents

A number of research limitations had also been identified:

1. Variation in NFF terminology
2. Limited access to sensitive industry NFF data and statistics
3. A reluctance in organisations to provide realistic responses to questions
4. A time limit on the academic literature review was place since 1990 – present.
5. A large response from a particular organisation may skew overall results

The above limitations were identified at an early stage of the research and mitigation strategies were employed to minimise their impact; these are summarised below.

Limitation	**Description**
Variation in NFF terminology	Over the past two decades, NFF has been associated with various phases of the system life cycle, and yet its theoretical understanding has proved to be rather limited. Various acronyms have been used to indicate the same problem, signifying the importance of the event context. As a general rule within this work, the acronym "NFF" is used throughout all discussions, surveys and publications.
Limited access to industry Data	Organisations are often reluctant to share information, especially issues that involve NFF which can adversely affect their reputation. To address this, the research group engaged with various other NFF teams and committees from all sectors. This includes engaging directly with the NFF working group, sharing knowledge with other universities – Perth Highlands University and Delft University – and reviewing existing public knowledge/reports. This resulted in a reliable flow of relevant information and support.
A reluctance in organisations to provide realistic responses	The research required individual to discuss their specialist experience, organisational practices and culture. This has the tendency to disclose information which indicates that the organisation has been carrying out a poor standard within their practices. This may influence individuals to avoid discussing such information and instead answer by stating 'what should be done' as opposed to 'what is done'. It difficult to avoid this. However, in order to mitigate it, anonymity was maintained and stressed participating organisations, and where relevant non-disclosure agreements were signed.
A time limit on the academic literature review	As research within this area is of practical importance, the scope of this work covers the time frame between 1990 – present, whilst concentrating on the last decade in particular, as this period has been deemed to have contributed most of the academic material on the topic.

A large response from a particular organization may skew the overall result	There is always the fear that a large response from a particular organization may influence the end result. This could be a result from specific operating parameters of a particular organisation, or the unique nature of a system. During the critical analysis phase, feedback from specific organisations where analysed to identify their maintenance setup and culture, which would help to identify if a particular part of the research is significantly different from other work.

Table 3: Limitations of the research

4 Data Collection

From the literature review, it was evident that the major causes for this problem not only include technical or design errors but human factors like organisational, procedural and behavioural aspects as well. Hence, apart from the questions related to the case study and fault diagnostic process, general question related to NFF phenomena were also addressed during the interview in order to get the interviewees perspective with regard to the human factors issue.

In order to map the fault diagnostic process a questionnaire template (see Appendix A) was developed to capture the details of different stages of the process. These included queries surrounding the fault reporting, detection and data recording processes. Table 4 lists some of the questions used during one-to-one interviews and the development of surveys.

Data collection phases	**Questions utilised to investigate the problem**
Case Study Info	Brief information of the system/application Electronic/mechanical/hydraulic system, technical specification Do you use any system modelling techniques? What are the components used in the system? Technical diagram, drawings, pictures The given system is used in which vehicle?
Reported fault	What was the reported fault How often it has been reported/ occurrence rate? What was the min. usage of the vehicle (km or miles) Who reported the fault? What were the symptoms of the fault? What were the fault indicators?
Fault reporting process	Who are the actors involved in the reporting process Actions taken by each actor, how was the reporting done? Experience of the actors What were the testing procedures?
Fault detection process	Who are the actors involved? What are the actions taken by each actor? What is the experience of each actor? At which level, or who concluded the event as an NFF? What were the actions taken to identify the root cause?
Data recording process	Do you record maintenance data? Do you have any specific data recording method? Do you share this data with others? Do you make use of maintenance data history for problem diagnostics

	Is it used for training purposes of new engineers and technicians

Table 4: Typical questions for capturing diagnostic information

4.1 Surveys

The research developed three questionnaires to gather information related to current NFF practice, its impact and realisation within maintenance echelons. These surveys were carried out in between 2012-2014, and a total of 254 participants had responded.

Survey on current practice: This survey captured the current practices on dealing with the nature and description of NFF events. It highlighted increasing electronic complexities as a major concern in the number of unknown faults that are being reported during operational service. This scenario worsens when faults occurring at the component level are intermittent in nature. These opinions stress the requirement to prepare maintenance experts and specialised intelligent systems that can detect early anomalies or adequate information for investigation.

Survey on cost: One of the key findings was that most participating aerospace organisations did not measure the NFF cost at all. A limited number of those who did used the following metrics: reliability rate[6], logistics costs, contractual variation within the customer base, repair cost, lost man-hour data, down time hours on the machine, time wasted on testing the unit, handling cost, shipping cost, assumption for cost to replenish stock during the shop visit and material cost. A major cost driver was the unidentified cause of the reported event; rising NFF rates tend to increase the frequency of component transfer between aircraft, which in itself is logistics induced maintenance cost. With reference to the cost associated with supply chain, the primary cost drivers were identified as the transportation costs, followed by machine downtime costs, packaging and handling costs.

Survey on terminology: The survey underlined the causes and perceptions of NFF within the aerospace industry. The results revealed that the term 'NFF' is the most popular when referring to this phenomenon. However, there are some other terms including Fault Not Found (FNF), No Trouble Found (NTF), Cannot Duplicate (CND), Re-test OK, (RTOK) and Repeat Arising (RA) which indicate the same event. Many believe that this disparity may have affected the ability to deal with the NFF issue. In fact, describing the issue as a Fault Not Found (FNF) which offers a statement telling you the problem has not been fixed! Rather than NFF which suggests an attitude of resignation and that there was probably no fault there anyway. FNF suggests that we must still do something to solve a problem and there is an acceptance that something must be done.

4.2 Industrial Case Studies

The study featured 33 interviews since 2011, which have concluded that the main NFF root causes include: electronic connections, ageing components, rogue units that increase the rate and occurrence but are not sorted out by inadequate processes and test equipment. Another factor was poor soldering that result in intermittent faults which may not show up during the test period. Besides these diagnostic designs, human factors such as changing a box because a pilot wants it or because it is quicker than taking the time to investigate properly and poor training were prominent issues.

[6] Such as Mean Time Until Repair (MTUR) and Mean Time Between Failure (MTBF)

The key areas where improvement could be sought to reduce the cost of NFF are better diagnostics such as ensuring maintainers only see messages that mean that they need to take an action. This requires better understanding of:

1. Built in test equipment (BITE)
2. Equipment integration issues
3. Health monitoring which allows data to be analysed separately
4. Enabling intermittent fault to be more easily identified and linked to the environments or actions
5. Process improvements
6. Recognition of true costs of NFF throughout the organization not just at first line maintenance. Establishing a dedicated resource to drive in the process and diagnostic improvements.

Following on from the one-to-one interviews, the research team at Cranfield identified several case studies within a variety of industries suffering from NFF relating to the above root causes. The purposes of these case studies are to demonstrate the various causes and impacts that NFF can have. In the rail industry train doors are seen as the 3rd highest reliability issue, if a door fails to open or close resulting in a delay in leaving the station longer than 3 minutes; then this is referred to as a service affecting failure. This must be reported and upon functional testing no fault will be found. These door mechanisms are complex systems comprising of electronic, electro-mechanical and software control systems all interacting in some way. The importance of this study illustrated the difficulties in troubleshooting complex equipment interactions, maintenance and operational pressures and the inadequacies of functional testing. Also, in the rail the domain the effect of NFF on passenger satisfaction is highlighted through the failure to troubleshoot and identify the root cause of passenger display units.

In the military domain, a case study based on a communication system was identified which illustrated the effect the operational environment can have on the manifestation of failures. Within the military domain the intermittent loss of communications can pose a serious safety risk to soldiers. This is also combined with looking at the problems with incomplete or free text data capture and how small changes to the fault reporting and coding of data can influence the identification of repeat NFFs.

In the aviation industry, the use of a dual distribution valve used in a de-icing system for a popular turboprop passenger aircraft was identified. The de-icing system is interesting as it is a flight safety system and demonstrates a coupling between the environment and electronic and mechanical systems; where the root cause of the systems failure is yet to be identified in either of these. The EWIS system is aimed to illustrate the difficulties in identifying the source of intermittent faults in systems which often have hundreds of connections.

By making use of the data obtained, a generic process model involving the operator, maintainer and OEM was realised (see Figure 2 for example result).

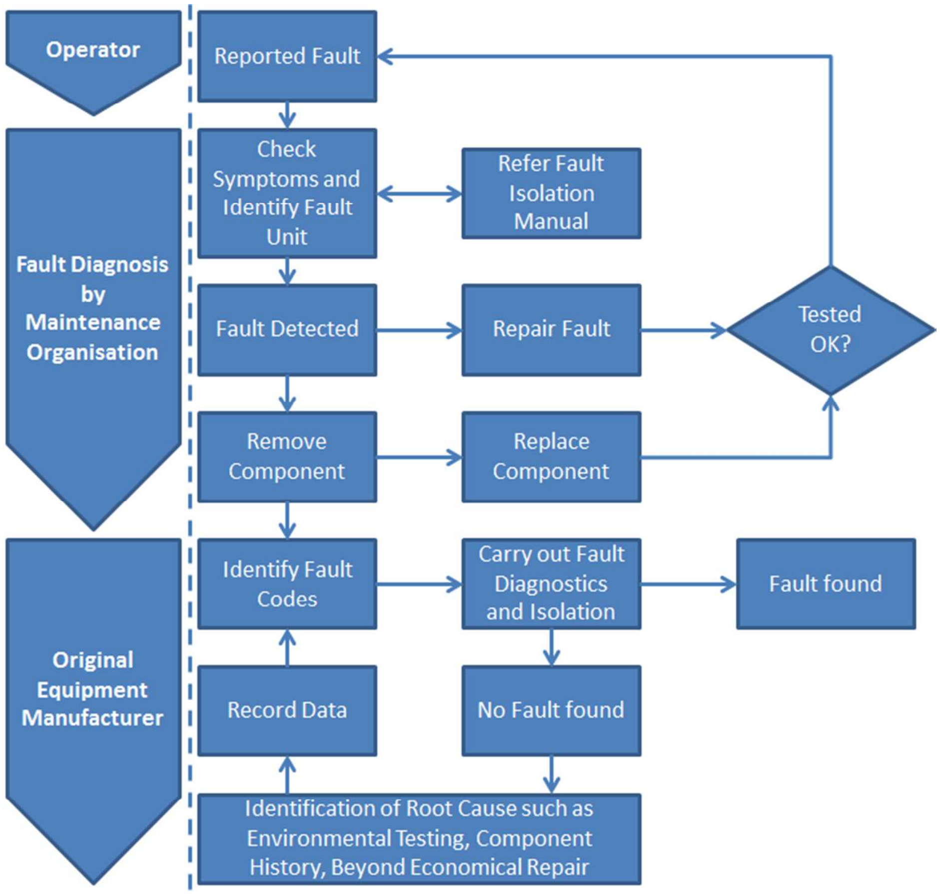

Figure 2: Example of carrying out a process mapping on existing diagnostic methods. Note: the participating industries have not been disclosed here.

The case studies indicate the importance of the information gathered at the initial stages of fault diagnosis process. This highlights the important of obtaining the appropriate fault symptoms and fault information from the operator/customer. Moreover, information needs to be interpreted correctly and hence, the fault reporting document s a crucial role. To conduct appropriate diagnostics, the allocation of resources is an important activity as maintenance managers need to decide whether the task requires an experienced diagnostic technician or a general service technician. This indicates that a NFF event can be initiated during these decision making steps.

Other factors include the levels of experience, training and knowledge of the technician dealing with the fault, which are crucial elements while conducting testing procedures. The importance of experience can be observed when the maintainer needs to reset the diagnostic system before testing the new component. Lack of training and instructions may lead towards a wrong path and make it practically impossible to find the root causes of the fault.

4.3 The No Fault Found Working Group

The ADS MRO & Logistics Network has established a No Fault Found Working Group with a view to cutting across organizational boundaries in pursuit of a joined- up approach to solving NFF across the aerospace industry. From the outset support from Cranfield University and other industrial collaborator like Copernicus Technology Ltd have been instrumental in the work of the group. The decision follows a strategic review of the UK MRO sector by members of ADS (the UK trade association for aerospace, defence and security industries) and the Aerospace, Aviation & Defence Knowledge Transfer Network. It was recognised that there is an opportunity to strengthen the UK MRO sector's capabilities and competitive edge by making a step-change in improvements to solve NFF problems.

In addition to the obvious aspirations to share knowledge and best-practice among the group, there has been an unequivocal appetite to deliver tangible out- comes rather than just being a `talking shop'. Consequently, the group is examining the potential to use members' maintenance data to identify opportunities for NFF improvement case studies and, in parallel with that it works with the TES Centre at Cranfield to peer-review a proposed taxonomy of NFF terminology to `get everyone on the same hymn sheet'. Beyond that, plans are also being developed to use the group as a forum for cross-sector NFF bench-marking and for reviewing the progress of and lessons from related research in other industry and academic projects.

4.4 Annual Symposium on NFF

The NFF research team has initiated an annual symposium on "No Fault Found in Maintenance Engineering". The event aims to establish itself as the first port of call for discussing NFF issues and to become the knowledge hub for solutions. Whilst bringing senior engineers and management to share their knowledge, it also promotes best practice and ideas for future standards development. Some of the prominent areas of discussion included operational procedures in maintenance engineering, contract, warranty, asset management, electronic diagnostics and prognostics technologies.

The Symposium has been attended by a total of 235 delegates from 105 different organisations. The key themes identified as the most influential contributors to the NFF problem include fault diagnostics, human factors, data management and system design. The key conclusions from the event were:

1. NFF is not a new problem, but all industries appear to still be roughly in the same place in their ability and willingness to tackle the problem
2. The financial impact of NFF still needs to be pinned down. If savings in the millions of pounds per year can be made once the problem is solved, then why is this amount not invested up front in order to achieve these savings?
3. To understand NFF we need to capture information on how close is the design to its true operating environment in order to improve the design of tests and diagnostics
4. Engineers must strive to understand how the burden of NFF changes throughout the lifecycle of the product
5. The 'blame culture' surrounding NFF hinders real progress towards a solution. The downstream effect throughout the supply chain needs investigating
6. More work is required to understand the link between equipment design, faults, diagnostics and NFF
7. There is a need to improve data capture and knowledge transfer which extends past merely information on the failure mode, but also includes operating environment and usage

8. Mechanisms for in-service feedback to designers and suppliers need to become more robust and better utilised
9. Having a data management process for in-Service removal events
10. Data mining can help in mitigation
11. Some "No Fault Found Best Practice" was developed during the reliability enhancement methodology and modeling program in 2002, however, this work was not openly published.
12. There is a need to educate design engineers on NFF issues and the impact that can cause to the overall system availability.
13. There is a need for 'smarter' troubleshooting and use field experience
14. Human factors issues:
    a. Lack of training is frequently quoted as a reason for deficiencies in this area
    b. Complexity factor
    c. The use of personal experience rather than maintenance manuals when undertaking fault diagnosis
    d. Manuals failing to provide sufficient information
    e. Operational pressure:
        i. insufficient time
        ii. deviate from procedures
        iii. management pressures adversely affects their ability

5 Discussion

Improving higher education in maintenance management has been identified as one of the most important challenges for university lecturers. Even as new maintenance graduates trained specifically in engineering education emerge, collaborations be- tween industries and universities will continue to be a critical component of engineering research. Quite often, there are boundaries between academic disciplines and roadblocks that often include, promotion and tenure requirements and department politics on one level and communication and competing truth claims on another. While some of NFF publications provide subjective evidence of these difficulties, surprisingly few of them discuss any empirical studies focused on budgeting and training processes. Although practical difficulties, like differences in terminology are commonly cited in discussions, research on disciplinary differences reveals more fundamental variation in the ways individuals in various disciplines discuss this problem and value knowledge. Most people will agree that engineering personnel at various maintenance echelons interpret events differently, but by understanding the underlying differences and how these can expand possibilities for planning, an important aspect of NFF management can be learnt. This knowledge will also influence invaluable cooperation amongst industrial sectors, communication and ultimately improve understanding. The curriculum is being developed to guide lecturers, teachers and module directors to provide continuous quality improvement within existing postgraduate level courses.

5.1 Continuing Higher Education

With an increasing interest in service and through-life support, specific NFF training can provide an essential foundation and overview of current maintenance practices and their limitations to the resolution of hidden failures. Cranfield University currently hosts a number of short courses that cover a range of topic related to reliability and maintenance that are aimed at developing competencies of middle- level and top-level management personnel. At present they do not contain material on NFF. Similarly, the current MSc programme in Through-life System Sustainment has been designed to target operating efficiency and system support capability, which are critical to meet shareholder requirements and will be an obvious candidate to include a significant amount of material on NFF.

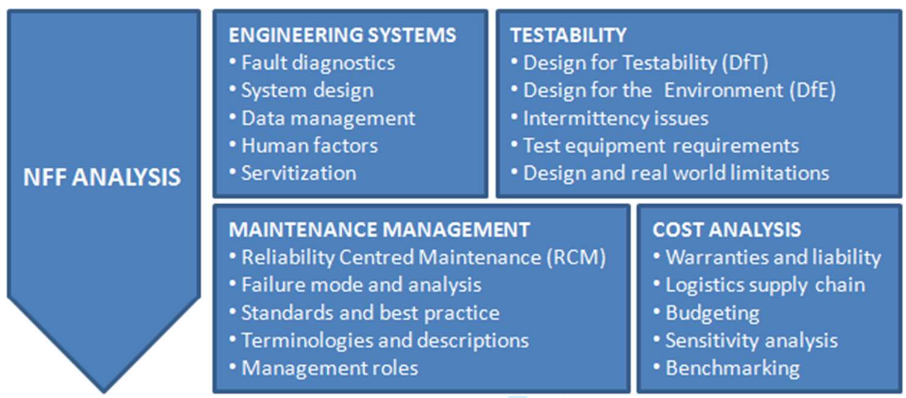

Figure 3: Identifying the fundamentals that form the foundations for teaching NFF concepts

Figure 3 depicts the essential concepts that form an appropriate model for providing the introductory material for transferring knowledge on NFF related topics. The training includes workshops where participants discuss work-related issues and interact with experienced researchers. The intended target audience comprise of system designers and senior management personnel, but also provide the theoretical basics for MSc students working within maintenance organizations. The primary focus is aviation, but discussions with other sectors such as automotive and electronic manufacturing indicate a high degree of interest. Lectures and industry case studies, including visiting speakers, will therefore consist of both aerospace and other interested industries.

To summarise, the intended learning outcomes from the NFF training will allow participants to:

1. Describe an in-depth view of common No Fault Found (NFF) issues across industries
2. Describe the role of senior management
3. Evaluate the ambiguity with NFF terminology
4. Apply recent technological developments in maintenance activities
5. Critically evaluate policies and process improvement guidelines
6. Construct arguments for improvements within their organisation

Combining the knowledge of these diverse areas makes this study challenging. Since existing taught university courses have little or no treatment of NFF impact and costs, it is important that the development of the training material is such that it can be used as supplements in other maintenance courses (where the topics are not being covered). Following completion of the training, participants will have an understanding, have obtained knowledge and be able to analyse issues as appropriate from the sections below. Depending on the course level and its length, the amount and depth will be adjusted. The overall content will take the form:

1. Introduction to the NFF problem (scale and scope)
    - Understand the link with diagnostics and diagnostic effectiveness
    - Understand the principles of why some maintenance tasks result in NFF
    - Analyse and breakdown of the problem technical, management, ergonomics, organizational, culture
    - Understand how NFF influences businesses cost, reputation, requirements and the business imperative to reduce NFF
    - Understand how a systematic approach can increase availability whilst reducing costs

2. Overview of Maintenance Concepts
    - Analyse what drives the requirements to challenge traditional maintenance?
    - Understand how strategies meet standards/goals whilst increasing operational performance and saving operating costs
    - Understand how to produce a functionally-based Failure Modes Effects Analysis (FMEA)[7].
    - Understand the need for continual Reliability Centres Maintenance (RCM)[8] review
    - Understand the need to enable a continual development process for diagnostic improvement.
    - Understand how to produce a maintenance solution to manage the consequence of failure.
    - Analyse the standards for best practice

3. NFF issues in detail
    - Understand the policies and best practices (ARINC 672)[9]
    - Understand how to measure NFF.
    - Understand the inconsistencies in taxonomy
    - Analyse the financial implications and understand how to break down the cost?
    - Analyse the specifications and contractual models of whether to include specification of NFF rates in contracts and how to attribute responsibility
    - Understand how to explain the problem to senior management how to present convincing information and how to get their attention

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[7] Failure Mode and Effects Analysis (FMEA) is a systematic technique for failure analysis. It is often the first step of a system reliability study and involves reviewing as many units and subsystems as possible in order to identify their failure modes, causes and effects on the overall system.

[8] Reliability Centered Maintenance (RCM) is a process which enables assets to continue to perform what their operators require in their present operating context. It is used to achieve improvements by establishing safe minimum levels of maintenance, changes to operating procedures and strategies and the establishment of capital maintenance regimes and plans.

[9] The ARINC 672 is a set of guidelines for the reduction of NFF in a holistic manner. It was introduced for the primarily aviation industry to develop an effective NFF event management process.

- Understand the roles and responsibilities
- Analyse the effect of ergonomics and human factors in causing NFF
- Analyse the effect on NFF of technological limitations, manufacturing process, legacy systems, environmental influence, system integration, inadequate diagnostics, built-in-tests, automatic test equipment, standard penetration test equipment vs general purpose test equipment
- Understand NFF causes in detail
- Understand how to design and development solutions.
- Understand the contribution of modeling in NFF analysis.
- Be aware of the various analysis options
- Analyse case studies of good and bad practice that deals with the issues identified.

4. Design and Development Solutions
    - Understand the current practices for mitigation.
    - Be aware of ARINC 672 solutions
    - Understand the opportunities to influence design from existing expertise, iteration in design, FRACAS[10], servitization process, liability contracts
    - Understand how the design for reliability and environmental testing
    - Understand how to track spare parts
    - Understand how to identify 'rogue units[11]' and develop solutions
    - Understand how to provide timely and effective information feedback
    - Understand how to design action that reduces on-going maintenance costs, improve decision making and allocation of resources
    - Understand the contribution of condition monitoring, E-maintenance and reporting mechanisms
    - Understand the importance of training, communication and time management
    - Understand NFF budgeting and the need for a NFF strategy and a plan to reduce NFF

5. NFF Research activity
    - Understand the NFF research goals
    - Be aware of the current research activities and capabilities

6. Workshops and case studies of best practice and solutions

5.2 The Role of Management

Murthy (2002) argues that maintenance management needs to be done in both strategic and operational contexts and further divide its organization into three distinct levels, each providing

[10] A Failure Reporting, Analysis and Corrective Action System (FRACAS) is a system that provides a process for reporting, classifying, analyzing failures, and planning corrective actions in response to those failures. It is typically used in an industrial environment to collect data, record and analyse system failures.

[11] A rouge unit is a component that has been taken out of service multiple times for repair. The problem is when it is sent in for subsequent tests, the standard workbench testing cannot reveal its unusual failure mode. As a consequence, the unit may be put back to service, where the whole cycle will repeat.

various vantage points on how decisions are made from each level. Similarly, a management structure for NFF can be adapted according to the following:

1. Top-level management: This level should aim to provide an overall view of knowledge management challenges for the global business, including:
    - Developing (or recognising) a maintenance strategy that conforms to the business' vision
    - Agreeing on contractual agreements on warranty and indemnities in the case of hidden failures
    - Consent to providing adequate training, material resources and authorisation for investigating NFF occurrences
    - Defining a specific allocation of funds for NFF within the yearly maintenance budget
    - Defining responsibilities to foster a culture that promotes interdisciplinary integration of maintenance lines on all levels
    - Identify key performance indicators
    - Reviewing yearly statistics on hidden system failures and evaluate them with formal customer requirements and safety standards
2. Middle-level management: This level should concentrate on developing procedures and the implementation of NFF strategies, based on the strategies set out by the top-level management:
    - Develop procedures (or instructions) that adhere to the NFF strategy set out by the top-level management
    - Monitoring the implementation of reactive maintenance objectives and performance
    - Communicate and feedback NFF information related to incident facts, resources used, statistics, performance to senior management
    - Ensure troubleshooting competence levels are preserved
    - Ensure solutions and expertise is fed back to design in order to suggest improvements
    - Make comprehensive decisions under operational pressure
    - Liaise and negotiate with OEM, or third-parties and outsourcing partners
3. First-line management: This level should be provided with fault isolation manuals (or troubleshooting guides) that contain all possible fault codes and step- by-step procedures. Personnel are encouraged to follow best practice guides and are often involved with:
    - Implementation and coordination of appropriate actions
    - Making comprehensive decisions under operational pressure

5.3 Future Research Collaboration

The collaboration has managed to increase the understanding in the subject area. At the same time, it has also opened up a wide area of future work. The core areas where efforts should be focused on:

1. The costs and its break downs are sensitive within and between organisations. The people within the company working in more commercial roles may have better access to these data

as accessed by the people who are working in NFF group. Hence interdisciplinary involvement will provide better understanding of the cost and its breakdown

2. Some of the costs such as loss of business, safety issue, product dissatisfaction and obsolescence cost are difficult to quantify and hence requires more work and a defined methodology and framework for its quantification
3. Involvement of international industries will also help in understanding NFF
4. Establishing a benchmarking tool is which can be used as an improvement opportunity toolset by linking key improvement activities to each activity and/or indicator. The aim here is to achieve a minimum level of non-value added activities in the timely diagnosis and resolution of complex system fault indications.
5. Mapping processes that represent the dynamic interaction experienced across internal departments and external suppliers to identify, analyse and solve NFF issues

6. Conclusions

Although it has been understood that there can be significant barriers to any successful collaboration and knowledge exchange between universities and industries, fewer studies have ventured to assess and record these perceived barriers.

In this paper, the authors have discussed the approach adopted by Cranfield University to engage with industry in order to investigate the impact of NFF within maintenance practice. The research has led to the identification of a core gap – lack of training and knowledge distribution on NFF failures and their solutions. As a consequence, a comprehensive training outcome has being outlined to ensure that experience and troubleshooting techniques can be disseminated as guidelines across businesses, while providing an introduction to NFF concepts and its resolution practices. The approach involves linking the technical, operational and commercial issues into an integrated framework. Successful initiatives are highlighted and the importance of the industrial collaboration was further emphasized though case studies. Moreover, emphasis was placed on the importance of fostering interdisciplinary integration within engineering education, that could be offered through training (including short courses or MSc programmes), along with suggestions for future improvements. The key components that must be included in any NFF educational offering includes:

1. Understanding hidden failures and their impact on businesses
2. Collection of adequate data and feedback to design for continuous improvement
3. Promoting knowledge sharing amongst various industrial disciplines
4. Identification of current best practices and supporting standards development
5. Distribution of knowledge on NFF mitigation and solutions

Appendix A

The NFF related questions are as follows:

1. What are the most frequent causes of the NFF problem?
2. Where does the impact of NFF fall within organisations? Who suffers? Where do the costs lie for NFF?

3. What mechanisms or processes (technical/procedural etc) can be put in place for dealing with the impact of NFF events and also to reduce the overall number of NFF occurrences?
4. Do organisations track rogue units or components, if so how?
5. What areas are of significant importance when trying to understand NFF?
6. What is the occurrence/ frequency rate of NFF events?
7. Are there any standard procedure/ method to identify the NFF?
8. What are the current practices to tackle NFF issues?
9. What are the limitations in the testing equipment or measurement tools?
10. Do you think that the inappropriate usages by the customer can also a cause NFF event?
11. Do you maintain any NFF data base? Is it been effectively transferred?

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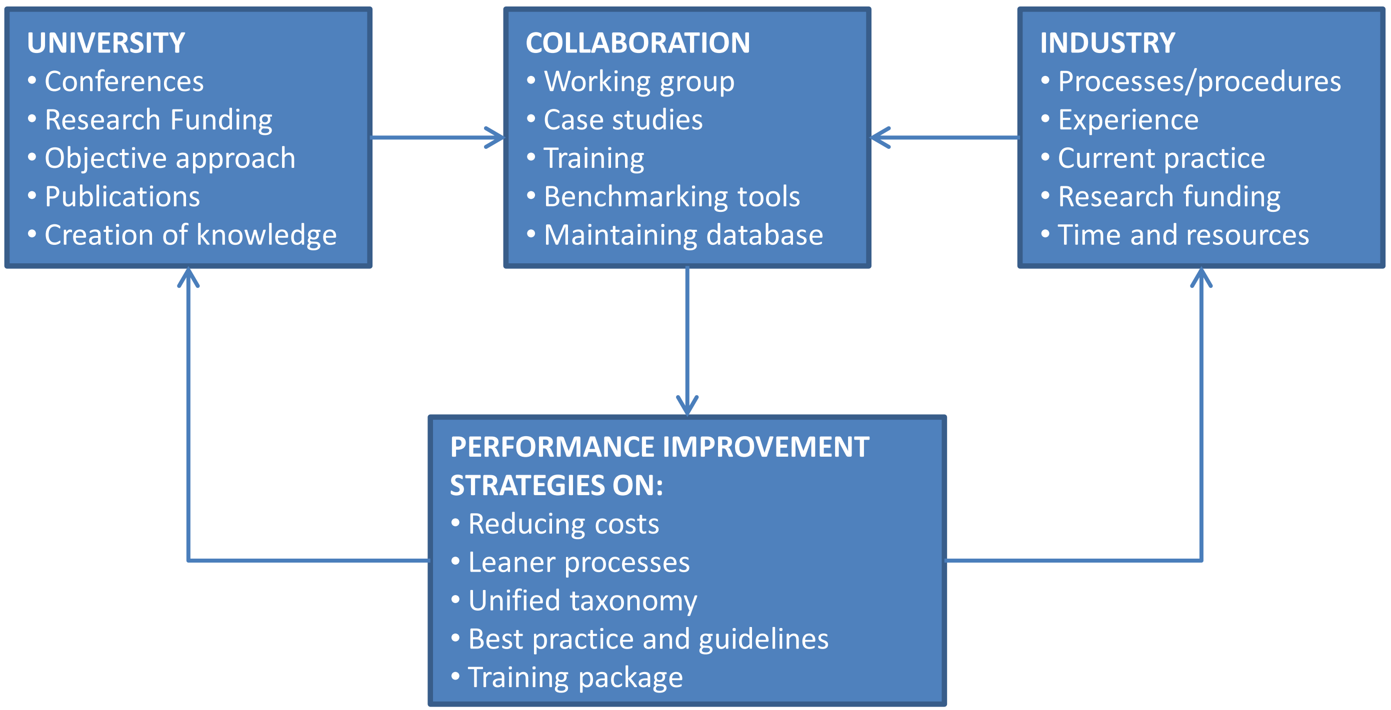
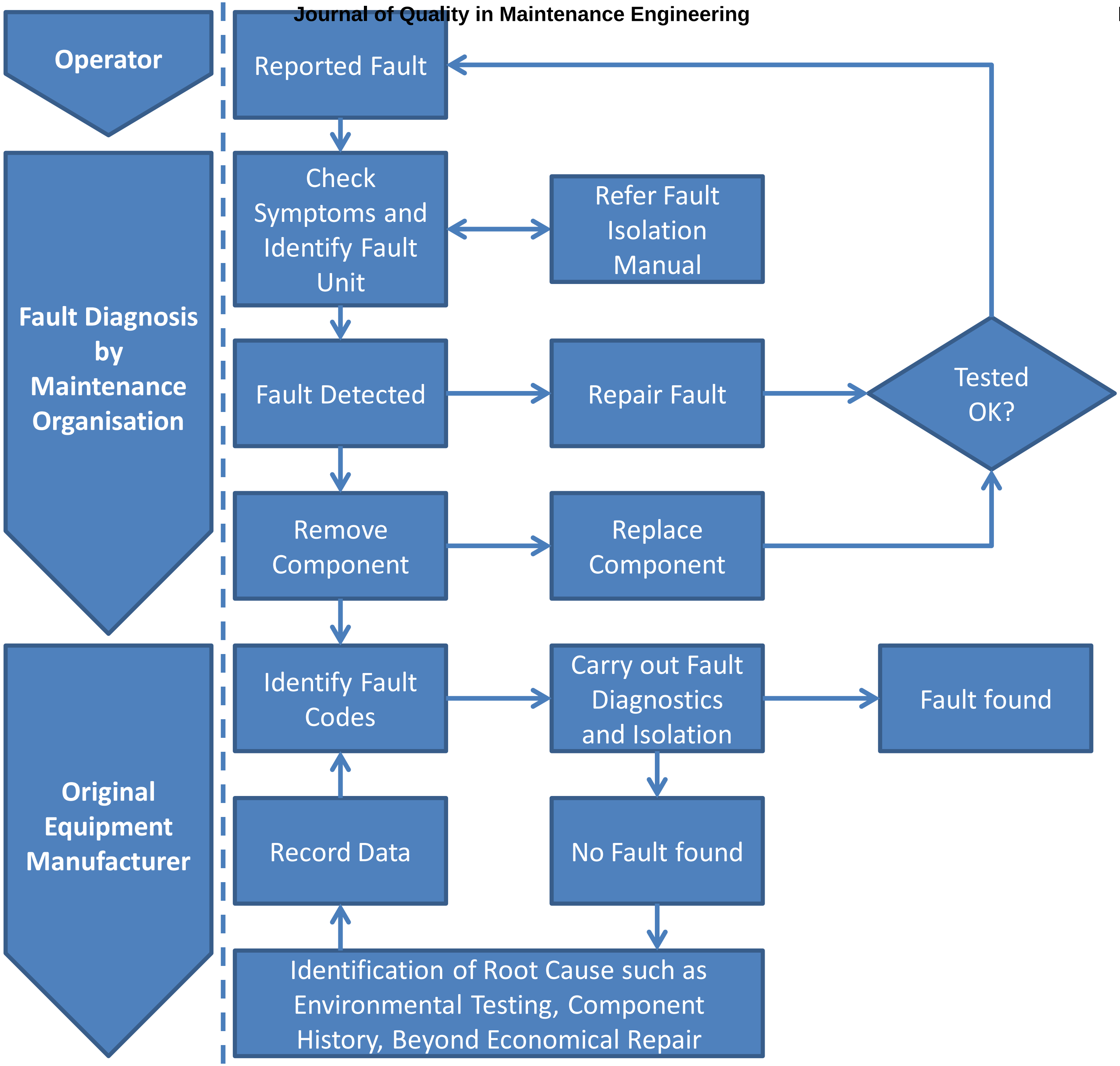
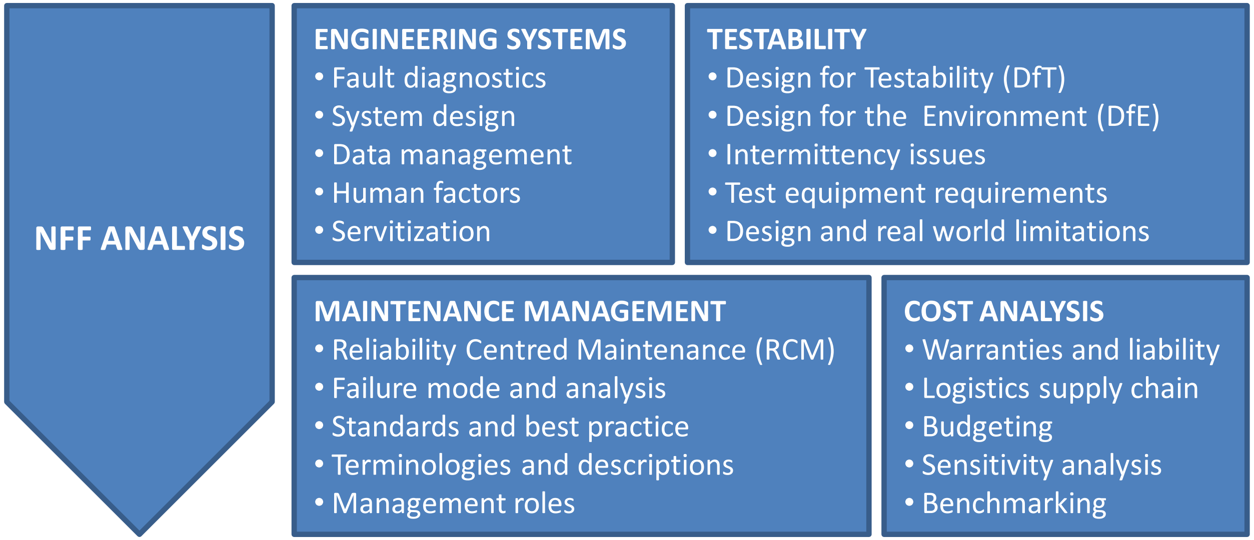

UNIVERSITY
• Conferences
• Research Funding
• Objective approach
• Publications
• Creation of knowledge
COLLABORATION
• Working group
• Case studies
• Training
• Benchmarking tools
• Maintaining database
INDUSTRY
• Processes/procedures
• Experience
• Current practice
• Research funding
• Time and resources
PERFORMANCE IMPROVEMENT STRATEGIES ON:
• Reducing costs
• Leaner processes
• Unified taxonomy
• Best practice and guidelines
• Training package


Operator
Reported Fault
Fault Diagnosis by Maintenance Organisation
Check Symptoms and Identify Fault Unit
Refer Fault Isolation Manual
Fault Detected
Repair Fault
Tested OK?
Remove Component
Replace Component
Original Equipment Manufacturer
Identify Fault Codes
Carry out Fault Diagnostics and Isolation
Fault found
Record Data
No Fault found
Identification of Root Cause such as Environmental Testing, Component History, Beyond Economical Repair


NFF ANALYSIS
ENGINEERING SYSTEMS
• Fault diagnostics
• System design
• Data management
• Human factors
• Servitization
TESTABILITY
• Design for Testability (DfT)
• Design for the Environment (DfE)
• Intermittency issues
• Test equipment requirements
• Design and real world limitations
MAINTENANCE MANAGEMENT
• Reliability Centred Maintenance (RCM)
• Failure mode and analysis
• Standards and best practice
• Terminologies and descriptions
• Management roles
COST ANALYSIS
• Warranties and liability
• Logistics supply chain
• Budgeting
• Sensitivity analysis
• Benchmarking