Cranfield University

Hamadalneel Suliman Jumaa Rashid

Human Factors Effects in Helicopter Maintenance: Proactive Monitoring and Controlling Techniques

School of Engineering

Ph.D.

January 2010

Cranfield University

School of Engineering

Ph.D. Thesis

2009/2010

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Supervisors: Prof. Graham Braithwaite and Dr. Simon Place

Academic Years 2005 to 2010

This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

ABSTRACT

Aviation maintenance errors account for between 13% and 23% of the global aviation incidents and accidents initiators, which require a wider global use of aviation maintenance safety improvement activities. The current research applies the Human Error Risk Management in Engineering Systems (HERMES) methodology that conceptualizes two main streams of study. These are the retrospective investigation of human errors within aviation maintenance contexts, and a prospective innovation of new tools that work to prevent errors occurring. In this research the impact of human reliability on aviation maintenance safety is investigated. Rotorcraft is taken as a focal case study.

A new model to represent the accumulation of crucial maintenance human errors causal factors, within aviation maintenance companies, is introduced. A total of 804 recent maintenance-induced helicopter accidents were reviewed, from which 58 fatal accidents and serious incidents were thoroughly analysed using Human Factors Accident Classification System - Maintenance Extension (HFACS-ME). A 4th order of analysis is newly introduced into the HFACS-ME taxonomy under the notion of 'Specific Failures' for better analysis resolution and comprehensiveness. Hypothesizing that human factors errors within aviation maintenance industry can be more effectively managed by applying proactive monitoring and early error detecting techniques - at both organizational and individual levels, a proactive Aviation Maintenance Monitoring Process (AMMP) is formulated. AMMP is a holistic hybrid retrospective / prospective integrated process that is to be simultaneously and collectively implemented by main industry stake-holders - regulators, manufacturers and maintenance organisations. The aim is to proactively monitor the existence of human error causal factors that are initiated during design practices, manufacturing processes, or at later stages due to workplace conditions. As a result, such causal factors can be gradually eliminated to reduce the overall risk of maintenance errors.

This generic AMMP model is based on a Root Cause Existence Scale (RCES) and a comprehensive sociotechnical user program, coded as 'ErroDetect', built applying the fuzzy Analytic Network Process (fuzzy ANP) theory. A total of 870 different assessment criteria were designed and then in-built within the software thus mapping the outcomes of the retrospective error causal factors investigative studies. Full simulation of the process is conducted, and then it was further validated practically in real world within industry for both design for maintainability within major rotorcraft manufacturer facilities, and for MRO's performance safety enhancement. Validation results were thoroughly discussed. The AMMP is found to have significantly enhanced aircraft maintenance proactive safety for both designers and maintainers. The tool can also be adopted for regulation purposes.

ACKNOWLEDGMENTS

All praises, sincere thanks, and great gratitude are all, but to God, The Most Beneficent, The Most Merciful. Without His all kindness, blessings and supportiveness, nothing of this would have been accomplished.

Well, it seems that I will find the language short of expressing my real feelings, having this work coming to an end, towards all those who taught, helped, and inspired me to reach hereabout. I will undoubtedly start with my beloved parents, Hafsa and Suliman, whose kind kindness, mixed with all the wisdom of life, really brought me up. I will never forget that morning when my mother took my hand and my pencil – all together, and guided them through my first written letter ever. My father was the fuel that energized me since then. This PhD thesis should really be dedicated to them.

Coming to Cranfield, I have described my two supervisors: Dr. Simon Place and Prof. Graham Braithwaite, just like the quote introducing the last chapter of this thesis says, as giants. Well, they really are. I think this work is totally built with their guidance, help, and encouragement. They both know, before anybody else that they went, during binging up this work with me, far beyond the normal, or even, beyond ultra-normal expectations that a supervisor can be, or can be thought of to be. I would just like to say: Thank you, and through you, to the entire great lovely team of the AT, my second home.

Many people and organizations participated to accomplish this job. The AAIB-UK, MEMS-UK, Bristow and CHC helicopters of the North Sea, BA at Cardiff, BEA of France, EU-JRC in Ispra-Italy, Baines Simmons-UK, Boeing Commercial airplanes, NTSP-USA, ATSP-Australia, CAA-UK, and Eurocopter-UK. This short list is undoubtedly but a part of all the support that this work received along the way back from 2005 up to date. For all of you: Thank you.

Now, my beloved wife Raga, my little women Ghaida, Ragda, Mozna, Masa, and my little friend Ahmed: You all know that this work is originally yours, because you made it, as an idea, as a project, and as a solid output. And because the language is standing short, I would only say: Thank you.

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ACRONYMS

AAIB	Air Accidents Investigation Branch - UK
AD	Airworthiness Directive
ADREP	Accident/ Incident Data Reporting system
AHP	Analytical Hierarchy Processes
AMMP	Aviation Maintenance Monitoring Process
AMT	Aircraft Maintenance Technician
ANP	Analytic Network Processes
APRECIH	Preliminary Analysis of Consequences of Human Unreliability (French).
ASMS	Aviation Safety Monitoring System
ASRM	Aviation System Risk Model
ASRS	Aviation Safety Reporting System (NASA- USA)
ATSB	Air Transport Safety Bureau -Australia
BBN	Bayesian Belief Networks
BEA	Bureau d'Enquete et d'Analyses- France
CAA	Civil Aviation Authority
CASS	Continuing Analysis and Surveillance System
CHIRP	Confidential Human Factors Incident Reporting Program - UK
EASA	European Aviation Safety Agency
ETA	Event Tree Analysis
EVMS	Engine Vibration Monitoring System
FAA	Federal Aviation Administration - USA
FAR	Federal Aviation Regulation - USA
FBR	Faulty Behavior Risk
FORAS	Flight Operations Risk Assessment
FTA	Fault Tree Analysis
GAIN	Global Aviation Information Network
HEAM	Human Error and Accident Management
HEC	Human Error Classification
HEM	Human Error Management
HERMES	Human Error Risk Management for Engineering Systems methodology
HEROS	Human Error Rate Assessment and Optimizing System
HFACS-ME	Human Factors Analysis & Classification System- Maintenance Extension
HFI	Human Factors Integration
HMEA	Hazard Mode and Effect Analysis
HMI	Human-Machine Interaction
HMS	Human-Machine Systems
HOMP	Helicopter Operations Monitoring Program
HRA	Human Reliability Analysis
HSIM	Hybrid Structural Interaction Matrix
HTA	Hierarchal Task Analysis
HUMS	Health and Usage Monitoring System
ICAO	International Organization of Civil Aviation
IFMI	Index of Factors Mutual Influence
IRR	Inter-Rater Reliability
INDICATE	Identifying Needed Defences In the Civil Aviation Transport Environment

JAR	Joined Aviation Regulations
LOPA	Layers Of Protection Analysis
MEDA	Maintenance Error Decision Aid human factors analysis tool (Boeing)
MEH	Maintenance Error History model
MEI	Maintenance Error Investigation taxonomy
MEIMS	Maintenance Error Information Management System
MESH	Managing Engineering Safety Health tool
MESS	Maintenance Environment Survey Scale
MGEEM	Methodology for Generating Efficiency and Effectiveness Measures
MRM	Maintenance Resource Management
MRO	Maintenance, Repair, and Overhaul organization
MTBF	Mean Time Between Failures (Michlin and Migdali 2004).
NASA	National Aeronautics and Space Administration - USA
NDI	Non Destructive Inspection
NDT	Non Destructive Test
NTSB	National Transportation Safety Board - USA
OL	Organizational Learning
PEAR	People-Environment-Actions-Resources model of human factors.
PHA	Process Hazard Analysis
PIF	Performance Influencing Factors
PIPE	Perception, Interpretation, Planning and Execution simple cognitive functions
PRA	Probability Risk Assessment , or Probabilistic Risk Assessment
PSA	Probabilistic Safety Assessment
PSF	Performance Shaping Factor
QPM	Quality Performance Matrix
QRA	Quantitative Risk Analysis
RAM	Risk Analysis Matrix
RCA	Root Cause Analysis
RCES	Root Causes Existence Scale
RFED	Research Front-End Design methodology
RM	Research Methodology
RMC	Reference Model of Cognition
RSA	Recurrent Safety Audits
SB	Service Bulletin
SF	Specific Failures
SHoME	Safety Health of Aviation Maintenance Engineering
SI	Safety Indicator
SMS	Safety Management System
SRK	Rasmussen's Skill-Rule-Knowledge framework
STS	Socio-Technical Systems
TA	Task Analysis
TATEM	Technologies and Techniques for new Maintenance Concepts project
TFN	Triangular Fuzzy Number
THERP	Technique for Human Error Rate Prediction
VHM	Vibration and Health Monitoring

PART ONE

FUNDAMENTAL AND FOCUSING RESEARCH STUDIES

1 Introduction: Outlining This Research In Aviation Maintenance Safety

There is nothing more difficult to take in hand,
more perilous to conduct or more uncertain in its success
than to take the lead in the introduction of a new order of things
Niccolo Machiavelli (1469-1527)

1.1 Introduction

1.1.1 Philosophizing this research in aviation safety

An absolute human reliability within complex sociotechnical systems has always been questionable. Human errors within such contexts are vital, yet unpredictable. Aviation maintenance, being critical environment for Human-Machine Interaction (HMI), shares a range of 12% to 15% of the global aviation accidents initiators (Marx and Graeber 1994, Patankar & Taylor 2004b). In this research, the impact of human reliability on aviation maintenance safety is investigated. Rotorcraft maintenance is taken as case study.

It is generally accepted that maintenance, as a dynamic HMI setting, attracts a large proportion of human factors-induced problems. In fact, in aviation for instance, a significant contribution of the technical causes of aviation accidents is attributed to human factors in various levels within maintenance organizations. These levels cover the base workforce of maintainers, middle supervisory body, and up to the higher management (Gramopadhye and Drury 2000).

Reporting the state-of-the-art, it can be seen that aviation maintenance human reliability and associated aircraft airworthiness have been the focus of many philosophies and research works previously. Reason (2003) discussed the human variability paradox when this variability acts – within complex human/ machine systems – both as source of error and a vital defence of the system. He thus questioned: “How can we limit one while still promoting the other?” In the same orientation, Hollnagel (2007) showed that risk and safety are, by definitions, always linked together. He gave the notion: “ Risk + barriers = Safety?” calling for higher safety acquirement through risk elimination. This writer sees that one path to such risk elimination goes through the pre-elimination of that risk’s causes in the first place.

Human error is defined as"the failure of planned actions to achieve their desired ends – without the intervention of some unforeseeable event" (Reason 1997). This definition clearly separates the erroneous controllable actions from mere bad luck attributes. It can thus be understood that human errors are typically associated with pre-planned actions, especially within systems of higher complexity, where the human element malfunctioned at some stages of the process. To this point, such a human error may be considered as a cause for some later-induced malfunctioning within the system. A good philosophy will then be the one that answers the question: Was that human error a cause which led to the system malfunctioning or was it a consequence of that system's seen and hidden defects? This question still holds well when it comes to the aviation maintenance context. The study of the human reliability within this industry is waited to emphasise the understanding of the causes and propagation mechanisms of maintainers' errors and the consequences of those errors on the overall aviation system safety.

In the same field, Reason (1997) explained that error, in general organizational settings like those of the aviation maintenance, can be managed through two broad strategies: Error reduction and error containment. Error reduction in turn encompasses many techniques such as the augmentation of error detective procedures, error intrinsic resistance enhancement, reduction of error liability regarding individuals or groups of workers, reduction of error vulnerability of particular tasks or task elements, and the elimination of error-producing (and violation producing) factors within the work place.

Literature is rich with plethora of theories and concepts discussing human reliability and associated error causal factors that always trigger incidents and accidents within safety-critical systems. The main characteristics of such safety occurrences - by definition - are their randomness, rare predictability, sophisticated yet vague sequence of propagation. Such characteristics can basically allow for retrospective analysis of these occurrences and their causes at various sectors and levels within industry such that the re-occurrence margins are reduced if not totally eliminated. The major drawback of such reactive treatment is the high social and economic cost that must be paid through the learning process. On the other hand, prospective research on human–centred safety is also furnished using numerous techniques that are mainly framed taking Probability Risk Assessment (PRA), including human reliability, as a corner stone. However, within these efforts, the quantification of human error probabilities as major part of such proactive safety techniques had always faced serious limitations (Richei et. al. 2001). Thus, a proper solution would undoubtedly be one that can collectively combine advantages from both the pre-discussed main streams of safety analysis, and avoid their limiting features. The purpose of this work is to introduce such a tool.

1.1.2 This chapter

This chapter gives an overall insight to this research, it discusses in brief motives and rationale, objectives, originality, methodology, and general layout of this thesis. The following paragraphs, as well, discuss major advances and gaps in the field of human error treatment in general and in aviation maintenance in particular.

1.2 Research background and problem identification

1.2.1 Research milieu and rationale

It has been estimated that for every one hour of flight, 12 man-hours of maintenance occur (Hobbs 2008). With such a colossal maintenance work span, the pre-indicated 12% to 15% of maintenance errors involvement in accidents is not surprising. This range almost doubles when serious incidents, developable into accidents, are included. Further, Goglia (2002) stated that of the fourteen Federal Aviation Administration (FAA) approved FAR-121 carrier hull losses that had occurred previously on USA registered aircrafts, seven had been implicated by maintenance shortfalls. Moreover, 19.1% of engine in-flight shutdowns were caused by maintenance errors (Marx 1998). Financially, maintenance errors have been estimated to be involved in 50% of engine-related aircraft delays and cancellations (Marx and Graeber 1994). This is of enormous financial penalties when it is realized that for a large aircraft such as a Boeing 747-400, a cancelled flight can cost the operating airline around USD $140,000, whilst a gate delay can cost USD $17,000 per hour on average (Hobbs 2008). Such statistics undeniably call for a wider aviation maintenance safety and efficiency improvement activities.

Human factor-induced error in aviation maintenance has been managed so far through several systems and procedures. Some of these are the Maintenance Resource Management (MRM), duplicate inspections, various reporting systems, multiple oversight groups, and many others (Van der Schaaf 1991, Patankar & Taylor 2004a, b, Hall 2005a). Albeit these efforts and advances have had their positive influence, the issue still calls for extra focusing.

1.2.2 Why Helicopters?

Helicopter flight performance is still far from achieving its expected safety goals. The number of fatalities in helicopter accidents during the last ten years for off-shore transportation and seismic operations is 10.6 and 58.5 times, respectively, that of commercial airlines per million hours of flight (Shell 2005). This is a clear indication of the high severity of helicopter accidents outcomes given the highly sophisticated and demanding operational roles that they perform. It is also found that 31% of the total helicopter accidents probable causes were technical where at least one component of the aircraft fractured or malfunctioned (Atkinson and Irving 1995). A significant proportion of such technical causes of helicopter accidents and serious incidents are in fact attributed, in their upper streams within organizations' higher managements, to maintenance human factors as well. Technical safe -guard monitoring systems such as Health and Usage Monitoring (HUM), Vibration and Health Monitoring (VHM), and Engine Vibration Monitoring System (EVMS) were thus introduced and managed to reduce the technical malfunctioning of the helicopter critical parts. Operational aspects have also been addressed recently through the Helicopter Operations Monitoring Program (HOMP).

Further, helicopter maintenance errors acquire higher criticality due to naturally associated rotorcraft characteristics, some of these being the single route to failure regarding the transmission and rotor systems, limited envelope of emergency manoeuvres, and high vulnerability to impact (Hessmer 2001). Lastly, the vast majority of the previous works often investigated maintenance errors and their roles in promoting aviation accidents from the fixed-wing aircraft perspective, this highly motivated this research to investigate the case of rotorcrafts.

1.2.3 The gap

Human errors in aviation maintenance are generally discussed through two main approaches: Human Reliability Analysis (HRA) and Human Error Classification (HEC). HRA, as part of the PRA theory, has always faced its quantification limitations, while HEC approach has always been described as behavioural, contextual, or conceptual in nature. It is thus concluded that the most obvious response to a human error is to identify its causal mechanisms and alter the system such that that error is not repeated (Latorella, and Prabhu 2000).

For aviation maintenance, tools to handle such mechanisms included maintenance resources management sessions, duplicate inspections schemes, various reporting systems, multiple over-sight groups, and many others, but nevertheless, each of these has its inbuilt limiting features as will be thoroughly discussed throughout this thesis. Consequently, this issue still requires more focusing. In addition, there is a fresh general industrial tendency to start a shift towards ‘proactive safety’ after the long saturated treatment of reactive accidents and incident investigations and the usually safety recommendations that expectedly follow. The call for this emerging philosophy has been reinforced by many writers (Braithwaite et al. 1998, Liou et al. 2007, Edwards 2007, Shyur 2008).. Further, In contrast to helicopters, some studies in the maintenance error causation were already carried out for the commercial fixed wing aviation. No previous studies concerning human errors initiation and propagation within rotorcraft maintenance industry could be found within literature. This research claims to be the first thus-oriented.

Summing this up, it is high time now to introduce a maintenance-monitoring tool devoted mainly to address the human contributing factors, and to detect early their potential error root causes and risks during helicopter maintenance practices.

1.2.4 Problem identification

In this research the Root Causes (RC) of human errors during helicopter maintenance are targeted. Once these root causes have been determined, an Aviation Maintenance Monitoring Process (AMMP)’ may be introduced. This intended AMMP is a proactive monitoring procedural tool that is to be integrated within the current maintenance industry activities in order to detect existence or over peaking of maintenance error root causes, thus eventually trapping and damping down human errors during maintenance practices. The research also addresses two other aspects of human factors affecting aviation maintenance in general and helicopter maintenance in particular, namely the scientific (procedural) determination of both the ‘Independent Inspection Items’ as required by the regulators (European Aviation Safety Agency - EASA), and the ‘Maintenance error - prone features’ of a given type as recommended by manufacturers. The overall output can then be processed as feedback into design phase and within maintenance workplace for further aviation safety enhancement.

1.3 Overview of research aim, objectives, and questions

1.3.1 Research aims

The target of this research work is to introduce new theory and applications that can bridge the aforementioned gaps by answering their associated questions. Major aims can thus be listed as follows:

1. Introduction of a new high resolution collective classification scheme to analyze human errors that occur during aviation maintenance, and use of other associated tools to precisely identify root causes of those human errors that develop within aviation maintenance, with particular focus to helicopter maintenance practices.
2. Introduction of new multiple intermeshing models and tools to study and assess the existence of root causes that induce human errors within aviation maintenance contexts such that these root causes could be proactively eliminated to enhance aviation safety.
3. The targeted tools should be applicable by various aviation industry stakeholders.

1.3.2 Research objectives

The above mentioned strategic aims of the research are sought through the achievement of the following objectives:

1. To study current human factors models, error management systems, and classification schemes when being applied to aviation maintenance.
2. To identify the root causes that induce or contribute to human errors that can develop during any of the aviation maintenance practices at both organizational and individual levels. Rotorcrafts are taken as case application.
3. To establish an industry-oriented AMMP comprising procedures to:
    a. Monitor and detect early the potential root causes of maintenance errors that can be initially triggered during aircrafts design phase, or can exist as hidden conditions within workplace contexts at aviation Maintenance, Repair, and Overhaul (MRO) organizations.
    b. Provide scientific procedures and practices to specify the ‘Independent Inspection Items’ category tasks for any given type maintenance program.
    c. Detect and assess any maintenance error - prone design features of any given aircraft type.

4. To verify the integrity of the developed process within the helicopter design, manufacturing, and maintenance industries with the aim of an overall aviation safety improvement.

1.3.3 Research questions and hypotheses

The idea, scope, and context of this research can be further illuminated through the following questions and adopted hypotheses.

1.3.3.1 Research questions

This research tries to establish scientific precise answers to a number of questions that are direct manifestation of the pre-discussed gaps in the knowledge pool of aviation maintenance human error causation and propagation, some of these questions are:

1. What are the effects of human factors – based errors in aviation as general and in helicopter maintenance in particular? How deeply they affect aviation safety?
2. What are the existing methods and techniques that address human errors during helicopter maintenance, what is the industry response towards them, and what are the gaps that are to be further addressed?
3. What are the root causes of human errors during helicopter maintenance practices? Can any safety margins be assigned to the rate or frequency of existence of each of these root causes?
4. Can helicopter maintenance practices be proactively monitored for existence and/ or over-peaking of these root causes in order to prevent or damp their consequent human errors? Can such proactive monitoring procedure be integrated within the industry's existing maintenance practices?
5. Can aviation safety in general and helicopter safety in particular be further enhanced by introducing procedures to determine the 'Independent Inspection Items' and the 'Human Error – prone Features' during maintenance practices and aircraft design phases respectively?

1.3.3.2 Research hypotheses

As a research in the air accident and incident causation field, this study adopts the below stated hypotheses and works to verify them:

Hypothesis 1

'*Human factors errors within aviation maintenance industry can be more effectively managed by applying proactive monitoring and early detecting techniques of error root causes at both organizational and individual levels.'*

Hypothesis 2

'An aviation maintenance task can be executed at a significantly higher level of safe performance such that human-induced undesired outcomes would almost be nil if possibilities of human error that can be initiated due to any design features associated with that task are eliminated'.

Hypothesis 3

'An aviation MRO can operate at a significantly higher level of safe performance such that human-induced undesired outcomes would almost be nil if the existing unseen accumulation of mutually- interrelated root causes that lead to maintenance human errors are eliminated'.

1.4 Overview of research methodology

The current work applies the Human Error Risk Management for Engineering Systems (HERMES) methodology first introduced by Cacciabue (2004a,b) for analyzing the HMI in complex contexts. This methodology is structured in a number of steps to preserve the basic requirements of congruence and consistency between both types of retrospective and prospective studies as well as to underpin the correspondence between recurrent HMI analysis and practical system safety and integrity. The retrospective (investigative) and prospective (predictive) phases of the methodology are highly mutually inter-linked with huge volume of data exchange taking place in between.

In this research, the impact of human reliability on aviation maintenance safety is investigated. A comprehensive literature review is conducted to explore the limitations of quantitative approaches in addressing maintenance human factors issues, as well as to discuss various concepts and tools furnished for predicting and monitoring maintenance safety variables. A new model to represent the initiation and propagation of crucial maintenance error within aviation maintenance environment is introduced as the 'Swamp' model. This led to the introduction of the industrial proactive AMMP. AMMP is a holistic hybrid retrospective/ prospective integrated process that may be simultaneously and collectively implemented by main industry stakeholders: regulators, manufacturers and aviation maintenance organizations. The aim is to proactively monitor the existence of human error causal factors that are initiated during design practices, manufacturing processes, or at later stages due to workplace or workforce conditions. As a result, such causal factors can be gradually eliminated to reduce the overall risk of maintenance errors.

This generic AMMP model is based on a Root Causes Existence Scale (RCES) and a comprehensive socio-technical user program built applying the fuzzy Analytic Network Process (fuzzy ANP) theory (Dagdeviren & Kurt 2008). A total of 870 different assessment criteria were designed and then in-built within the software thus mapping the outcomes of the retrospective error causal factors investigative studies.

1.5 Key results and contributions of this research

1.5.1 Key outputs

This research worked to achieve its announced objectives through accurate application of the HERMES methodology. The following deliverables are claimed to be satisfied:

1. Mechanisms of aviation maintenance error initialization and propagation are totally understood. On top, new models are introduced within the research to set the scene for further achievements in this field.
2. The AMMP is introduced as a strategic concept comprising practical tools to proactively eliminate root causes of maintenance errors. Further more, this process, with its dedicated software coded ErroDetect, can be utilized to help practitioners scientifically identifying the 'Duplicate Inspection' lists for each aircraft type as well as enhancing the design for maintainability process in much earlier stages.

3. All the three above mentioned hypotheses are verified to be true. Details are discussed through out this thesis chapters including the final conclusions.
4. The current research enjoys several elements of originality as well as multiple series of new introductions as will be better discussed within the following chapters. A final brief listing of these novelties can also be seen within the research final conclusions.

1.5.2 Contribution to knowledge

The current research claims to have added the following contributions to the pool of human knowledge in the field of aviation maintenance human factors:

1. Setting bases of new knowledge of maintenance error causes initiation and propagation that comprised the introduction of the generic Maintenance Error History (MEH) and Swamp models.
2. Introducing AMMP strategic concept and its tools for proactive treatment of aviation maintenance errors, thus significantly improving aviation safety.
3. Introducing new algorithms within fuzzy logic arithmetic to resemble the role of expert's systems, thus significantly elevating practicality and flexibility of such fuzzy ANP applications.

1.6 Thesis Structure

This thesis is composed of 10 chapters covering all activities carried out as governed by the adopted methodology. The thesis is laid in four successive parts mapping the various folds of the methodology. Figure 1.1 illustrates the general layout of this thesis put in contrast to the various stages of the applied methodology.

Part one of the thesis comprises the first three chapters that exhibit fundamental studies required both by the methodology as well as the research academic terms of conduct. Chapter 1 is an introductory opening to the conceptualization of the research theory and practices. It illuminates the overall spectrum of the research design, and reflects some of its outcomes. Chapter 2 consults a significantly large number of previous publications taking aviation safety, accidents and incidents causation, aviation maintenance, human factors, and human error as major leading keywords. The generic notions and speculations of research methodologies are examined within Chapter 3 that discusses and describes the front-end design of this research. The selection of HERMES methodology to incorporate this research is abundantly justified within this chapter as well. The thorough literature review in Chapter 2 is the central mast of the fundamental foundation stage on which the adopted methodology is built.

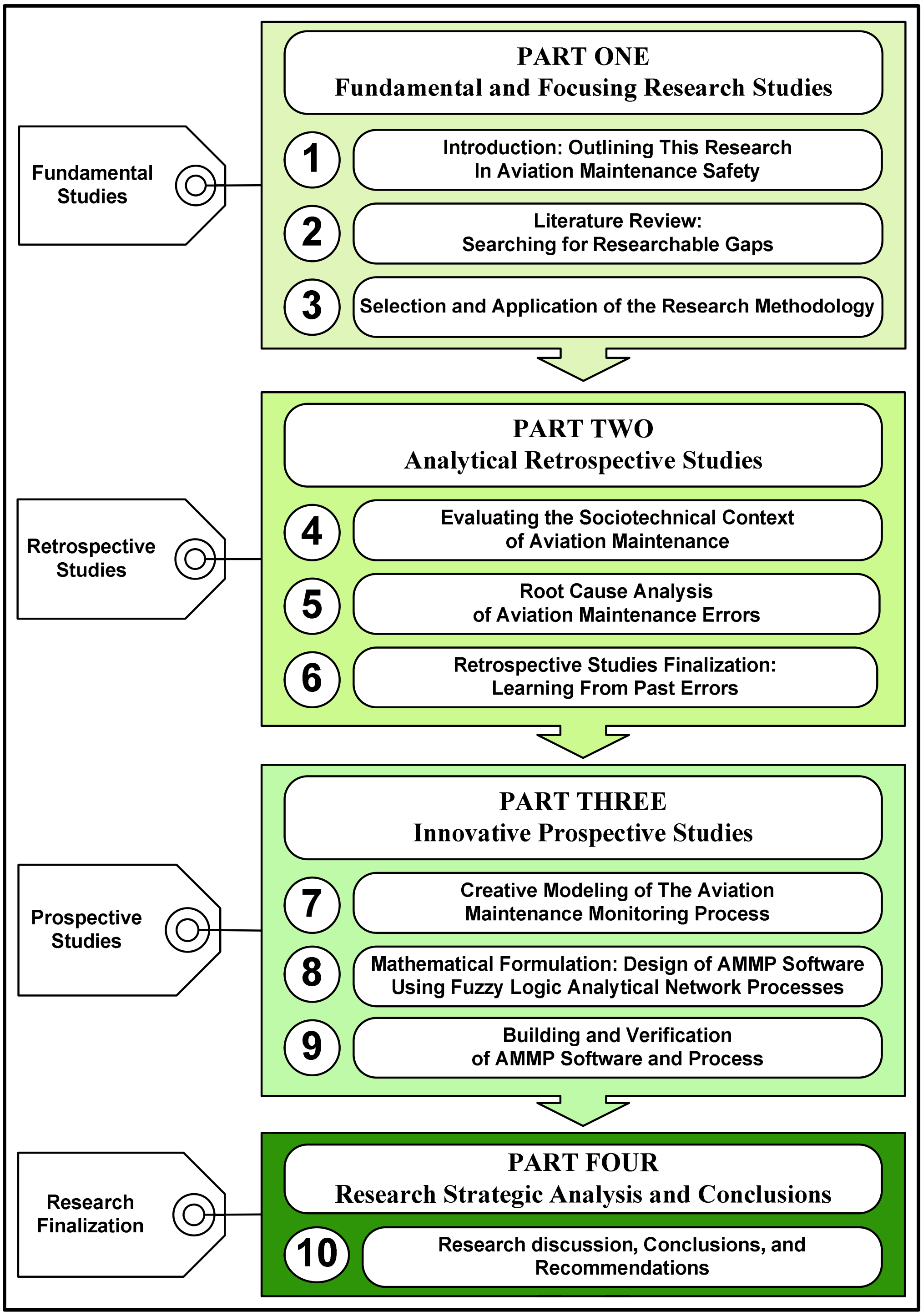


Figure 1-1 General arrangement of the thesis structure as indicated by the applied methodology

The Second part of the theses is the manifestation of the retrospective studies folder of the methodology. Successive three chapters form this part. Chapter 4 deeply explores the sociotechnical environments within the aviation maintenance industry. Elongated ethnographic studies, in the course of which this writer recalls his two decades of participant observation experience, summed out most of the ins and outs of this industry. Maintenance task design techniques are also present. The fifth chapter investigates multiple mechanisms of aviation maintenance initiation, propagation, and consequences. Chapter 6 sums findings of the previous chapters in order to furnish the most optimum techniques that can be implemented as proactive solutions to the standing problem.

The prospective phase of the methodology activities are covered by the next three chapters of Part Three. Chapter 7 starts the innovative introduction of error management models as well as the strategic concept of the AMMP. Chapter 8 is fully dedicated to the mathematical formulation of the AMMP tools through enlarged fuzzy analytical network processes, while Chapter 9 explains the overall building of the AMMP tools and their simulation and verification processes with total reference to industry. Part four encompasses the last tenth chapter, which is a conclusive one that provides overall strategic analysis of the research methods and findings. Conclusions and recommendations for further works are then furnished as the final crease of the thesis.

1.7 Chapter summary

This chapter highlighted the outlines of this research in aviation maintenance safety. Main aspects of the research rationale, aims, objectives applied methodology are paraded an in-built part within the overall conceptualization of the advocated research itself. The importance, relevance, rigorousness, and innovativeness chances associated with the spotted research gaps were listed .This is coupled with brief presentation of salient results and contribution features.

2 Literature Review: Searching For Researchable Gaps

"Research is to see what everybody else has seen,
and to think what nobody else has thought"
Albert Szent-Gyorgyi, 1937 Nobel Prize for Medicine, 1893-1986.

2.1 Introduction

2.1.1 Review targets and scope

This research's front end design activities were started by acquiring the basic know-how of successful sociotechnical research implementation. This was achieved through methodical digestion of relevant literature, experts' consultation, as well as close interaction with industry. The main purposes of this literature review were to obtain the basic knowledge and to update existing information on various related topics that form the background for this research. By knowing the scope and orientations of the recent / current works in the aviation safety generally and helicopter maintenance in particular, the gaps to be addressed are more likely to be exposed and thus treated. The review also scans a wide range of relative methods and techniques applicable to the research as well as highlighting various data sources and analytical tools.

The scope of this review, more precisely, covers areas of relevance such as aviation accidents and incidents causation, safety concepts, organizations and safety, aviation maintenance goals, techniques, and over- sighting. Other basic streams covered by the review address the elements of human factors, human errors in maintenance, individual and organizational errors, human factors models and frameworks, human risk and reliability concepts, and human factors errors in helicopter maintenance in narrower focusing. Figure 2-1

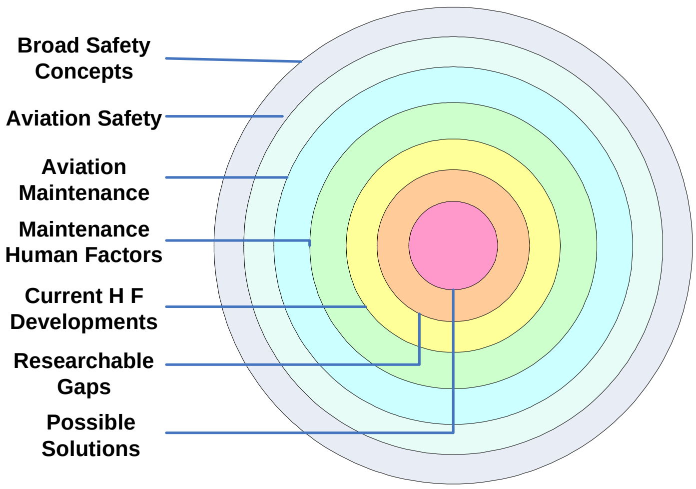


Figure 2-1 Conceptual scoping of the literature review for the current research

gives a conceptual representation of this review. In this figure, mutual influence is witnessed between each two successive zones in both inward and outward radial directions.

2.1.2 Research review methodology

As a part of the main research methodology, an inter-connected sequence of practices was conducted to set the main design of the proposed study. This sequence, as illustrated by Figure 2.2 included a main enlarged initial literature review for further familiarisation with subject field, appreciation of current knowledge stock, and scanning for viable research gaps. The importance, relevance, rigorousness, and innovativeness chances associated with the spotted research gaps were verified to demonstrate high levels of required research scholarship and methodological excellence. The main theoretical hypothesis was then set, followed by research aim and objectives. These objectives were then resolved through careful scientific interpretation into research questions. Main features and capabilities of the required methodology to answer these questions were then determined.

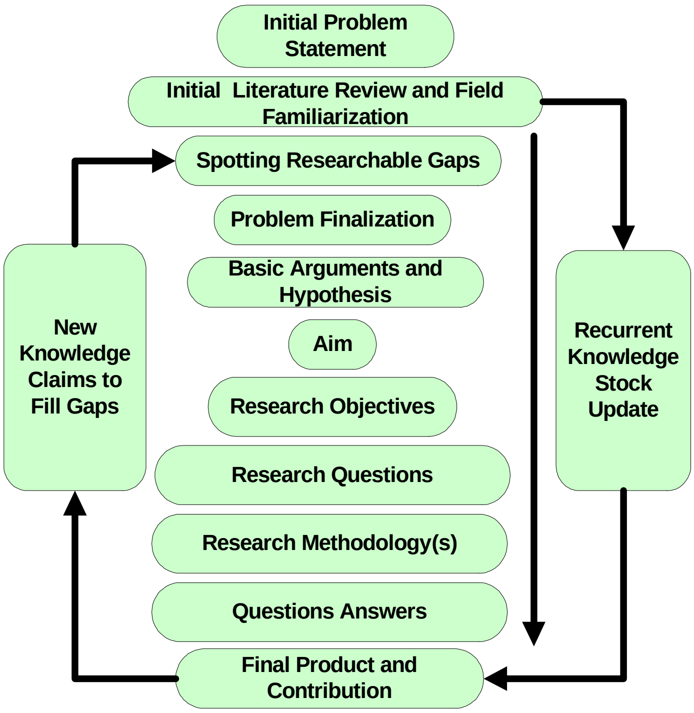


Figure 2-2 Literature review as a main stream of the research methodology

2.1.3 Review focus

As a genuine part of this methodology, a focussed continuous process of knowledge-updating took place throughout the successive research stages as designed. This comprised a variety of information and data sources. However, the dominant part of this update was an unbroken follow-up to emerging literature within the whole industry that discussed maintenance human factors. This is also indicated by Figure 2.2.

2.2 Aviation safety

2.2.1 Aviation incidents and accidents: Trends and causation

A recent statistical study by Boeing (2004) showed a total of 1371 commercial fleet aircraft fatal accidents worldwide for the years 1959 to 2003. The study further emphasized the fact that although the overall rate of fatal accidents is declining but the overall number of fatalities is growing due to the vast expansion of the world commercial air lift capabilities. Similar statistical behaviour of aviation accidents trends was also observed by EASA (2006). A moving 10-year average of commercial airliner fatal accidents worldwide is calculated to be 36 accidents that resulted in 1005 fatalities per year.

According to Patankar and Taylor (2004 b), it is widely accepted that about 12% to 15 % of all commercial aviation accidents are attributed to human errors that occur during maintenance tasks execution. The authors also showed that maintenance activities can account for as much as 20% of an operator's direct operating costs and have remained at this level for many years. Additionally, errors in the maintenance process can impact on aircraft safety. The occurrence of a need for unscheduled maintenance can introduce costly delays and cancellations if the problem cannot be rectified in a timely manner. Hale et al (1997) discussed variety of factors contributing to accidents in complex safety-critical systems such as aviation, they gave thorough presentation of the nature, goals, and methods of pro-analysis of safety events. They also concluded that generic social characteristics like shame, blame and liability usually have vital role in shaping the overall organizational safety culture.

Aviation accidents are defined in many different ways in accordance with the definer’s interests and intellectual requirements. Strauch (2002) presented many of those, including the official definition of aviation accident given by the International Civil Aviation Organization (ICAO): “An occurrence associated with the operation of an aircraft which takes place between the time any person boards the aircraft with the intention of flight until such time as all such persons have disembarked, in which: a person is fatally injured, or the aircraft sustains damage or structural failure, or the aircraft is missing or completely inaccessible”. Other government or international agencies use similar definitions, even though specific to the particular domain. It is well accepted that a better understanding of accidents causation scenarios allows for better development of preventive measures (Pajan et al. 2006). Various factors and conditions were highlighted throughout literature as causal contributors to aviation accidents. In this regard, increased sleepiness, physical and mental fatigue, and decreased performance initiative were discussed by Tvaryanas et al (2006).

Matthews (2002) examined the relationship of 17 broad indicators of social, economic, and political conditions to hull-loss aviation accident rates in 164 countries and 13 regions. He confirmed that national wealth is a major factor among several others that correlate with national and regional accidents rates. His core finding was that broad social and economic factors and general measures of the state of governance are strongly correlated with aviation safety.

Li, Wen-Chin and Harris (2006) provided an understanding, based on empirical evidence, of how actions and decisions at higher levels in the organization result in operational errors and accidents. Organizational processes, in deeper analysis, comprise root causal factors promoting accidents from initial stages of the design phase. Kinnersley and Roelen (2007) investigated the validity of the claim that 60% of accidents root causes arise in the design stages. Their results later showed that for aviation and nuclear industries accidents, about 50% have a root cause in design which is, still, a significant score. The rates in both industries (being 51% and 46% respectively) are remarkably similar. Additionally, it is showed that while quantification of rail data was not so consistent, but design was a major contributor to main recent rail accidents. Vast number of publications attributes aviation accidents, as well as accidents in similar safety-critical industries, to human factors associated with personnel activities and / or personnel existence in-built within those systems (BASI 1997, Adams2006).

Oppositely, Australia’s fatal accident rates for fixed wing aviation is generally stable, while the rate for private aviation there is further declining for the period 2001 to 2005, this positive aviation safety record is attributed to a set of conditions and policies that significantly enhanced the Australian aviation safety performance (ATSB 2006, 2007a, Braithwaite et al. 1998).

2.2.2 Broad safety concepts and functionalities

In a broad conceptual definition, Petersen and Aase (2007) interpreted safety as “a collective competence that is learned and maintained in local workplace”. Patankar and Taylor (2004b), more previously, gave similar brief definitions of safety in general context such as: “safety is freedom from risk”, and also “safety is management of risk within a value that is acceptable by the society”. They indicated, particularly addressing the aviation safety issue, that there are three main categories of safety to consider:

a. Personal safety: Usually refers to personal injuries happen to individuals while at work on ground. This is a ground safety committee’s duty to consider.
b. Aircraft safety: Issues encompassing incidents such as incorrect or incomplete repair, incorrect documentation, or ground damage to aircraft outside of the ‘chocks – off’ to ‘chocks – on’ period. This is an airworthiness committee focus.
c. Flight safety: Includes events that occur between ‘chock - off ‘and ‘chock- on’ essentially, that is the duration of a flight. Hence, such events affect both aircraft and individuals, a flight safety committee concern.

To face the increasing pressure for further efficiency and growth in both passenger and freight traffic volumes, a high level of safety in air transport must be maintained. The development of a safety management system is recommended in order to develop appropriate measures to ensure that safety and security targets are set and optimised for all the areas of the air transport system (EU-JRC 2003).

De Graff (2001) predicted that as the air transport industry will continue to grow, the public perception will be focussing on total accidents and fatalities rather than the relative safety that the industry is achieving now. Further ambitious new aviation safety targets are being set which will certainly require more improved knowledge of accidents causes and better understanding of the effects of new technologies and procedures. In the same direction, Sanfourche (2001) highlighted that a ‘Vision 2020’ Position Paper gives an overall prediction of the near aviation future as: “In 2020 the skies are safer than ever because safety has remained the top priority of the aircraft builders and operators and of air traffic managers”. To actually keep safety as a permanent top priority as planned, Sanfourche recommended that various contributing parts of the aviation industry: Aircraft, engines, equipment, air traffic management, communications, navigation, surveillance, airports, maintenance, pilot training, human factors and other aspects should be collectively and legitimately kept at optimum standards regarding safety.

Hollnagel (2007) analysed the common safety model that is based upon eliminating system hazards, preventing incidents and accidents triggers, and protecting against bad outcomes. He further discussed the various physical, functional, symbolic, and incorporeal types of barriers necessary for both prevention and protection safety strategies mentioned.

2.2.3 Individual and organizational errors

According to Reason (1997), there are two types of accidents: those that happen to individuals and those that happen to organizations. Organizational accidents, though very rare, but they are often catastrophic and have adverse effects on uninvolved population, assets, and the environment. They always take place within complex modern technologies such as nuclear power plants, commercial aviation, petrochemical industry, marine and rail transport. Reason (1997) indicated that there must be some underlying principles of accident causation, and that organizational accidents may be truly accidents in the way in which the various contributing factors combine to cause the bad outcome, but there is nothing accidental about the existence of these precursors, nor in the conditions that created them. This theory can be highly illustrated through the hazards, defences, and losses relationship as shown in Figure 2.3.

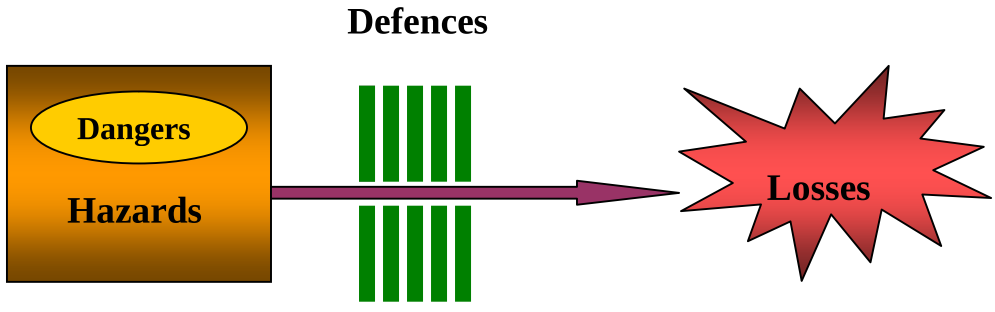


Figure 2-3 Relation between hazards, defences, and losses (Reason 1996)

This theory adopts the idea that all organizational accidents entail the breaching of barriers and safeguards that separate damaging and injurious hazards from vulnerable people or assets (collectively termed as losses). This theory is so famously known as the ‘Swiss Cheese’ model of accident causation. The barriers mentioned can be breached by three types of factors: human, technical, or organizational. These form the overall accidents background. These factors are totally governed by two processes common to all technological organizations: production and protection. The ‘Swiss Cheese’ model was recently revisited by many safety professionals including Reason himself (Reason et. al. 2006) who concluded that this model, though widely used, has its limitations in the practical field where the concept of barrier provides only one of the few opportunities to model interaction and complexity in high risk domains.

Le Coze (2008) discussed the organizational dimension in accident scenarios and their following investigations. He analysed various theories and models utilized to pinpoint the ever challenging organizational inputs that – unintentionally- set path to undesired safety occurrences. Le Coze introduced a graphical classification that helps locating appropriate approaches to tackle each event through adopting 'the model that should fit the data' or the 'data that should fit the model' principles extracted from the human and social sciences theorising and interpreting process. Events investigation usually follows a backwards orientation in the time scale through various levels of the organization. This is illustrated by Figure 2-4 below.

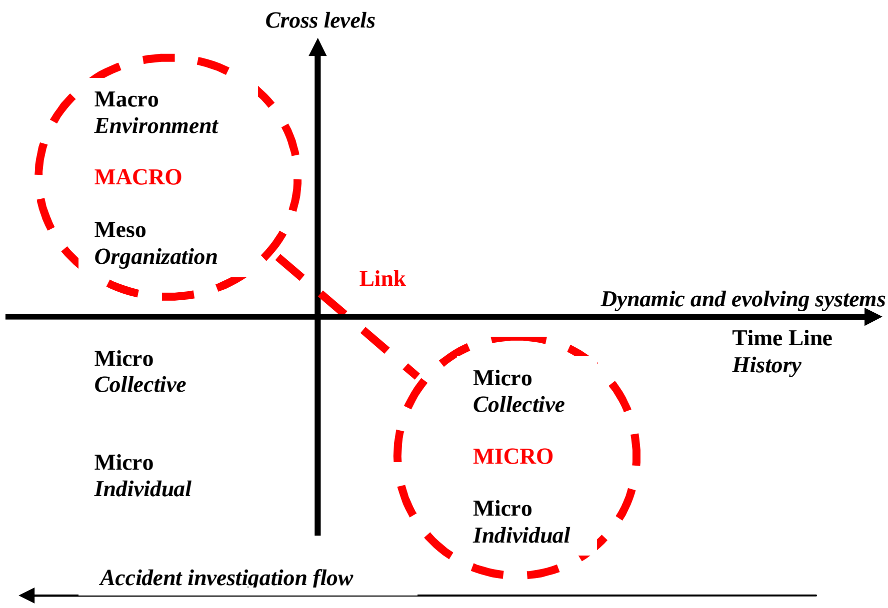


Figure 2-4 Events investigation at higher and lower levels of organizations (reproduced from Le Coze 2008)

Many writers (Yeray et al.2002, Fogarty 2004, Etienne 2007, Grabowiski 2007) call for developing better understanding of 'organizational accidents' and to transfer the overall knowledge of organizational reliability from the retrospective post-accident analysis to a more proactive procedures. It is assumed that the safety management process is influenced, together with other factors, by the type of understanding held when humans try to identify the ways leading to optimum safety management. If further efficiencies and better productivity are expected in the near future from the aviation maintenance sector for instance, then this must not come at the cost of reduced safety margins. This can be achieved by thorough digestion of compiled variables such as moral, psychological health, turnover intentions, and error management. Thus active intervention strategies can be built to avoid future adverse occurrences.

A similar argument is given by Korvers and Sonnemans (2008), they showed that reoccurring disruptions during daily operations were present in the path of a large number of accidents recently occurred in the process industries. The reoccurring disruptions can be seen as pre-warning signals. Their existence forms a gap with the common proactive safety indicators. This gap is represented by the information already available in daily operation, of which it is unknown (to the local assessor) that it may lead to unsafe situation or accident. The authors thus suggested that these reoccurring events should be analysed, weighed, and then included in the safety indicators list of the given organization.

Patankar and Taylor (2004b) defined organizational norms as "the unwritten rules, the way things are actually done". Some of these norms are positive, but most of them are negative. Aviation maintenance personnel are quite resourceful and take pride in being able to do their job. So when their company is unable to provide them with the ideal equipment or manpower, they improvise. For example, a company may have a policy that require the mechanics to use wing-walkers before they push back an aircraft from gate, however, in reality the company may never allocate enough people to allow for wing-walkers, therefore, the organizational norm is formed. In majority instances, such norms may not result in any undesirable consequences, however, such actions do perpetuate the continued use of improper practices and tools.

2.2.4 Organizational safety culture

Merritt and Helmreich (1995) defined culture as "the values, believes, rituals, symbols and behaviours that we share with others that help define us as a group, especially with relation to other groups". Culture gives cues and clues on how one can behave in normal and novel situations, thereby making a system encompasses that culture less uncertain and more predictable. The authors further defined two layers of culture: The surface structure that contains the open observable behaviours and 'outlook' such as uniforms, signs, logos, and documents. The deep structure which is the core part of the culture that consists of the values, believes, and assumptions forming the base for surface structure and draw the outlines that shape the members behaviours. As a result, it is the organizational culture which eventually crafts the perception, relative importance, and member's activities regarding safety.

Reason (1997) further indicated that organizations can be positioned within a theoretical two polar safety space. An organization's position within the safety space is determined by the quality of the processes used to combat its operational hazard. The two extreme poles of this safety space is that an organization being either of high resistance or high vulnerability to withstand operational hazards. The closer the position of the organizational behaviour to the resistance pole, the more safely is its overall performance. This exactly applies to maintenance organizations. This is illustrated by Figure 2.5.

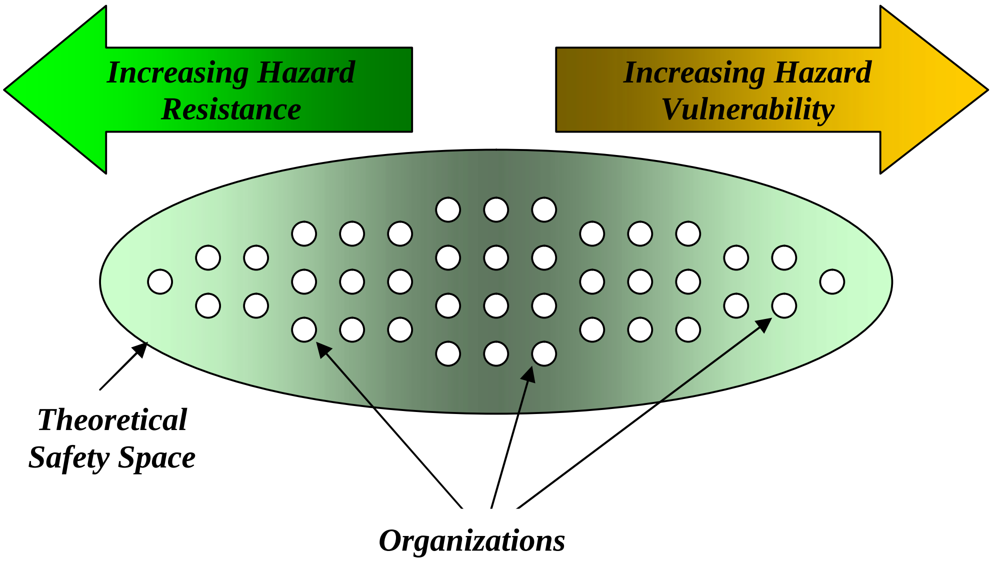


Figure 2-5 The safety space and location of organizations within it (Reason 1997)

Many investigative works (McDonald et al.2000, Reiman 2007, Gill and Shergill 2004, Choudhry et al. 2007) studied the relation between safety culture and applied SMS's in various aviation MRO's, emphasis was drawn to how different organizations manage safety and the position of human factors within that management. Differences in safety attitudes and climate were found between various occupational groups even within the same organization. It is argued that when complexity of work, technology, and social environment increases, the significance of the most implicit features of organizational culture (as a means of work coordination and achieving safety and effectiveness of the activities) also increases. The common attributes of safety culture usually comprise good organizational communication, good organizational learning, high individual responsibility, and high senior management commitment to safety (Sorensen 2002, Kind 2004). Li, Wen-Chin et al. (2008) hypothesized that different cultures will show different patterns in shaping causes that lead to accidents. Reiman and Oedewald (2007) studied the organizational assessment in sociotechnical systems. They showed that current models of safety management are largely based on either a rational or non-contextual image of an organization, and the sociotechnical systems are socially constructed dynamic cultures. It is concluded that: to assess a complex sociotechnical system, an organization's core task must be appreciated and understood as a base on which to build the system's effectiveness and safety.

Wilpert (2007) raised the question of where should the system boarders be when it comes to the safety culture issues. He then derived a conclusion that safety related regulatory bodies and their regulatory styles are usually genuine parts of the safety critical system under analysis due to their indisputable influence on other input variables, thus the usual reduction of the regulator role when adjusting the safety equation of a system, aviation maintenance for instance, is undoubtedly questionable. In an addition to the importance of the regulation process, Arocena et al. (2007) found that the emphasis of the innovative dimensions of prevention activities, the intensive use of quality management tools, and the empowerment of workers are all factors contributing to reduce injuries. On contrast, the implementation of flexible production processes is associated with higher rates of accidents.

Organizational climate, on the other hand, is analysed by many authors throughout the last 20 years. It is being gradually but consistently absorbed, as a concept, by different sectors and levels of industry (Haukelid 2007, Zhou et al 2007, and Pousette2007). Dov (2007) defined the organizational climate as the shared perceptions between members of an organization regarding its elementary properties of policies, procedures and practices. This climate can further be furnished to lower sub-organizational and even to group climate. Safety climate, in this regard, is a particular sub-division that is greatly influenced by the overall complimentary surrounding organizational climate. In the same orientation, Hahn and Murphy (2007) gave a similar definition of the safety climate: They showed that such climate represents a background for the day to day operational practices, and that the commonly-shared perceptions amongst an organisation's staff are usually driven from main input factors including management decisions, safety norms, and the overall organizational expectations.

2.2.4.1 Safety culture change

Taylor and Christensen (1998) discussed the organizational safety change. They showed that management must work especially hard to shrug-off its traditional time-consuming model of safety enhancement that only takes local improvements in isolation. Instead, management must reach for a larger point of view that keeps the best of the old, but puts it firmly within context of whole-system thinking. Two very different choices face maintenance management as shown in the Table 2.1.

Table 2-1 Choices for maintenance management (Taylor and Christensen 1998)

Mechanistic Practices	Systemic Practices
• Treating people as extension of aircrafts, as tools	• Treating people as complementary to mechanical things, as masters
• Seeking to optimize technology	• Seeking joint optimization: social and technical systems
• Maximum task breakdown, narrow specialization working in isolation	• Optimum task grouping, multiple, broad skills, working in teams
• People as expandable, easily replaceable spare parts	• People as key resources with further potential
• External controls: supervisors, outside experts, procedures	• Internal controls: self regulating sub-systems
• Tall organization chart, autocratic style	• Flattened organizational chart, participative style
• Organization's purpose only	• Member's and society's purposes too
• Discouraging innovation, initiative	• Encouraging innovation, careful experimentation
• Completion, gamesmanship	• Collaboration, team work

Grote (2007b) called for 'safe' organizational change regarding safety. She noted that some organisational changes which are not directly related to risk and safety management issues within an organization may eventually turn to be very safety-related events at a time. These changes may be of objective nature such as workload distribution, or of subjective nature such as motivation. Based on that, the assessment of an organization's risks should always make room for change management during large organizational changes. In a wider industrial context, Cooke (2002) argued that organizational change may lead to the requirement of new maintainers' skills, and that interpersonal skill may be an important skill element required.

2.2.5 *Safety measures*

The literature shows many ways of measuring various safety aspects within aviation as well as other safety critical domains. Hobbs and Williamson (1999) surveyed the Australian aviation maintenance personnel regarding safety understanding and practicalities. Statistical results showed that the most witnessed unsafe acts among the maintenance workforce are procedures shortcuts, misunderstandings, and memory laps. In fact most of the surveyed population considered that it was sometimes necessary to 'bend the rules' to get the job done. Further, the maintenance workforce mostly referred to issues of pressure, fatigue, coordination and training as causal factors leading to safety occurrences. In a similar approach Ayomoh and Oke (2006) applied the Hybrid Structural Interaction Matrix (HSIM) tool to prioritize safety parameters in an organization. The technique was introduced to overcome the previous drawbacks of similar ideas, mainly through easier application and reduced subjectivity.

Many models have been introduced as well to measure variables of aviation safety with main concentration on commercial airlines (Villera et al 1999, Liou et al 2007, Shyur 2008, WHO 2006, ATSB 2005). The basic straightforward technique for measuring safety variables (and thus identifying various locations of organisations, nations, or regions within the safety space) is the direct gathering and analysis of statistical data that directly or indirectly influences safety. Such data may include hours flown, departures, passenger movements, aircrafts movements in airports, aircrafts ages, personnel licensing (flight / maintenance) , number and rates of accidents, fatal accidents percentages and fatalities records, airprox incidents, etc. Safety - in broad understanding - can also be evaluated for existence by observing the interrelationships between various civil system sectors such as health, transport, environment, and industry stakeholders.

Nielsen et al (2007) discussed various techniques used to measure both safety culture and safety climate at long and short time intervals respectively. In a deeper context, Cabrera et al. (2007) introduced a new cultural measuring instrument focussing on organizational practices relative to the safety management systems. The core of this tool is based upon a 7-dimensional questionnaire that surveys the empirical structure of safety culture values and practices. The model is elaborated around four quadrants representing organizational culture or models that show shared different values of the organization life, these are: human relations model (clan culture), open system model (adhocracy culture), internal process model (hierarchy culture), and finally rational goal model (market culture). Safety climate, in the other hand, is also subjected to various measuring techniques. Lin et al. (2007) presented a questionnaire-based model to measure safety climate in China. Several critical factors shaping the safety climate were found, including safety awareness and competence, communication, organizational environment, management support, risk judgement, safety precautions and training.

2.3 Aviation maintenance and airworthiness

2.3.1 Basic aspect s of aviation maintenance

Kinnison (2004) gave various definitions of maintenance from previous literature and then gave his own: “Maintenance is the process of ensuring that a system continually performs its intended function at its designed – in level of reliability and safety”. This definition implies the servicing, adjusting, replacement, restoration, overhaul, and anything else needed to ensure the proper and continued operation of a system or equipment within an inherent or designed-in level of reliability and safety

Chiu et al (2004) proposed the use of case-based reasoning concept to provide in-advance support to the aircraft maintenance personnel when tackling technical problems. Reliable and effective support can be provided building on previous repair experience. Case-based reasoning is a continuous learning method that compares previous similar cases to solve the current problems. Generic algorithms were set to enhance dynamic weighting and the design of non-similarity functions. This gives more superior performance when compared to the traditionally known tools that have either equal/ varied weights or linear similarity functions. Further, maintenance scheduled tests frequencies of various helicopter components could be remarkably improved by utilizing new decision making algorithms, the overall target being reduced frequencies of inspections at the same previously designed Mean Time Between Failures (MTBF) (Michlin and Migdali 2004).

Aviation maintenance manpower and hardware chain of supply have captured the attention of many writers throughout the previous decades (Sherif 1982, Fisher 1990, Dukstra et al.1991, Yan et al 2004, Quan et al 2007). Aviation maintenance also has always been constrained by several factors such as rising costs of manpower and material, increased complexity of systems, cannibalization, and increased quality requirements. Several algorithms were developed to handle optimization of various types of inspection and maintenance schedules in regard to such limitations. These maintenance supportive algorithms adopted numerous approaches such as Markov process model, utility theories using Pareto optimal solutions technique, decision support system based on Lagrangian relaxation, and mathematical programming solvers such as Matlab and CEPLEX. The ultimate goal of these tools and many similar others is to provide analytical support regarding decision making with respects of the two extremes: maintenance requirements and maintenance constrains.

2.3.2 Influence of maintenance on aviation safety

The authentic effect of maintenance reliability on the overall aviation safety was discussed (Matteson 1985, Hummels 1997, Sachon and Cornell 2000, Lutters and Ackerman 2002, Sherali et al 2006). It is found that aircraft reliability is the sum of all aircraft's sub-systems reliabilities, these sub-system reliabilities are in turn overall sum of partial components reliabilities. Several concepts attempting to quantify such reliability trains were introduced. These include mechanical delay rates (dispatch reliability), log entries per 1000 flying hours, significant failure rates components, etc. Further, maintenance-related aviation safety is considered to be a direct resultant of continuous interaction between several modular inputs such as management decision variables (e.g. maintainers' level of qualification), flight delays handling policy, maintenance performance quality, and organizational internal and external moral.

2.3.3 Aviation maintenance quality promotion

Many tools were introduced regarding efficiency and productivity enhancement within various sectors in the aviation industry. Orton (1989) initially demonstrated the visibility of utilizing the "Methodology for Generating Efficiency and Effectiveness Measures (MGEEM)" in military terms to measure and increase productivity and efficiency within the US Navy. Two similar military facilities from the same department were set as the experimental and control fields respectively. The MGEEM was fully applied to the first of those. Results showed that productivity increased by 43.7% after the implementation of the model.

More recently, Abeyratne (1998) argued that "the pre-eminent concern of the air transport industry and aircraft manufacturers at the present time is safety in the air". He also showed that this air safety is the first concern of all regulatory bodies headed by ICAO, such that the basic strategic objective of the ICAO's strategic action plan adopted in 1997 was to further improve safety, security, and efficiency of international civil aviation.

Aviation maintenance, as an influential component of the aviation industry, can be highly improved in quality through numerous windows, two basic approaches to these are appropriate personnel training and certification, in addition to performance oversight functions. As for safety inspection and maintenance activities oversight, Luxhoj and Williams (1998) have developed a decision support system for aircraft inspectors. Their research aimed at introducing more refined 'alert' indicators to nationally compare maintenance activities and aircraft performance data in order to signal out any potential problem areas by aircraft type for the use of safety inspectors. Data analysis and integration aspects are carried out in two levels: integration of technical aircraft components that influence the decision support system, and then integration of this decision support system with individual behaviour

On the other hand, Kinnison (2004) also referred, during discussing maintenance oversight functioning, to the FAA Regulation (121-373) that indicates the need for *monitoring* the aviation maintenance activities, to ensure that the maintenance and inspection programs of a given operator are effective enough. In this direction, the FAA's Continuing Analysis and Surveillance System (CASS) is introduced. Many operators interpreted this regulation to mean the establishment of a quality assurance program as well as a reliability program. Essentially the CASS is a program to detect and correct deficiencies in maintenance programs effectiveness and performance. It looks at possible problem areas, determines corrective actions required, and tracks the activities afterwards to determine the effectiveness of the corrections. This is accomplished through data collection and analysis and through monitoring of all the activities in the maintenance function of the operator, its suppliers, and its contractors. The author addresses the oversight functions (within aviation maintenance organizations) required by the CASS. Each oversight function encompasses specific areas of interest such as the quality assurance, quality control, reliability and safety.

2.3.4 Regulating aviation maintenance

Reporting of aviation safety occurrences is one of the main tools that regulatory bodies use to derive required knowledge about specific safety-critical issues or potential problems that need more focussing. According to ATSB (2007b), reporting officially encompasses two main schemes: immediately reportable matters and routine reportable matters. Safety–oriented reporting, as a legal and regulatory requirement, has been adapted by almost all national and international regulators (Chaparro and Groff 2001, Perezgonzalez and Smith 2005, Masson and Koning 2001, Abeyratne 1998). In this regard, much national and international legislation have been put at act such as Transport Safety Investigation Act 2003 (Australia), EASA Part 145.A.60 (Europe), and the Joined Aviation Regulation (JAR) known as JAR.145.60 Amendment 5 (International).

To this end, human input in aviation safety has always been decisively considered by regulators. Human factors training, in this regard, is being increasingly adapted and furnished by almost all sectors of aviation industry. This wave is, to a great scale, being powered by various national and international regulators (CAA 2002 a and b, CAA 2003 a and b, EASA 2004, FAA 2006) . The CAA-UK issued, for instance, many publications in human factors training, human factors influence in maintenance (CAA 2003c), and Safety Health of Aviation Maintenance Engineering (SHoME) tool. FAA, in the other hand, issued the Flight Standard Service Plan for Maintenance Human Factors "to provide an overview of maintenance human factors activity within the flight standard service". The tasks within these standards are grouped as regulatory support and guidance, workforce support, and research and development. Activities are represented in past, present, and future prospectus. A list of facing challenges is also discussed. Similar more recent research took place in various fields, the most common of these are the human factors –oriented analysis of incidents and accidents databases (BASI 1997, Hall 2005b and 2007, ATSB 2007c), and the international survey of the maintenance human factors trends (Hackworth et al. 2007, Johnson 2007). Further details of human factors in maintenance are given through next pages.

2.4 Human factors influence on aviation maintenance

2.4.1 Basic definitions and concepts of human factors

2.4.1.1 Human factors definitions

Human factors have been assigned numerous definitions that comply with various perspectives of areas of interest to different parties and authors. Patankar and Taylor (2004b) listed many definitions for human factors:

- “Human factors are the discipline that tries to optimize the relationship between technology and the human” (Kantowitz and Sorkin 1983).
- “The central approach of human factors is the application of relevant information about human characteristics behaviour to the design of objects, facilities, and environment that people use” (Grandjean 1980).
- “The goal of human factors is to apply knowledge in designing systems that work, accommodating the limits of human performance and exploring the advantages of the human `operator in the process” (Wickens 1984).

The author also provided various definitions of the term ‘ergonomics’. One of these is:

- “Ergonomics is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and methods to deign in order to optimize human well-being and overall system performance” (International Ergonomics Association).

It is also concluded that ‘ergonomics’ is used as the umbrella term in Europe and ‘human factors’ is used as the umbrella term in the USA, both primarily in terms of human -machine environment perspectives.

Taylor and Christensen (1998) similarly indicated that the term ‘human factors’ “denotes a multi disciplinary field devoted to optimizing human performance and reducing human error, it incorporates the methods and principles of the behavioural and social sciences, engineering and psychology”. The two authors further saw the human factors as an applied science that “studies people working together in concert with tools and machines. It embraces variables that influence individual performance and variables that influence team or crew performance”.

Kinnison (2004) gave a brief definition as: “In capsule form, the nub of human factors can be considered as the process of designing for human use”, while Cacciabue

(2004a) defines human factors as: "the technology concerned with the analysis and optimization of the relationship between people and their activities, by the integration of human sciences and engineering in systematic applications, in consideration for cognitive aspects and sociotechnical working contexts".

On anther orientation, Baybutt (n.a) listed the following types of studies concerning human factors and their influence on industrial safety:

- Human error analysis: "The systematic identification and evaluation of possible errors that may be made by operators, maintenance engineers, technicians and other personnel in the plant (examples: using checklists, task safety analysis, and task error analysis)".
- Human factors engineering: "The analysis of the interface of people with the process and its impact on system operation (this includes: human factors engineering review, human factors engineering evaluation)".
- Human reliability analysis: "The assessment of impact of humans on the reliability of process plants (this involves task analysis plus quantification using event and fault trees)".

2.4.1.2 Human factors general concepts

Human factors influence on modern aviation maintenance has been addressed – as a concept – by numerous writers. An overall perception of this can be traced in the obligation of industry to rely on human capabilities whatever the case of the technology advancement. Sherritt (1998) concluded: "Maintaining an aircraft is a complex business, and anything we can do to eliminate complications and reduce stress will be beneficial to all. Modern technology has brought new pressures, some that that our aviation forebears never had to deal with, other oddly familiar. Each new design requires advanced training for the manufacturing and maintenance personnel who will build or repair it. But some of the new technologies, computer software and composite repairs for example, don't lend themselves readily to inspection after the fact. Much as for the tradesmen of old, we are forced back into reliance on the integrity of the practitioner. Back to reliance on the human factors".

Kinnison (2004) indicated that human interaction with systems makes it imperative that the users, operators and maintenance people be considered as parts of the system, and thus can be considered during design, development, and operational phases of the system’s life. Since the effects of human presence are as real as the presence of voltage or mechanical linkages. The human being is an element of the system, when all elements are working properly, the system as a whole work properly. He also showed that human factors in the past has usually referred to physical characteristics of people such as size, strength, physical dexterity, and visual acuity, now other attributes are introduced such as lack of knowledge or understanding of a system, human forgetfulness, or personal attitude as examples.

Cacciabue (2004a) indicated that human factors are a transversal to other well-established sciences, such as physics, mathematics, psychology, and sociology. Human factors extend over four essential domains: engineering, psychology, sociology, and computer science. It requires blending the existing theoretical methods in all those four fields, generating new and specific theoretical formulations and paradigms. Thus it becomes possible to represent real sociotechnical aspects in theoretical forms, which then needs further simplification and elaboration, so as to develop practical applications and quantifications for use in, or assessment of, real working contexts.

Stanton et al. (2005) analysed many human factors methods that can be utilized for Human Factors Integration (HFI) applications. They wrote: “the HFI provides a process that ensures the application of scientific knowledge about human characteristics through the specification, design, and evaluation of systems”. The HFI covers areas of manpower, personnel, training, human factors engineering, system safety, and health hazards. HFI process is intended to be an activity that supports attention towards all of the above six domains during the entire system design lifecycle.

During discussing various aspects of Human-Machine Systems (HMS), Cacciabue (2004a) showed that two main factors have contributed to generating relevant concern and attention on the human factors role in safety: the improved reliability of hardware, and extensive use of automation. In this way the contribution of human factors to safety analysis has been enhanced, and the ‘human error’ has become the primary cause of most accidents in all technologically developed domains. The author defined the HMS as “a composite, at any level of complexity, of personnel, procedures, tools, equipment, facilities, and software. The elements of this composite are used together in the intended operational or support environment to perform a given task or achieve a specific production, support, or mission requirement”. The sociotechnical elements of HMS are organizational processes, personal and external factors, local working conditions, and defences, barriers, and safeguards provisions. In this regard, a Human Error and Accident Management approach (HEAM) can be emphasized through the definition: "HEAM is the variety of methods and measures designed to reduce inappropriate and risky human machine interactions at different stages of a system life time, by offering means and ways to recognise and prevent them, to contain and escape their adverse consequences when full recovery is not possible".

2.4.2 Human factors in maintenance

A considerable proportion of the technical causes of helicopter as well as other aircraft type's accidents and serious incidents are in fact attributed to human factors in various levels within the maintenance organizations. It is generally accepted that maintenance, as a potential environment for critical interaction between humans and machines, attracts a large proportion of human factors induced problems. As introduced in Chapter 1 before, human errors in aviation maintenance are generally discussed through two main approaches: HRA and HEC. It is also understood that identification of the causal mechanisms that led to a human error is the most vital input to that error's rectification (Latorella and Prabhu 2000).

Different human error-inducing factors were discussed as regard to aviation maintenance. There are always multiple publications discussing each and every one of such error causal factors in depth. Some of these problematic maintenance areas are: fatigue (Goranson 1997, Signal et al 2006), language (Drury and Ma 2003), situational awareness and work load (Hendy 1995, Pritchett et al 1996, Endsley and Robertson 2000, Folkard 2003, Gregoriades and Sutcliffe 2007), implementing new technologies (Johnson 2001, Weigmann and Rantanen 2002), non adherence to procedures (Karwal et al. 2000, Patankar 2002), supervisor – subordinate relations (Lee 1995), technical documentation (Chaparro and Groff 2001, Chaparro et al 2002, Chaparro and Groff 2002, CAA 2003d, Rogers et al 2005), aircraft design (Steinberg and Gitomer 1993, Zha et al 2001, Besnard et al 2004, , Bristow and Irving 2007), psychological health (Schofield et al. 2006), and training (Walter 2000, Hall 2005a).

Crotty (2002) gave executive definitions to some aspects involving human factors in maintenance, some of these definitions are:

- Maintenance human factors: “It is the study, compilation, and establishment of principles related to human capabilities and work place aspects relative to the optimum and safe performance of maintenance and inspection work”.
- Maintenance error: “Refers to place, element, activity or inactivity in a maintenance system where a breakdown or error has occurred but doesn’t explain why it occurred”.
- Maintenance error reduction efforts**:** “Programmes of airlines and maintenance organizations that are focussed to identify high error vulnerable areas, take steps to eliminate or reduce these areas and improve the investigation of such occurrences”.

Reason (1997) stated that there are three types of human activities that are universal in hazardous technologies, control under normal conditions, control under emergency conditions, and maintenance–related activities. The last type is the one having the largest human factors problems. The greatest hazards facing modern technologies comes from people, and most particularly from the well intentioned, Greater awareness is needed of the varieties of human fallibility and the error–provoking nature of large parts of the maintenance task, especially during installation or reassembly. Similar attitude was also expressed by McDonald (2001).

Patankar and Taylor (2004a) discussed implementing the human factors in aviation maintenance from three behavioural perspectives, individual, organizational, and collegiate. They referred to NASA’s Aviation Safety Reporting System (ASRS) as well as the JAR66 and JAR 145 requirements. The authors analysed effects of various human factors on aviation maintenance such as the Dirty Dozen (CAA.2003c), and similar lists. They showed that a review of history of human factors in maintenance indicated that their success tends to be attributed to at the individual level, and failures tend to be attributed at the organizational level. The authors also concluded that it is essential that academic community should also incorporate appropriate human factors principles, because sustenance of changes in safety practices is a cultural change, and as such , it needs to take place at both workplace level as well as collegiate one.

Maintenance programmes usually meets the requirements of the manufacturers (i.e. design goals, safety, reliability), and the regulators (safety, airworthiness etc), and then the operator who adds his needs to these requirements. Thus the adjustment of tasks intervals must be in the line with the human capabilities and requirements concerning work schedules, endurance, appropriate tools, documentation, and skill make-up of the work crew to avoid over work, fatigue etc.

Bussalino (1999) discussed various issues concerning human factors in aviation maintenance. He described the theories involved in assessing errors, violations, error mechanisms, types of errors, and various human factors models. Bussalino discussed thoroughly the areas of conflict and corresponding remedy procedures concerned with human factors in aviation maintenance. A survey conducted by the researcher gives comprehensive results concerning the type of organizational cultures, reporting systems, maintenance personnel particularities such as training, age, shift changes and so on. The research further discusses the role of the manufacturers and regulators to enhance safety through optimizing performance in the maintenance side of the industry.

In contrast to helicopters, many studies in the maintenance error causation were already carried out for the commercial fixed wing aviation. Hobbs and Williamson (1995) used the Rasmussen's Skill-Rule-Knowledge (SRK) framework to identify the types of errors made by aircraft maintenance technicians and the systemic or organizational failures which set the conditions for such errors. It is found that errors due to inadequate knowledge were rare and were usually committed by trainee technicians. Absent-minded skill based slips and lapses occurred in approximately 25% of the total incidents studied, while the majority of the errors were found to be rule-based mistakes. These results gave the view from the 'hangar floor', thus the authors cited that a more thorough investigation may have revealed different factors as well.

Schmidt et al.(1998) showed that, during the 1970s through 1990s, human error in naval aviation maintenance did not decline at the same rate as material / mechanical aircraft failure, and in the late part of that period, human error has not only levelled off but may be increasing. This underscores the need to combat more effectively all forms of maintenance human error. The Human Factors Analysis and Classification System-Maintenance Extension (HFACS-ME) taxonomy was introduced to classify causal factors that contribute to maintenance related aviation mishaps. Fogarty et al (1999) investigated the causes of maintenance errors. Analysis showed that individuals were mostly at fault, making errors because they failed to follow procedures and were inadequately supervised at percentages of 32% and 40% of the studied sample respectively. Organizational variables such as pressure created by poor planning were also cited. A Maintenance Environment Survey Scale (MESS) was introduced to measure a range of psychological, physical, environmental and organizational variables considered to be related to maintenance performance.

As an extension to their work, Schmidt et al. (2001) also applied HFACS-ME to analyse 15 of the National Transportation Safety Board (NTSB) reports describing major commercial fixed wing airliner incidents and accidents. A value of 0.85 Cohen's Kappa level of agreement was achieved indicating high suitability of the taxonomy to analyse such types of maintenance - related safety occurrences in both military and civil contexts. This work further emphasised the ability to address the 'why' question instead of only stating 'what' had happened regarding aviation safety occurrences. Results obtained by Schmidt and his group, given in Table 2.2 concluded that HFACS-ME was effective in capturing the nature of, and relationships among latent conditions and active failures presented in the addressed mishaps.

Table 2-2 15 maintenance related aircraft accidents analysis using HFACS-ME (Schmidt 2001)

Main causes of human error in maintenance	Citation of causes within the analysed sample
Supervisory conditions	Cited within 60% of the analysed sample
Organizational conditions	Cited within 26.7% of the analysed sample
Maintenance crew conditions	Cited within 20% of the analysed sample
Environmental and workspace conditions	Cited within 13.3% of the analysed sample
Maintainer errors	Cited within 87% of the analysed sample
Maintainer violations	Cited within 46.7% of the analysed sample

Crotty (2002) indicated that efforts should be directed at improving the investigation process and establishing a data bank of maintenance error causal factors related to accidents and incidents. He suggested HFACS-ME and the Maintenance Error Decision Aid (MEDA) of Boeing to represent major tools for maintenance error analysis and understanding.

Krulak(2004) examined 1,016 aircraft mishaps using the information from the Maintenance Error Information Management System (MEIMS) web-based database. These mishaps, categorised as of high and low severities, were also categorised using HFACS-ME. The population, composed of aviation mishaps between years 1996 and 2000, was examined in order to determine the third level HFACS-ME factors which were present, and the possible existence of correlations between maintenance errors and mishaps frequency and severity. This examination yielded 4,325 individual third level factors which were unevenly distributed.

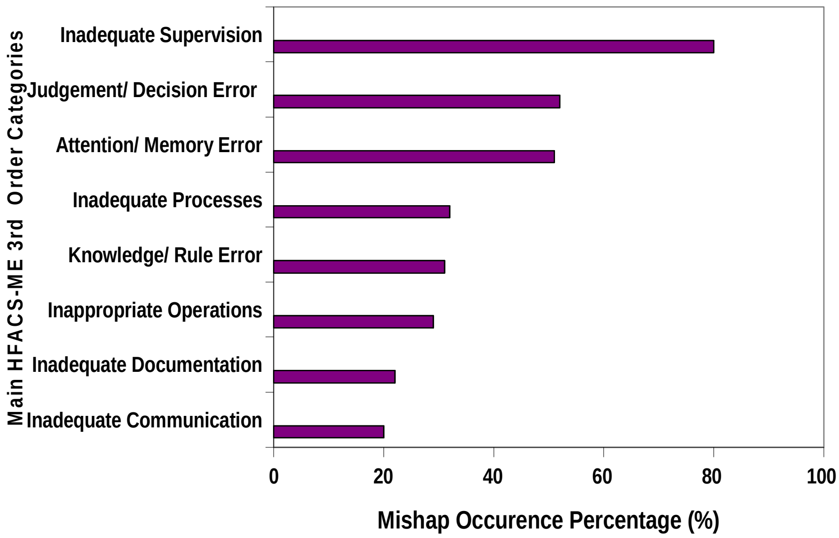


Figure 2-6 Mishaps causal factors analysis using HFACS-ME (Krulak 2004)

The factors of inadequate supervision, attention /memory errors, and judgement /decision errors were respectively involved in 80%, 51%, and 52% of the whole population of mishaps studied. Figure 2.6 demonstrates the uneven distribution while focusing on all factors with at least five times the expected frequency (3%).

2.4.3 Error management

Human error has been addressed in its wide prospective by many authors. Wiegmann and Shappell (2000) provided safety parishioners with an overview of the prominent human error perspective in aviation particularly when being approached through the organization / individual interaction orientation. They also highlighted a set of objective criteria that can be used to evaluate different human error frameworks. Similar overview studies are given by Dhillon and Liu (2006), Walia and Carver (2007).

Hale et al (1997) and Strauch (2002) discussed the long complicated process of organizational learning through backward analysis of accidents and incidents in safety critical contexts. Many other writers discussed the available error management tools or gave various proposals for new measures. Examples of such orientations are the well established error reporting schemes (Fogarty 2003), team error management (Sasou and Reason 1999), layers of protection in process industry for safety enhancement (Baybutt 2002, 2003a,b), cognitive error analysis in incidents and accidents (Busse 2002), managing the impact of safety climate on maintenance error (Fogarty 2005).

As discussed in Chapter 1, Reason (1997) showed that in the organizational scope, error management has two components: Error reduction and error containment. These include, for instance, measures that are required to minimize error liability of individuals or teams, reduce error vulnerability of particular tasks or task elements, discover, assess, and then eliminate error-producing (and violation producing) factors within the work place, etc.

One other relative work was conducted by Ashworth (1998) who gave definite steps to create an error management program. Once appropriate attention has been given to establishing an 'Error Threshold', an error management programme must be defined in a template that provides a road map through the error management process. Primary components of such programme can be:

- Structured human factors- based error investigation system.
- Validation of investigation results.
- Data analysis.
- A management – backed corrective action system.
- A metrics system to track the success or failure of corrective actions.
- A feedback / training system to ensure results dissemination to the work force.

An error reduction strategy must, however, be clearly communicated both to employees and customers if buy in is to be attained. Although improving safety, reducing rework, and enhancing financial performance are valid goals, however, the error management philosophy must be driven by actions and objectives that are tangible to the work force and visible on a daily basis.

A more formal address to error management within aviation maintenance organizations is given by the Safety Regulation Group in UK (CAA.2003c). This regulation, as given also highlighted before in section (2.3.4), addresses safety management from an organizational perspective and describes the elements of a Safety Management System (SMS). Emphasize now is upon human factors and error management programmes which should form significant part of an organizational SMS. The regulating document CAP 716 (CAA.2003c) is structured around the main syllabus topics in EASA GM -145 requirements, thus it furnishes perfect simple guide for human factors training and / or practicing in aviation maintenance.

2.4.4 Risk assessment of human performance

Risk, as a broad concept, has been widely discussed in literature, and it is always considered as a major indicator of the overall system safety. As for aviation, risk in reality is inspired within almost all components of the system: Aircrafts, flight conditions, air traffic systems, aircrafts maintenance, and above all, the human input to all of these. Janic (2000) has overviewed all such measures involved in aviation risk and safety under the ever increasing industry pressures, and proposed a model to quantify risk and safety within the larger civil aviation sectors. Similar perceptions were also highlighted by Abrahamsen et al. (2006), Arezes and Miguel (2007).

Risk has further been studied with regard to maintenance workforce and maintenance activities in a higher resolution. Specific more problematic areas have been afforded deeper focussing in literature such as workers fatigue (Rhodes 2001, Rhodes et al 2003), non-destructive inspections (Aldrin et al 2006), helicopter operational pressure (Hokstad et al 2001), and loss prevention techniques (Lees 1996).

Patankar and Taylor (2004b) discussed in details the concepts of risk and reliability when generally applied to aviation maintenance. They defined the risk as “the probability of an unfavourable outcome”. In aviation industry risk could be expressed in terms of number of accidents per allocated number of flight hours, thus ideally, the safest activity would have a zero probability of accidents. However, safety is dynamic as well as relative because it is the probability of an accident that is acceptable to a given society. In other words, as long as a society perceives the benefits of a certain activity to be greater than the risk of failure in that activity, then that activity will be considered ‘safe’ in that society.

Risk is introduced into the system due to errors committed by every entity connected with aircraft operation. Thus, redefining safety as management of risk within the society expectations: To achieve total safety, either errors must be avoided completely or systemic redundancies must accommodate all possible errors. In aviation industry, risks are controlled largely by specifying the minimum acceptable standards through both national and international regulations.

Kirwan (1998a,b) showed the close relation between risks and error identification. He indicated that the risk assessment process of determining whether a plant is safe to operate or build, or whether it should be altered, shut down, or cancelled, is critically dependent on human error identification. Patankar and Taylor (2004b) discussed types of risks taken by aviation maintenance professionals. Four levels of risks are listed in this domain:

- Good Sarnaritan Risk: an inherent risk present in every maintenance action that involves re-assembly of aircraft parts after job is complete.
- Normalized Risk: Every time a maintainer deviates from the prescribed course of action (procedures) without adverse events, there is reinforcement that perhaps that deviation was acceptable. This is called ‘normalization of deviance’.
- Stymie Risk: It is the situation in which a mechanic needs to remove a part or disable a system in order to gain access to his / her specific task. When a person ‘disturbs’ the original installation or configuration of an ‘interfering part’, that person takes risks of not returning that disturbed part to its original configuration.
- Blatant Risk: these risks are clearly under the individual’s span of control, like performing maintenance without proper training, poor tool control, sign-off work not performed, and use of old parts as references to obtain replacement parts, etc.

Literature is rich of theories and models that propose various approaches to resolve the tight spot of risk associated with the ever growing HMI. Kanki (2002) and Ling Hsu (2004) listed and compared a group of risk analysis techniques, these included PRA, Hazard Mode and Effect Analysis (HMEA), Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Flight Operations Risk Assessment (FORAS), Risk Analysis Matrix (RAM), and risk specific safety index products-performance indicators. Kariuki and Lowe (2007) proposed an approach that integrates human factors into process hazard analysis with a focus on risk identification.

2.4.5 Human reliability

Gertman and Blackman (1994) generally defined the quantitative reliability as "the probability that an item (component, equipment, or system) will operate without failure for a stated period of time under specific conditions". In another hand, Patankar and Taylor (2004b) defined reliability from a technical sense as "the measure of how often a system or a component meets its standards". They further defined failure as "a non-conformance to some predefined performance criterion". Reliability is always defined in terms of failure rates while safety is measured in terms of risk.

Human reliability is further defined as "the probability that a human will perform a given maintenance action to the established standards consistently" (Patankar and Taylor 2004b). The authors also argued that "unlike machines or physical components, human tends to degrade in their performance more than simply fail". Such degradation is not absolute and certainly not irreversible (i.e. can be cured), hence, it is difficult to detect even by the individual who is affected. Some such degradation factors include, stress, fatigue levels, limitation in technical knowledge or skills, ambiguity in /or lack of correct and current technical literature, lack of appropriate equipment and resources, unreasonable environmental conditions, etc'. Human reliability is taken further as a key factor when theorising an answer for the question: Are accidents generally avoidable? Two arguments were introduced in this regards:

- High reliability theorists, they believe that all accidents are avoidable.
- Normal accident theorists, they believe that at least some accidents are unavoidable.

Both sides have strong theoretical foundations and empirical data at hand.

Wong (2002) stated that "human error can never be totally eliminated. The methods used to assess human reliability require considerable knowledge and experience on the part of the user". Many other writers also discussed the concept furnishing dependence of the technical aviation system reliability (aircraft systems reliability) on the human reliability of the workforce in manufacturing, maintenance, and operations phases. Deodatis et al (1996) investigated the reliability of aircraft structures under non-periodic inspection sessions. It is found that human reliability has a direct influence on this as an overall integrated process. Similar results were obtained through other research works regarding human reliability during maintenance activities (particularly inspections) (Narasimha 1977, Lewis et al 1978, Floyd 1993 a and b, Floyd and Schurman 1995, Floyd 1996, NATO 1998, Coolen and Schrijner 2006).

Numerous methodologies were established to quantify human reliability in maintenance, Kirwan et al (2007) generated human reliability data for the air traffic sector. Similar works include, as examples, a computer-based model for system level reliability (Byrd et al. 1992), a non-probabilistic prospective and retrospective human reliability analysis approach (Vanderhaegen 2001), and a safety, reliability and risk management integrated approach (Cox and Tail 1998). Vanderhaegen (1999) introduced the human 'unreliability' analysis method (APRECIH) which was built on the assumption that errors during task performing can result due to three behavioural malfunctioning factors: acquisition related failures, problem solving related failures, and / or action related failures.

Mosleh and Chang (2004) called for a new generation of human reliability models that provide explicit cognitive causal links between operator's behaviour, and the directly or indirectly measurable causal factors of safety occurrences.

Finally, it is generally accepted, referring to the literature, that human reliability can be increased as follows:

- At individual level by better managing the workforce degradation factors.
- At organizational level by building appropriate redundancies in number of systems / components that can perform a required function, or in number of functions assigned to each part of the system.

2.5 Applications of human factors concepts to aviation maintenance

2.5.1 Human factors models and frameworks

The literature is rich of works that proposed several types of theories, methods, models and frameworks that address the human factors in general, and that of aviation maintenance in particular. The Global Aviation Information Network (GAIN) issued a guide to methods and tools for airline flight safety analysis. A large number of all the currently used human factors–related applications are listed and thoroughly discussed. These included safety events reporting, flight data monitoring, risk analysis, and statistical approaches to human factors induced problem (GAIN 2003). Another annotated bibliography was previously given by Weigmann et al (2000). Their listing included human factors errors and accident causation theories, frameworks, and applied analytical techniques. Similar works was prepared by Kontogiannis et al (2000) and Everdij (2007) who compared the available accident analysis techniques for the man - machine critical interaction systems within complete safety methods databases.

In the same orientation, many models were introduced to address the human factors issue. Johnson and Maddox (2007a,b) proposed the 'People-Environment-Actions-Resources' (PEAR) model to explain human factors in aviation maintenance. The model is built on the assumption that human behaviour within this industry is the overall resultant of four interacting components: people, environment, actions, and resources. Hall and Silva (2008) introduced a conceptual model to analyse accidents and incidents in safety critical systems. Other computer based simulator tools addressing the maintenance environment were built by Bellamy et al (2007b) and Truitt and Ahlstrom (2001). On the other hand, Leach (2005) proposed a new approach to maintenance error prediction. The theory of his model is to provide a flowchart-based tool that can estimate the criticality of various maintenance activities such that more focus could be assigned to those tasks, specially those of higher critical consequences, if any human error is encountered when they are performed. A similar model was also proposed by Simmons (2002). Several other approaches were furnished as well by Drury and Prabhu (1996), McFadden and Towell (1999), Fojita and Hollnagel (2004), Clarke (2005), Vinnem and Aven (2006). Large proportion of these mentioned frameworks and models and other ones within literature were introduced, by way or another, as direct or indirect reflection of major theoretical hypothesis' in the field of HMI. These theories represent a base for most of the recent research. The following sections briefly discuses some of these basic theories:

2.5.1.1 Sociotechnical systems

Patankar and Taylor (2004b) reported that "Socio-Technical Systems (STS) is a powerful organizational model describing purposeful work systems in complex environments". STS presumes that any system is a set of parts or pieces that are closely interrelated with reference to their shared environment. STS is a specific kind of system-thinking which helps to determine 'goodness of fit' among people and technology within their surrounding environment. STS's contain three elements:

- The technical subsystem or program tools and processes.
- The social subsystem or people and their roles which are expected to provide judgment and guidance for the technical subsystem.
- The enterprise system which defines purposes, values, objectives, boundaries, and environment.

During maintenance daily activities, there are usually instances in which ambiguity or uncertainty will occur, such cases are called ‘voids’. It is of prime importance to manage such void experiences to prevent errors, and thus to prevent accidents and incidents. An effective STS is the one in which ‘management in the void’ is not only possible, but planned-for through the so called ‘performance by design’.

2.5.1.2 Maintenance resource management

Crotty (2002) defined the MRM as “the training addressing various principles and good practices concerning management of personnel and resources to improve maintenance work efficiency and effectiveness and therefore indirectly improve safety”. Taylor and Patankar (2004 b) indicate that MRM is more than a training programme. It is a tool to provide individuals and groups with the skills and processes to manage errors that are within their control, such as communication, decision-making, situational awareness, work load management, and team building. Part of MRM is training, but part of it must be the application and management of the attitude, skills, and knowledge the training and behaviour can provide.

MRM can be classified into four generations, the first of them was introduced in 1989 with the intention of reducing maintenance errors through improved interpersonal communication and team work. The second generation started in 1992 as a set of focused groups of foremen and mechanics, these programmes led to the ‘on-shift’ meetings and mechanic’s participation in planning technical changes that improved safety. The third generation were essentially programmes consisted of training that enhanced mechanic’s safety awareness and improved individual coping skills in dealing with safety issues. The last generation of MRM programmes currently taking place are characterized by commitment to long term communication and behavioural changes in maintenance. It is now a continuous process of increasing trust among maintainers, their managers, and their regulators that enable them to learn from present by behaviours in order to improver future quality and efficiency.

2.5.1.3 Defence in depth (Swiss cheese) model

According to Reason (1997), ideally all defensive layers would be intact, allowing no penetration by possible accident trajectories, however, in reality each defensive layer has its weaknesses and gaps through which accident trajectories penetrate. These defects (holes) are due to 'active failures' or 'latent conditions'.

Active failures are the unsafe acts committed by individuals that have a direct impact on the safety of the system, thus causing immediate adverse effects resulting in accidents. These acts usually form the final stages of the accident causation sequence. Latent conditions are properties of technological organizations that may be present within them for many years prior to accidents occurrence. These latent conditions (states) arise from strategic other top level decisions of the organizational policy makers. The impact of such decisions spread through out the organization shaping a distinctive corporate culture and creating errors–producing factors within individual or place. Latent conditions are present in all systems. They are an inevitable part of organizational life, nor they necessarily the products of bad decisions, although they may well be. Latent conditions can increase the likelihood of active failures through the creation of local factors promoting errors and violations. They can also aggravate the consequences of unsafe acts by their effects upon system's defences, barriers, and safeguards.

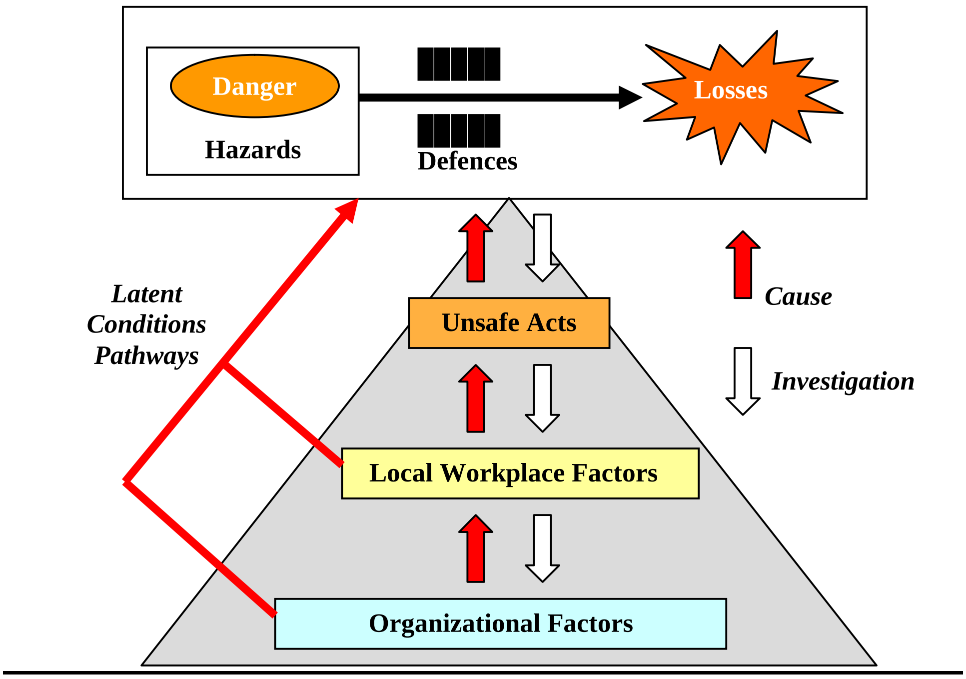


Figure 2-7 Stages in the development and investigation of an organizational accident (Reason 1997)

The combination of latent conditions and unsafe acts usually leads to accidents. Having an organizational accident occurrence, investigation can follow an opposite flow direction from the last active failure that produced the immediate accident down to its roots in a wider organizational concept. This is given by the previous Figure 2.7.

2.5.1.4 The SHELL Model

The SHELL model is one of the two most common theories of organizational accidents used in aviation psychology (the other being Reason's model). SHELL model is first advocated by Edwards (1972) and later modified by Hawkins (1987). The component blocks of the model which need to be matched were interpreted as Liveware (humans), Hardware (machines), Software (procedures, symbology), and Environment (the conditions in which the Liveware – software – hardware system must function).

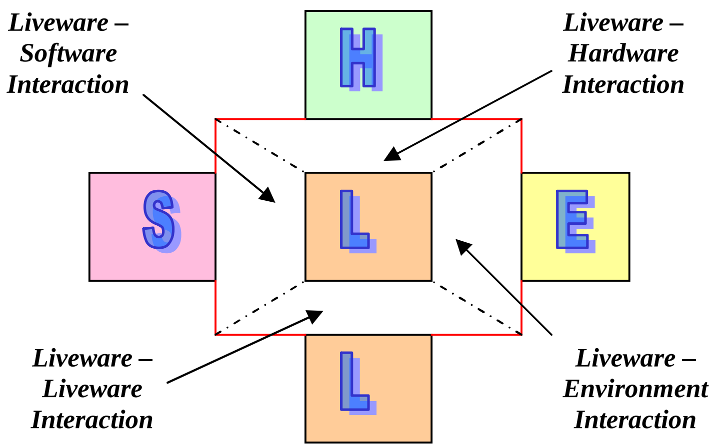


Figure 2-8 SHELL Model (from Edwards (1972) and Hawkins (1987))

Liveware is at the centre model, and it is necessary for the other components to be adopted and matched with this component. SHELL, as in Figure 2.8, is a human factors model that helps understanding errors from a system's perspective. In this model, It is highlighted that most problems or errors occur at the interfaces, and Liveware-Hardware interface has been the focus of most human factors studies, for instance, ergonomics particularly deals with the human / machine interface.

2.5.2 Human factors methods applied to aviation maintenance

Many applied methods were introduced as tools to handle human factors influence during aviation maintenance. Leonelli (2003) discussed the CASS introduced to evaluate, analyse, and correct deficiencies that may arise during the performance of maintenance and inspection activities given in air carriers programmes, and the effectiveness of these programmes. Other applied methods include a generic reliability monitoring system (Tan 1983), a technique for error reduction in maintenance (Tanja 2002), inspection workcard management (Drury et al. 2000), paperwork design (Drury 1998), fault diagrams (Sheppard and Butcher 2007, Remenyte and Andrews 2006), performance optimization (Mjelde 1984, Coolen 2006), expert judgement (Goossens et al. 2007), safety integrity level (Baybutt 2006), and safety events reporting (Sanne 2007).

2.5.2.1 HFACS-ME taxonomy

Human Factors Analysis and Classification System–Maintenance Extension (HFACS-ME) is an error analysis system that is designed to deeper analyse human factors related to aviation maintenance and classify them. This taxonomy was discussed by a number of references including Shappell and Wiegmann (2001), Wiegmann and Shappell (2003), USA Naval Safety Centre (1997), Schmidt et al (1998), Crotty (2002), and Krulak (2004). HFACS- ME was derived from the operational HFACS programme devoted to flight crews. HFACS-ME is a frame work that can be used to identify targets for intervention of errors in the maintenance cycle. It is adapted to capture human factors errors in maintenance and to facilitate the recognition of absent or defective defences at four levels: Unsafe management conditions (organizational and supervisory), maintainer conditions, working conditions, and maintainer acts. Each level of these is sub-classified into three stepping down orders to address the root causes of errors. Order one factors are the broadest in scope, and order three factors were the narrowest (roots of causes). The first three levels each influence the next successive level and they are in rank order furthest from the site of an accident. Failures or absence of defences at any of these levels are considered ‘Latent failures’ which can exist or be dormant for some period of time, even years, before coming into play when being actualized. The last level four, say the ‘proximal failure’ is the unsafe act. This is the only active failure in Reason’s model. This system works to answer the question ‘why’ the accident or incident (related to maintenance) took place? According to Marx (1988) “human factors have been (under-served) by traditional maintenance error analysis systems, they adequately identify ‘what’ happened, but not ‘why’ it occurred. Now this HFACS-ME works to answer this ‘why’.

2.5.2.2 MEDA taxonomy

MEDA is similarly described in many publications, an example is that given by Crotty (2002) who indicated that this tool is a structured process used to investigate errors made by maintenance personnel. It is an industry standard maintenance error investigation tool developed by Boeing 1992. By using MEDA as analytical tool, organizations can learn from their mistakes as a part of their SMS. To carry out a MEDA error investigation, the investigator will interview the worker who made the error to find out the contributing factors to the error. The interview outputs are represented in a specially designed MEDA results form that covers specific error descriptions such as installation error and servicing error.

Further, MEDA identifies a group of contributing factors which negatively affects how worker does the job, thus they contribute to the error, and these factors include:

- Organizational philosophy (policies, procedures, process, quality improvement).
- Supervision (planning, organizing, positioning, instructing, feedback, performance, management, team building)
- Immediate environment (facilities, weather, design, time pressure, team work, communicating, on-the-job training).
- Worker (knowledge, skills, abilities, other characteristics).

Stanton et al (2005) provided a range of human factors methods that can be used in system design and evaluation. The book discussed over two hundreds of various theories, models and tools applicable to human factors analysis, particularly in complex systems. The authors also provided some guiding factors for choosing the appropriate method for each type of analysis, some of these factors are:

- The accuracy of the method (especially if prediction is involved).
- Flexibility of the method (prediction or evaluation).
- The criteria to be tested (e.g. time, errors, communication, movement, usability).

2.5.3 Recent developments in aviation maintenance human factors

As a previous precedent to the works of Simmons (2002) and Leach (2005), Yu et al. (2000) applied a human error criticality model that aimed at improving the assembly process of an initiator. Sorting such criticalities of personnel in work activities gave hints to areas that needed more concentration during the assembly process. The tool also helped reducing production costs by decreasing the overall time and material waste. A brief listing of other recent research includes using of virtual reality technique for aircraft visual inspection training (Vora et al 2002), the development of an aircraft maintenance continuous improvement system (Ward et al (n.a)), using Analytical Hierarchy Processes (AHP) for estimating human error probabilities (Park 2007), a functional integral model of human factors, safety management system and organizational behaviour (Bellamy et al 2007).

The European Commission Research website (2005) showed a variety of projects being conducted in the fields of aeronautics and aviation. One of those is known as the Technologies and Techniques for new Maintenance Concepts (TATEM) project. The objective of this integrated project is to validate technologies and techniques which can be used to transfer unscheduled maintenance to scheduled maintenance, and provide the means to make the maintenance task more efficient and effective. The technologies and techniques to be validated include: Novel onboard sensor technology to gather data from the aircraft systems (avionics, utilities, actuation, engines and structures), maintenance-free avionics, signal processing techniques (e.g. fuzzy logic, neural networks, model-based reasoning) which can be used to convert data into information describing health of systems, and diagnostic methods to identify and locate failures and malfunctions so as to reduce number of incidences of ‘no fault found’. Other techniques are the prognostic methods that provide support for preventative maintenance actions, decision support techniques to provide the maintenance crew with process-oriented information and guidance, and the human interface technologies to provide the ground crew with information at their point of work. Reporting simple safety-influencing shortages and / or near-miss critical occurrences is another vital applied concept. Reporting has always been considered as a powerful organizational learning tool that can – if effectively applied – help reoccurrence prevention. Van der Schaaf (1991) outlined three basic purposes of a confidential incident reporting scheme: Modelling, monitoring, and motivation. Building on that, Harris (1994) thoroughly discussed the importance, functionality, and limitations of confidential reporting schemes and their application to aviation.

ATSB (n.a) introduced in the late 1990's a proactive safety method called Identifying Needed Defences In the Civil Aviation Transport Environment (INDICATE). This was intended to provide critical and continuous examination of air operators' safety systems, as well as reporting possible weaknesses in aviation regulations. INDICATE was first implemented within major airlines in four successive steps: hazards in areas of flight operations, maintenance, and ground operations were identified and ranked in order of importance, then the already-in-place defences were listed for each identified hazard. The effectiveness of each of the defences was then evaluated and all possible deficiencies were pointed out to establish any required modifications or additional controls. INDICATE was preceded by a number of proactive tools (ATSB (n.a), Reason 1997) which are intended to periodically monitor organizational latent conditions that develop safety failures. Some of these tools are: Managing Engineering Safety Health (MESH) of British Airways, Aviation Safety Monitoring System (ASMS) of the CAA- NewZealand, and several others tools in other industries such as well.

Fogarty et al (1999, 2004) developed MESS, a questionnaire that measured variables relating to maintenance activities. These variables addressed organizational and individual aspects such as: Rewards, physical conditions, safety attitude, training, documentation, stress, fatigue, job satisfaction, supervision, turnover intentions, etc. It is found that organizational factors have strong direct influence on individual factors, which ultimately lead to errors. Re-adjusting input variables, an overall maintenance performance can be predicted regarding safety and efficiency of a given organization.

Luxhoj (2002) introduced the Aviation System Risk Model (ASRM) to explore the interrelationships between various organizational, tasks, environmental, and individual variables that usually combine and lead to incidents and accidents. ASRM is based on the 'Swiss cheese' model of accident causation, coupled with the Bayesian Belief Networks (BBN), BBN, in turn, are formed by assigning conditional probabilities to a 'Swiss-Cheese' model-evolved influence diagram as the one shown in Figure 2.9. ASRM handles both qualitative and quantitative methods of tackling various scenarios of errors and their consequential outputs. Numerous variations of defences breach can be applied in order to predict all the relative possible results and their different degrees of severity. This enables closer acknowledgement to the complex interrelationships that mutually influence HMI systems. The model again utilized the contribution of subject matter experts and analytic generalization from relative case studies.

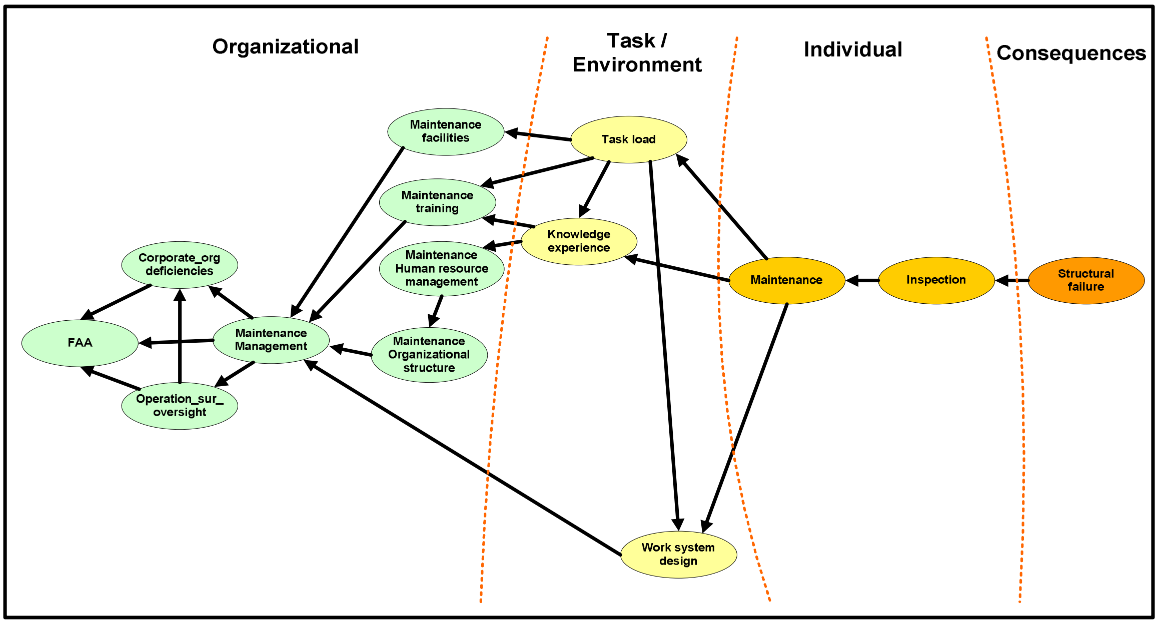


Figure 2-9 Overview of an ASRM influence diagram (Luxhoj 2002)

Cacciabue et al (2003) developed a model and a computer based simulator to analyze and predict the task performance of a virtual aviation maintenance technician. Based on the SHELL and RMC/PIPE models of cognition and human-machine interaction (Neisser 1967, Hollnagel 1993, Cacciabue 1998), this numerical simulator provides a reasonable device to repeatedly tackle the huge volume of data associated with maintenance environment, task properties and requirements, and the Performance Influencing Factors (PIF) affecting the technician behaviour. A model of maintenance action execution is firstly given where the physical and cognitive input parameters of the Aircraft Maintenance Technician (AMT) and the surroundings are analyzed to give a consequential output for each task or sub-task executed. These outputs should be correct actions, omission errors, commission errors, or recovery actions. Various stages of the simulator are given in Figure 2.10.

Thorough mathematical treatment is carried out to calculate each PIF regarding environment, management, and individual properties. The Simulator enables deep analysis and prediction of the AMT possible erroneous behaviour through swift random or manual alterations to various influencing input data that may shape a given task execution. The tool can give detailed representation of the AMT level of expertise, physical and mental fatigue, motivation, situation awareness, skills of communication and other aspects depending on the initial settings fed in or altered later.

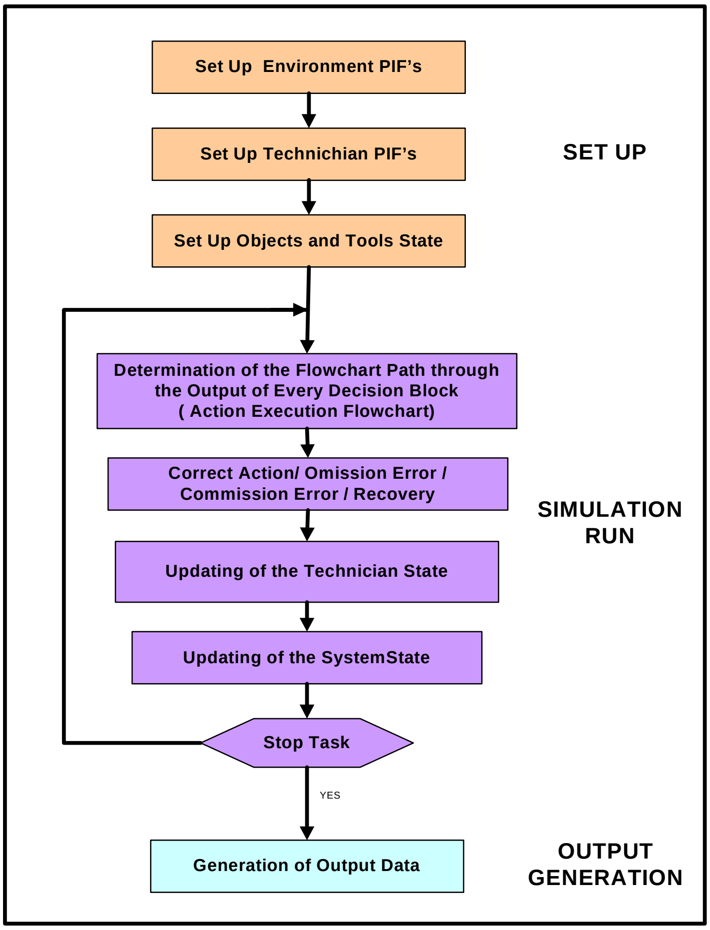


Figure 2-10 ATM Simulator (Cacciabue et al 2003)

This is of great benefit for the aircraft designers, the maintenance procedures writers, and for the overall research and training purposes. The authors discussed the difficulties associated with setting the initial highly complicated input parameters that can resemble real working environment. Other point is the limited possibility to validate the simulation outputs due to lack of actual data from the field that can be used as exact comparators. Team work concepts and software usability features are also to be addressed in later versions of this simulator.

Hsia (2007) gave a tool for safety-based evaluation of the writing quality of aircraft maintenance technical orders. He applied the well known Quality Performance Matrix (QPM) method to capture two main indices, the readability and the importance of technical orders, thus providing clear practical guidelines for urgent and future amendments needed for more reliable technical maintenance manuals. The general

QPM approach, as cited by Hsia, is highly effective in identifying weak, maintainable, or that zone which require various level of re-evaluation. Figure 2.11 represents a typical QPM of a profit-oriented company. Two main indices were considered: Customer satisfaction (along the i-axis) and customer expectations (along the j-axis). According to the rating of each performance variable against these two indices, a relative performance quality zone can be identified for that specific variable. The QPM methodology proved high efficiency in predicting areas of weaker or over-controlled measures that can be addressed by a given firm management for optimum performance. It can also identify priorities at which these out-of-target variables can be handled. In the same sense, QPM approach can be utilized as a safety-related variable analyzer to capture risk describing parameters such as events frequencies and associated degrees of severity.

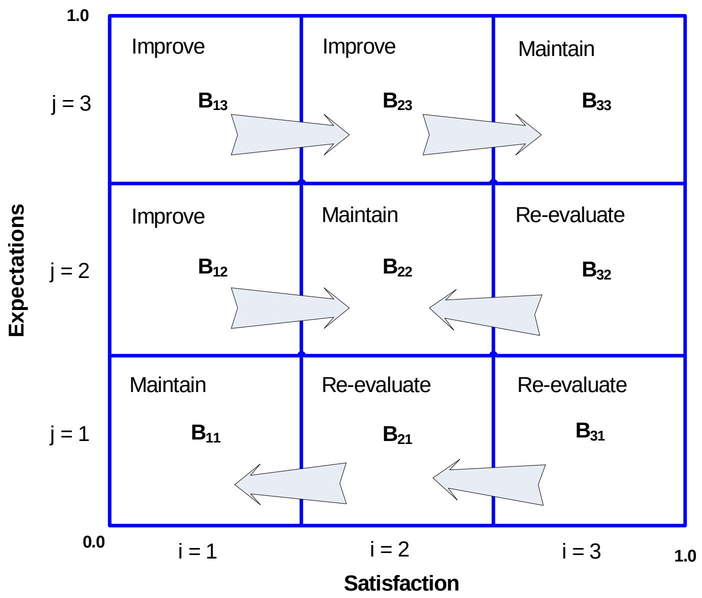


Figure 2-11 Typical quality performance matrix (Hsia 2007)

Edwards (2007) introduced the concept and practicalities of maintenance compliance monitoring within the aviation maintenance environment. He called for the systematic check of the total compliance with established procedures by all the organization staff at all levels such that both process and practice may be insured to be carried out as intended by the procedures. This in turn will greatly help reducing risks associated with the ever existing work-around phenomena, well known at almost all maintenance organizations.

2.6 Current gaps and possible solutions

2.6.1 Limitations of quantitative approaches to address maintenance human factors issues

Harris (1994) discussed issues associated with targeted quantitative analysis of the qualitative data present in the confidential incident reporting schemes like UK-based Confidential Human Factors Incident Reporting Program (CHIRP) and the USA Aviation Safety Reporting System (ASRS). He showed that for a meaningful analysis to be undertaken, incidents need to be given in larger categories to identify the reasons 'why' things happened not only 'what' happened. This should involve deeper representation of psychological precursors within the reports layout. Even after, the process of driving useful quantitative trends by coding qualitative data given in such reports still faces deep inter-reliability difficulties. Categories like 'workload' and 'tiredness', 'cockpit ergonomics' and 'misleading displays' usually fail to attain a desired degree of inter-rater reliability either due to difficulty in distinguishing between such similar pairs of categories, or due to insufficient information given within reports.

Johnson (1999) indicated that human error modelling techniques have had little impact upon improving safety in many industries, he argued that human factors research has failed to seriously consider the problems of actual systems development. Examples of such shortages are the poor documentation and/or presentation of most of these error modelling techniques, as well as the fact that many of them depend entirely upon the skill and intuition of human factors experts. Many companies have failed to positively assess both the merit of those experts and their techniques due to lack of professional accreditation. The published advice on how to apply human error analysis to tackle reality in complex organizations is relatively very limited. Johnson highlighted that models of human and organizational failures will continue to be of little actual benefits until the practical problems associated with their application are solved, some of these problems are:

1. Lack of agreed standards and methods.
2. Dependence on expert's interpretation.
3. No provision of real time prediction.
4. No support for design phase prediction.
5. Focusing on individual errors rather than team failures.

6. Focusing on operational aspects not regulatory requirements.
7. Need to reduce errors during error analysis in the first place.

Johnson concluded that most human factors research helped to improve understanding of human error, but very limited part of this research can be directly utilized - as it is given - to reduce the frequencies of such errors or to lightening their impact in actual industrial sense.

Melloy et al (2000) studied the explicit trade-off between speed and accuracy in the structural inspection of aircraft. They modelled the processes of searching an aircraft structure as sequence of fixations of vision on each area (cell) of the structure. Many factors influence the accuracy at which a defect may be detected. These include the likelihood of the inspector fixating on a given cell, time available for that fixation, complicity of the target and its distance from the centre of fixation. All these factors and others as well greatly influence the conditional probability of defect detection such that certain amount of uncertainty is always expected. This necessitates the introduction of some assumptions in order for the proposed quantification process to be achieved.

Richei et al (2001) introduced the Human Error Rate Assessment and Optimizing System (HEROS) to evaluate and optimize HMI in Probabilistic Safety Assessment (PSA). The authors firstly showed major disadvantages of the current HRA methods as:

1. Lack in quality of reliability data and questionable transferability.
2. Insufficient criteria for choosing the Performance Shaping Factors (PSF's).
3. A scope virtually restricted to skill and rule-based behaviour, and hence a limited capacity for evaluating cognitive behaviour.
4. Human error is considered as a phenomenon with little attention paid to its causes.

The authors, in a trial to overcome such previous shortages, gave a thorough presentation of HEROS as an analyzing and optimizing tool for man-machine systems with computer implementation. HEROS is built on basis of the Technique for Human Error Rate Prediction (THERP) method (Swain and Guttmann 1983) but with more ability to address and evaluate different PSF's to determine the human error probability associated with different tasks execution such that necessary improvements may be implemented. HEROS uses the fuzzy set theory to capture the normal data uncertainties as well as describing the general human behaviour, however, the system limits its handling of the impact of ‘management’ on human performance (e.g. motivation, training, education, decision hierarchy, safety culture, and team composition) to the three basic behaviour categories given by the pre-mentioned SRK model (Rasmussen 1983) namely, rule-based, skill-based, and knowledge-based behaviours. HEROS comprises a simple model to treat the knowledge based behaviour. Again, this model is still to be verified. Lastly, the given system, although having addressed many shortcomings of previous tools, but it still depends widely on expert participation and judgment, the thing that may not always be available for daily practice within industry.

Cacciabue (2004b) divided the methods developed through the last decades to tackle human factors issues, as being introduced within the Quantitative Risk Analysis (QRA), into two generations: The first generation (1970’s to 1980’s), wherein methods like THERP mainly focused on behavioural aspects of human performance. These methods, as means of HRA, provided the required probabilities of human error. However, they strongly focused on quantification in terms of success / failure of action performance with lesser attention to in – depth ‘causes’ and ‘reasons’ of erroneous human behaviour. These methods generally didn’t answer ‘why’ humans made their undesired errors, and thus these first generation efforts stood short to contribute to recovery and mitigation aspects required by typical modern Human Error Management (HEM) techniques. Other shortage of this group is their tendency to capture only static dependencies of the human behaviour rather than addressing dynamic aspects of HMI. The second generation of methods, started in the 1990’s, tried to overcome these difficulties, thus several techniques for identifying causal factors of human errors in complex industries were furnished. The main common problem that faces most of these more modern techniques is the rare availability of adequate supporting practical data.

2.6.2 The need of proactive measures to enhance aviation maintenance safety

A reliability programme for the aviation maintenance is essentially a set of rules and practices for managing and controlling the maintenance programme. The main function of a reliability program is “to monitor the performance of maintenance activities and the associated equipment and call attention for any need for corrective actions, to monitor the effectiveness of those corrective actions, and to provide data to justify adjusting of maintenance intervals or procedures whenever those actions are appropriate" Kinnison (2004). A good reliability programme consists of seven basic elements as well as a number of procedures and administrative functions. Those elements are: Data collection, problem area alerting, data display, data analysis, corrective actions, follow-up analysis, and periodic (may be monthly) reporting. The data collection allows operators to compare present performance with past one in order to judge the effectiveness of the maintenance and the maintenance programme. An alerting system should be in place to quickly identify those areas where the performance is significantly different from the normal. Standard event rates are set according to statistical analysis of past performance, and deviations from those standards (the alert level) are detected and treated as required.

On another side, Patankar and Taylor (2004b) discussed the required steps for changing the aviation maintenance sociotechnical system into a safer one by introducing these three pillars of change:

1. Management support : Successful change requires an equivocal top management support, or making the sociotechnical system safety principles part of the culture
2. Quality intervention : successful change requires a well conceived and relevant quality intervention
3. Measurement and feedback: Successful change requires timely and appropriate feedback through a broad range of measurement and evaluation.

During analysing the effects of human factors and human errors in aviation maintenance and the corresponding responsibilities of various parties, Kinnison (2004) indicated that the airframe and equipment manufacturers have implemented human factors programs to improve design such that maintenance can be performed more easily and reduce the number of possible errors that can be made. Improvement in maintenance manuals and other documents are also under manufacturers' scrutiny, also certain academics are looking into the problem of human errors, but 'operators also have a responsibility to monitor the processes and procedures they employ, and to modify those with respect to human error reduction'.

Cacciabue (2004a) showed that safety assessment can be performed through three quite different perspectives: Design-based accidents, QRA also known as PSA or PRA, and the Recurrent Safety Audits (RSA). The constitutive elements of complex technologies have been identified in the presence and interconnection with four factors, namely: Organizational and culture traits, working conditions, defences-barriers-safeguards, and personal and external factors. He also indicated that the assessment of the safety level throughout a system or organization requires that these four above factors be evaluated at periodic intervals. These types of evaluations focus on data, critical system functions, specific human/ machine characteristics that require particular attention. The safety assessment of an organization generally attempts to evaluate the safety state (level) of an organization with respect to a variety of safety indicators and markers. Cacciabue further showed that the improvement of the safety of a system can not be achieved by tackling actual inappropriate performance that has occurred or may have happened during an accident, but rather by understanding:

- 'Why' operators took certain steps and 'what' are the root causes that may have caused that, or may have generated or triggered-in the failure, or inappropriate human behaviour?
- 'What' forms of inappropriate behaviour was produced, or could result, from such sociotechnical root causes?
- 'How' can systems be developed and human be trained to further enhance safety?

Braithwaite (2001), Nelson et al (1998), Holmgren (2006), Reinman (2007), Shyur (2008), Liou et al. (2007), Edwards (2007) and others as well highlighted the general tendency to start a shift towards 'proactive safety' after the long saturated treatment of reactive accidents and incident investigations, and the expected safety recommendations that usually follow. This proactive perception should not only address but also dominate the overall aviation industry thinking.

As a practical step, Zolghadri (2002) used the flight parameters abnormalities as an early warning and error prediction mechanism for overall system safety enhancement. Beabout (2003) discussed application of statistical process control in aviation maintenance as an overall predictive identifier of problematic areas. Chen and Yang (2004) introduced a predictive risk index for safety performance in process industries. Their predictor is based on regular observation of unsafe acts and conditions. These unsafe observations are then quantified through a simple rating comprising estimates of probability of danger, frequency of work exposure, number of persons at risk, and maximum of probable loss. Similarly, Primatech (2002, 2005) introduced the Layers Of Protection Analysis (LOPA) concept, a simplified risk assessment method that can be applied as a production process to evaluate risk of hazard scenarios, and compare that with the risk tolerance criteria available. LOPA can be seen as an extension to the Process Hazard Analysis (PHA) which usually involves subjective engineering judgements. LOPA is meant to eliminate such subjectivity. Jorgensen (2007) called for systematic use of information from accidents as predictive indicators to prevent reoccurrence.

Korvers and Sonnemans (2008) discussed the concept of Safety Indicators (SI's) within an organization. They defined two types of SI's: Reactive SI's, which are indicators 'after an accident' that are resembled by lessons learned, and proactive SI's 'before the accident' that work to prevent undesired events in advance. Proactive indicators are in turn categorized as predictive (to identify the safety related risks before any operational activity has been executed) or monitoring (to indicate risks from the on-the-job pre-warning signals) as given respectively in Tables 2.3 and 2.4.

Table 2-3 Predictive safety indicators (Korvers and Sonnemans 2008)

<table>
<tr><th>Indicator</th><th>Tools</th><th>Data</th></tr>
<tr><td>'Old' safety risks</td><td>Handbooks,
procedures, standards</td><td rowspan="2">Substance properties,
process conditions,
piping & instrumentation diagrams</td></tr>
<tr><td>'New' safety risks</td><td>Process hazard analysis</td></tr>
</table>

Table 2-4 Monitoring safety indicators (Korvers and Sonnemans 2008)

Indicator	Tools	Data
Safety deviation	---------------------	Near misses, minor safety-related disruptions
Safety measure check	Inspections, observational programmes	Presence and functioning of safety measures
Organizational risk factors	Audits, inspections	Presence and functioning of organizational safety factors
Safety attitude	Safety climate, safety index	Opinions of employees regarding safety of the organization

The authors indicated that in spite of all these tools implemented in various industries to predict or monitor safety status, accidents still happen occasionally. Consequently the two writers derived a hypothesis that: "There still exist safety risks that are not covered by current SI's". To support this thinking they analyzed a large sample of reported accidents and found that most of those were preceded by 'early signals' which can be identified in recent accidents trajectories, but are not covered by current proactive SI's. This is because normally for a' pre-warning signal' to be included in the active SI's lists, it must be either tangible or measurable, which is not always the case. In fact, the used SI's are usually based on 'safety related data' while those pre-warning signals are 'not safety related' or at most are 'indirect safety related data', thus they are normally ignored when setting up SI's, and therefore they are not fed as input for the current active safety tools. Current safety tools, while being very efficient, but they are generally fed only by 'safety related data', thus large amounts of information from these 'signals' are usually left out, a fact that creates 'holes' within these systems. The two writers recommended that focus should be given on reoccurring disruptions that are present in daily operations because they include important indicators of potential accidents. The writers also called for the knowledge regarding this to be mutually extended between various safety-interested actors within industry.

In a forerunner approach, Grabowski et al (2007) discussed the safety indicators application to high reliability virtual organizations. Safety indicators are similarly categorized as lagging (reactive, focusing on organizational malfunctioning with large scale of analysis), and leading (proactive, primarily covering individual to departmental levels with small units of analysis). This is indicated by Figure 2.12. The writers then proposed an approach to adapt the leading safety indicators (objective and subjective) in a collective proactive process to identify hazards, and control risks.

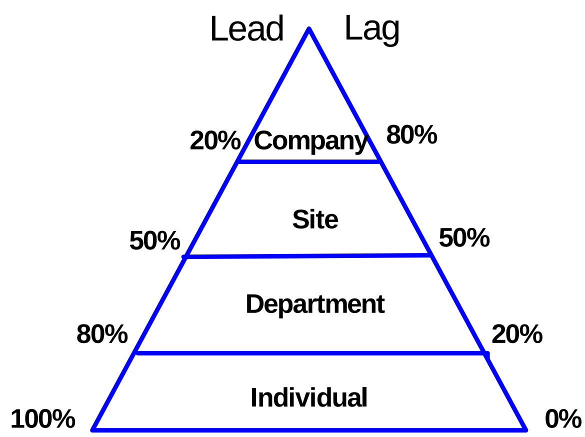


Figure 2-12 Leading and laging safety indicators (Grabowski 2007)

Hollnagel (2007) discussed the relations between risk, barriers, and safety. He concluded that any organization may face all or any of three safety threats: regular threats of frequent presence such that standards could be developed to tackle them, irregular threats which normally are one-off events that can be imagined but can never be faced with known standards, and unexampled events which are virtually impossible to imagine and which exceed the available collective experience. Both irregular threats and unexampled events are infrequent and unusual that they can not be treated in the conventional way of designed barriers. Their distinguishing feature is that they emerge out of situation, thus the ideal way to deal with them is to proactively address the situations and conditions where they can occur.

2.6.3 Fuzzy logic approach to human reliability enhancement

Fussy logic was first introduced by Zadeh (1965) to address the need for new mathematical tools that can be used to accurately model a variety of uncertainties within different systems and activities, the thing that may not be possible through using conventional mathematical techniques. The core importance of the fuzzy logic theory is its ability to convert data of uncertain and subjective nature into a usable certain, objective, and quantifiable data that can be utilized, with high accuracy, to built mathematical modelling for problems within imprecise, vague, ill defined, ill separable or doubtful contexts or data sources (Kaufmann and Gupta 1985, 1988).

Fuzzy logic, though only recently introduced, but it is spreading fast and finding new applications within complex engineering areas each day. Very recently fuzzy logic has similarly been used to model problems of HMI systems and human reliability quantification (Cox 1999). Dagdeviren et al (2007) introduced a fuzzy ANP model to identify faulty behaviour risk in work system. The ANP is an extension of the AHP and it is applied in fuzzy context using pair-wise comparison matrices to quantify risks associated with various activities within a production plant.

Some other emerging research works that applied fuzzy logic to various extents are: A real- time decision- making of maintenance using fuzzy agent (Lu and Sy 2008), application of extent analysis method on fuzzy AHP (Chang 1996), multi-criteria analysis with fuzzy pairwise comparison (Deng 1999), quality function deployment planning using fuzzy ANP (Kahraman et al 2006), inductive learning in fuzzy systems (Castro and Zurita 1997), selecting efficient maintenance approaches using fuzzy logic (Al Najjiar and Alsyouf 2003), knowledge-based linguistic equations for defect detection (Gebus et al 2007), a process monitoring module of fuzzy logic and pattern recognition (Devillez et al 2004), extracting syntactic information from java code using expert system (Depradine 2003), a fuzzy modelling application of CREAM methodology for human reliability analysis (Konstandinidou et al. 2006), a fuzzy approach to the conditioning monitoring of a packaging plant (Jeffries et al 2001).

2.7 Chapter Summary

Literature is rich with theories, concepts, and models discussing human reliability and associated human error causal factors that always set the scene for incidents and accidents to occur within safety-critical HMI systems. As initially titled, the chief purpose of this chapter is to exhibit the search for researchable gaps within scientific knowledge of the aviation maintenance field, and the impact of human fallibilities on it. The chapter described a review methodology that covered concentric folds of safety, aviation maintenance, and more focally, maintenance human factors. The aim is to systematically absorb the previous available information within literature from the broad spectrum of safety to deeper focus into the thesis subject matter. The chapter is also intended to elevate from the limited local understanding and familiarization with the subject that usually features co-existent reviews, to higher level of openness as a conclusive referee document. This systemized prospectus necessitated this elongated feature of the chapter.

3 Selection and Application of the Research Methodology

Give me a lever long enough and a fulcrum on which to place it,
and I shall move the world.
Archimedes

3.1 Introduction

3.1.1 The importance of a research methodology

A Research's Methodology (RM) is its core. It is the second elevation in a triangular podium that joins also research scholarship and research contribution as indicated in Chapter 1. More precisely, this writer sees RM as 'the holistic integration of theories and actions that work systematically to develop answers to that research's questions emerging from current knowledge gaps'. It can thus be considered as a logical manifestation of those questions, and subsequently, of their upstream triggering gaps, all in nature, quantity, and depth. Figure 3.1 illustrates the vital role of a RM within the research paradigm conceptualization. The overall notion of RM is to provide the indispensable channels bridging current knowledge pool to future discoveries, solutions, and innovations in all fields. According to Mellenbergh et al.(2003), RM "is an essential part of research and teaching in the behavioural life and social sciences". They further

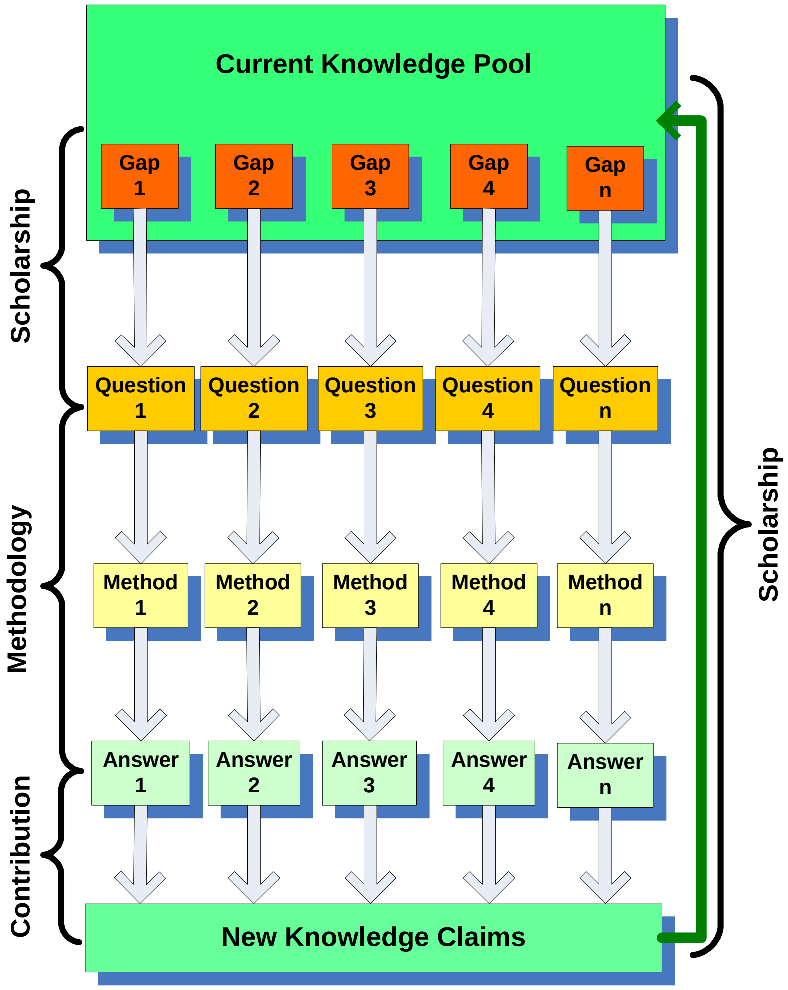


Figure 3-1 Research Methodology Paradigm

indicated that RM is intimately linked, on one side, to substantive areas of knowledge such as engineering, medicine, education, sociology, psychology, and economics. On the other side, RM is also linked to statistics techniques and computer science with their expanding applications, and to the philosophy of science as an overall imperative abstract structure. Still, RM should always be clearly separated from all these fields.

Although RM initiates from substantive researchable information cavities and applies statistical tools and insights from other fields, but it cuts its own path in creating, building, and applying new models, methods, and insights. The importance of RM as a decisive element formulating the advancement of a specific research is inescapably high. This is absolutely evidenced by the facts that correct design or selection of solution roadmaps, appropriate application of sequential intermeshing sub-methods, adequate provision of analysis reliability measures, proper interpretation and usage of research findings, etc. - being all about methodology – are, in parallel contemplation, key factors for any targeted success.

The adopted methodology for the current research, as will be discussed shortly, greatly inspires such an understanding. This methodology is totally taken with firmness, throughout all its stages, to resemble the research's first booster to achieve its objectives. Its importance stems from the very complicated context of the problem: Tackling unpredictable human errors within dynamic safety-critical sociotechnical system of aviation maintenance.

3.1.2 This chapter

This chapter furnishes the necessary conceptual platform supporting the selection of the main methodology of this research. An overview of various ideologies, schools, and paradigms of research methodologies is comprehensively presented and discussed. Then, with adequate reference to this research's questions and objectives, a general set of characteristics needed for the main RM is identified. A new generic procedure for methodology selection is subsequently introduced. Using this procedure, the main RM is selected and justified. In the course of further describing the adopted methodology, a brief account of the main activities carried out within this research is laid, leaving full details to next parts of the thesis.

3.2 Identifying characteristics of the required methodology

3.2.1 Adopting a research methodology: The basic Know-How

Mellenbergh et al. (2003) discussed the two well-established folds of research mechanisms: The theory-driven and the data-driven poles of research. The theory-based research, also known as the confirmatory analysis is usually launched by dedicated theoretical notions that are used to construct a model. This model is fitted, in turn, to empirical data in the course of validation. The theory is then either falsified or backed-up according to the degree of empirical data fitting within the model frame. The major drawback that this confirmatory analysis faces is that a model, being only an approximation of reality, can never be completely correct.

In distinction, the data-driven research, also known as exploratory data analysis, starts from empirical data and works to derive a model from that data. This is possible if relations between data variables can be patterned. This approach also suffers a major problem: the derived model persuasively fits, by nature, the data within the specified sample. However, it is not definite to fit the data form other populations. In philosophy of science, both approaches are evidently recognized in the tendency to distinguish between a milieu of discovery, within the data-triggered research, and a perspective of justification within the theory-launched research. In practice, an ambitious research designer must often make a mindfully consideration of these two mechanisms.

Other major classification of research works put them into either quantitative or qualitative respects. It is, in the main, acknowledged that picking of a qualitative or a quantitative approach during a research's front design is significantly decided referring to the original orientation of that research, and whether any of the two approaches is more effective in achieving its announced objectives. This depends on the state of the research being formulated to test or create a theory. Delattre et al.(2009) declared that "the main objective of qualitative research is to create a methodology for approaching, understanding, analysing and explaining management phenomena at a social or company level". Thus, a qualitative research can result in certain intellectual formulations that usually accommodate the needed explanations, dissimilar to quantitative systems that often look at validity through simplifications and generalization. Delattre et al (2009) cited also many works (Marshall and Rossman 1989, Stake 1995) when listing the following characteristics of the qualitative research:

- It provides ‘in depth’ learning of societal phenomena.
- The allowance for close and yet holistic understanding of complex organizations, groups, or communities and the significant roles of human element within them. Not like quantitative works that target the validation of hypothetical contents via a small capacity of variables.
- Attentively focus on more intensely exploring the origins and varieties of believes, opinions, actions, and accumulative traditions.
- When studying companies, qualitative research considers management conditions as a unity, this facilitates contextualization of the whole study elements.
- Aims at producing new theories
- The resultant theoretical construction is not finalised before the end of all qualitative field study activities. This is because newly emerging questions may come up during the interface between “theorisation and empirical realism”, and thus, the main research query can even be customized, as the research advances, to have room for the results from the field.
- Data collection is usually more flexible and fluidized through qualitative approaches when compared to quantitative ones.

Flick (2002) listed many current schools in qualitative research applications including grounded theory school, narrative and biographical analysis, objective hermeneutics, phenomenology, ethnography, cultural studies, and gender studies. Ethnography, according to Flick, works to provide understanding of the insides of the social context involved. This understanding can be achieved by actually participating in the processes leading to the events under focus instead of just performing limited surface interviews or observations. Ethnography, launched early 1980’s, encompasses many methods including formalized interviews, documents analysis, or observation. .

Farmer et al. (2006) tinted the state-of-the art in various techniques followed to enhance reliability of qualitative research methodologies. One of such techniques is ‘triangulation’; the “methodological approach that contributes to the validity of research results when multiple methods, sources, theories, and/or investigators are employed”. However, although many works in social sciences cited the magnitude of triangulation as a duplicated validity of the research methodologies, but only little of these works ever explained the practical aspects of this triangulation application.

A challenging matter to a research designer, as well, is the 'depth' to which the research 'digging' mechanisms should go. In other words, how much data are to be collected, and more importantly, how deep that data should be analysed in a fashion that satisfies the equation joining the terms of research objectives and its allocated resources, nonetheless of these are manning, finance, and time. In general, the depth and comprehensiveness of the required analysis will always be dictated – at least temporarily – by the complexity of the problem, its questions and its expected answers, if any can be predicted.

To conclude: The quality of pragmatic research is significantly secured by its applied methodology's obstinacy. A successful research, with salient methodological rigor, must be aptly and robustly designed with sufficient consideration paid to measuring instruments, as well as various methods construct, practicality, validity and reliability. Samples are to be selected as to provide highest levels of suitability and capacity of representation. Analysis and findings reporting stages, regardless of the depth that analysis may set out, must also be well performed with the required levels of accuracy and soundness.

3.2.2 A methodology to set 'The Methodology'

The front design stage of a research in a field as multifaceted as safety enhancement within the sociotechnical context of aviation maintenance is a real demanding challenge. The detailed problematic issues concerning human reliability there-within is not of lesser complexity either. Thus, good planning and concrete evidence of methodology setting correctness will be main requirements bridging to any targeted success. For the purposes of this particular research, a detailed preparatory procedure was followed to get to the final methodological setting that is later implemented in the course of the current study fulfilment.

As illustrated by Figure 3-2, an initial all-ranging sequential procedure was followed to 'set' the required research methodology that is most predominantly capable of answering the research questions, and satisfying its objectives within the available resources. For convenience, this procedure is given the code: Research Front-End Design (RFED) methodology. RFED, although essentially launched within this research, but it is so generic that it can support early design stages of limitless applications of research studies.

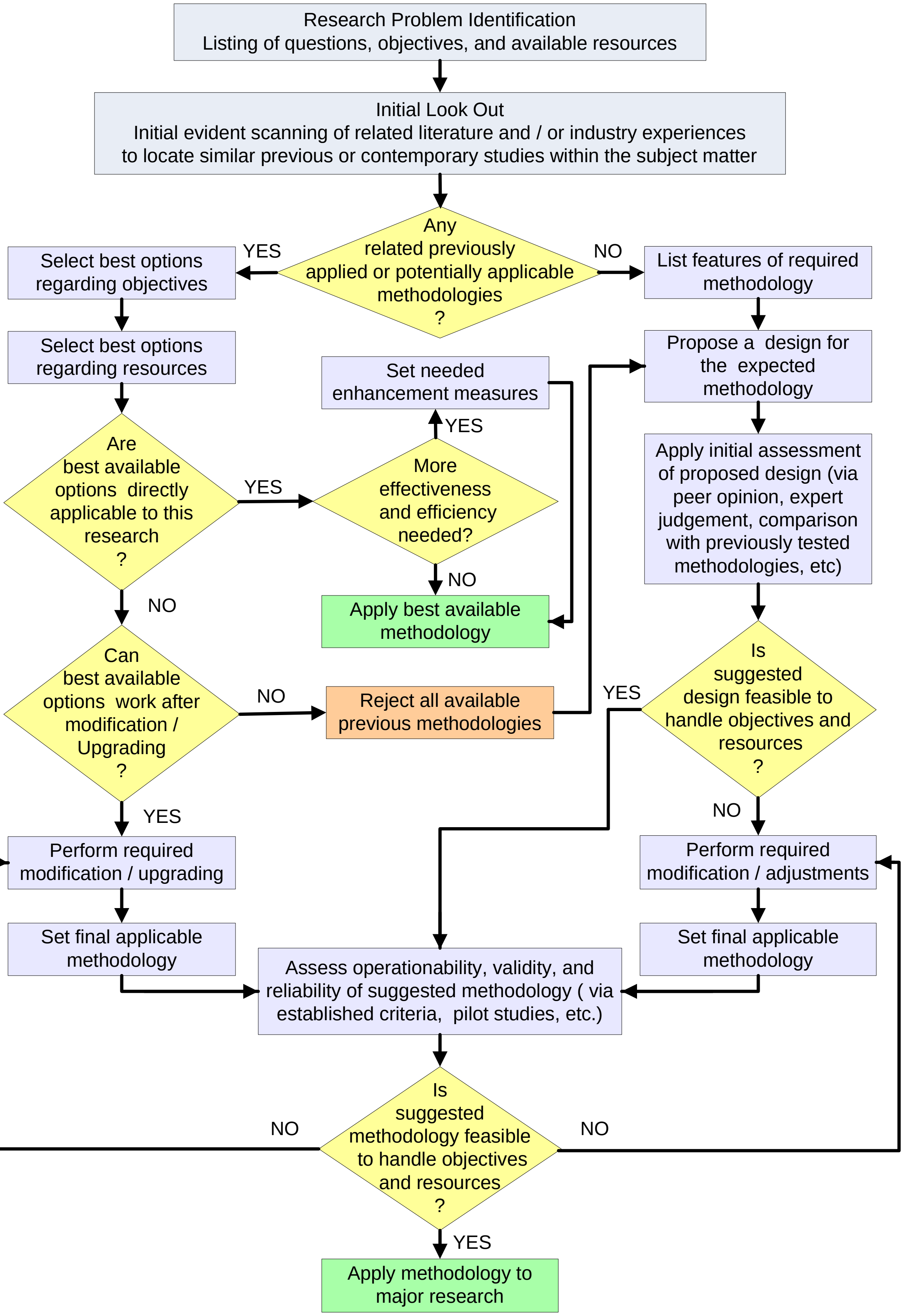


Figure 3-2 RFED generic procedural methodology

This procedure, in fact, exposes a mini-methodology that objectivists setting the major research methodology. The sequence of steps accordingly followed, in the course of designing this research, was performed to ensure that the targeted major methodology satisfies the following capital characteristics:

- It demonstrates evidence of understanding of philosophical, empirical, as well as academic implications of the problem under investigation.
- Its final design is concluded after thoroughly refining a affluent assortment of methodological choices, including inventing new methods.
- Its selection, modification, upgrading, or introduction is totally justified.
- It demonstrates capability of fulfilling the announced research objectives with the highest operational competence possible.

More practically, in the course of RFED implementation, a broad methodology-oriented literature review was initially conducted in the fields of human factors, human reliability, aviation maintenance, aviation accidents and incidents investigations, human error causal factors, organizational and safety cultures, and many other folds of the research subject matter. This literature scanning was simultaneously accompanied by active industry insights and consultations regarding aviation maintenance-induced safety occurrences and the available remedy practices. Thus, a clear image featuring the state-of-the-art in this regard was obtained. This standing preliminary surveying acts, moreover, highlighted a large number of theories, models, methods, taxonomies, tools, programmes, case studies and research activities all dealing with human reliability within aviation maintenance complex context in particular, as well as the all-surrounding broader organizational safety management and safety culture perspectives.

The above probing booster process, more to the point, was widened to accommodate openings from other safety-critical fields such as nuclear industry, medicine, and other modes of transportation, mainly rail and marine. This early illumination led to the appreciation of a number of previous and current works and associated methods in these fields. Accordingly, the sequence given in Figure 3-2 was exclusively followed such that the working major methodology of this research was ultimately set in the light of the required capital characteristics discussed above. Details will be presented in the coming sections, however, it is worth stressing here that the term ‘methodology set’, as used here, is precise. The ‘setting’, depending upon many variables, is a collective behaviour that can include: adopting an already established and practically validated methodology, making an integrated consortium of pooled methodologies, accepting a methodology after doing necessary modifications and / or upgrading on it, or explicitly crafting and introducing fresh methodologies of mature or invented ingredients and techniques. For this writer, it is at this stage, in which such behaviour is conducted, when the basic research methodology is sensibly 'set'.

3.2.3 Required characteristics of the research methodology

In addition to the basic targeted methodological characteristics discussed in the previous section, and according to Shrivastava (1987) and Varadarajan (2003), a successful research methodology is the one that, furthermore, satisfies a range of other intermeshing research and methodological features. These features, some of which are listed here below, were adopted by this thesis as further influential methodological guidelines:

- The methodology structure was carefully set to effectively answer the research questions
- Measures were taken to ensure exactness and yet flexibility of data collection processes as well as related measurement influencing issues, such as applied methods practicality, validity, reliability, and data aptness to the risen questions.
- Appropriate methods of human factors and human reliability-oriented analysis were applied, followed by necessary statistical and numerical procedures and formulations that empirically treated the research questions and the overall research objectives.
- Necessary arrangements were furnished for the validation of findings and their practical implications
- Utmost care was paid to ensure proper and accurate reporting, analysis, and discussion of this research's findings in addition to the entire set of theories and actions that led to them.
- The research design was laid such that all research objectives are to be achieved within available resources, nonetheless of is time span.

These guidelines formed a well-constructed instrument that greatly shaped the finally-applied research methodology as will be discussed thoroughly in the following sections.

3.3 HERMES methodology: The concept and application

3.3.1 The methodology concept

The adopted methodology, which is justified as the best leading to this research's objectives, is known as Human Error Risk Management in Engineering Systems (HERMES) first introduced by Cacciabue (2004a,b) for analyzing HMI in complex contexts. This methodology encompasses a complex mosaic of human factors analysis and modelling techniques. It is structured in a number of steps to preserve the basic requirements of congruence and consistency between both types of retrospective and prospective studies as well as to underpin the correspondence between recurrent HMI analysis and system safety and integrity. An illustrative presentation of the HERMES methodology is given in Figure 3-3.

HERMES, with its embodied analysis techniques, was introduced to fill the need to correlate retrospective and prospective studies in a logical analytical process that can support the considerations of sound HMI practical industry-oriented approaches. Its major fields of application are accident and incident investigation, human factors training, human factors design enhancement, and safety assessment of complex engineering systems.

As Figure 3-3 shows, the methodology structure starts with two main simultaneous streams leading to actual realization of the emerging problematic phenomenon: A meticulous evaluation of the sociotechnical context enveloping the problem under focus, and a thorough theoretical background furnishing the state-of-the art of the conceptualities governing or influencing that problem. This preliminary stage of the methodology involves ethnographic studies, task analysis, HMI models and taxonomies. It sets the pace to "identify the conditions that favour certain behaviours, which may foster accidents" (Cacciabue 2004a). The correlation between humans and machines shaping the phenomenon under investigation can thus better be acknowledged, and a firm base of understanding regarding the problem can be formed. This will greatly influence the formation and execution of the next two investigative and predictive stages of the research. The retrospective (investigative) and prospective (predictive) phases of the methodology are mutually-linked. Although they are varying in sequence of application time-wise, but huge volume of data exchange is expected to take place between the two stages.

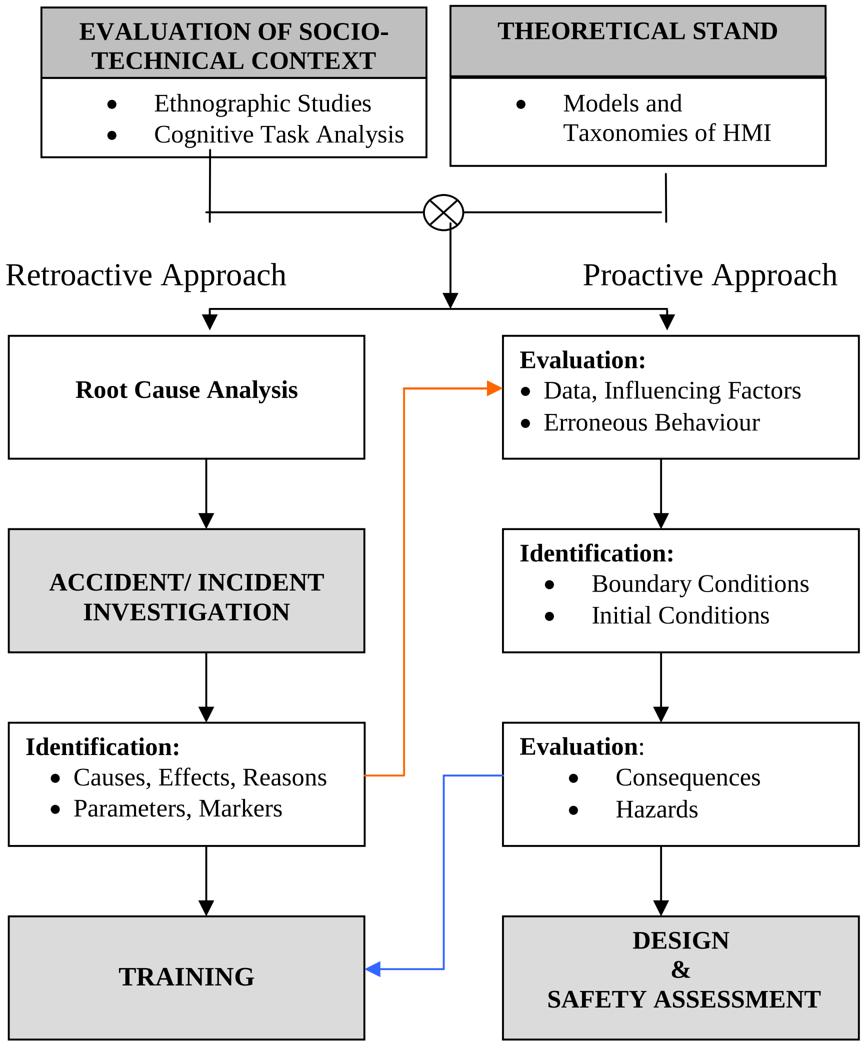


Figure 3-3 HERMES methodology structure (from Cacciabue 2004a)

A general sequence of correlation within these two investigative and predictive streams of activity can be briefly highlighted as follows:

- The retrospective stage starts with a detailed investigation of the past events' causes, sequences, and patterns. This is conducted through a comprehensive detailed Root Cause Analysis (RCA) of such events. Both individual shortages and / or organizational systemic malfunctioning that led to these events are identified, this is a deeply-engaged secondary accident investigation activity.
- Accidents analysis will provide highly sophisticated information on the causes, effects, and reasons of accidents, as well as related parameters, indicators of possible malfunctioning within the overall system.

- Detailed human factors-oriented training programmes can thus be undertaken using the knowledge acquired through this post-event examination of safety failures when put in contrast to the initial data and theoretical background information.
- The output from the retrospective analysis is directly utilized to determine and evaluate the individuals and organizational performance influencing factors, thus various forms of possible future erroneous functioning scenarios can be predicted in generic modes.
- These generic behavioural scenarios can then be further elaborated to identify initial and boundary conditions for the required prospective analysis. These conditions are the ones setting exact description, context, environment, and even culture of the predicted erroneous scenarios of the future. These initial and boundary conditions are merely generated out of the subject-matter knowledge, expertise, and brain creativity of the analyst.
- By containing the safety occurrences data, indicators, performance governing factors, initial and boundary conditions, and the various HMI models and taxonomies involved, it is possible then to apply risk methods in order to predict future weaknesses and to set possible remedies on-the-spot. This is applicable for both general safety assessment as well as design-for-safety enhancement.

3.3.2 Why choosing HERMES for this research?

The decision to select and modify HERMES to form the working methodology for this research was taken after carefully applying the previously discussed RFED procedure. This crucial decision is justified through the following focal describers:

1. The selection of HERMES for this research can firstly be justified by accrediting its original in-built resourceful characteristics such as:
    - This methodology is a generic framework with applications in the fields of accident / incident investigation, human factors training, human factors design enhancement, and safety assessment of complex engineering systems. This multipurpose orientation ensures greater degrees of operational flexibility.
    - Its ability to link retrospective and prospective types of studies in a logical analytical process that supports the considerations of sound HMI approaches.

- It is a hybrid methodology firmly joining theoretical concepts with practical implementation. It has already been successfully applied in a variety of safety-critical industries such as aviation and rail.
- The smooth association between persistent HMI analysis and system safety and integrity.
- Flexibility in selecting sub-techniques and particular HMI tools within the generic methodology layout to satisfy specific progressive tactical targets.

2. HERMES's core concepts and practicalities are all directly relating to this research's subject matter, namely the influence of HMI in the total system safety.
3. This methodology provides suitable environment to effectively accommodate all previously discussed characteristics and properties (section 3.2.3) required for the methodology of this research. In this regard it holds open opportunities to free selection of suitable sub-methods and localized models, plus flexible room for data and analysis reliability assurance. Further, it calls for triangulation, empirical data collection, practicality, and full application of brain creativity and innovativeness within its final stages.
4. The possibility of meaningfully re-crafting the detailed structure of HERMES to exactly suit this research's objectives and resources without altering the general conceptual sequence of the methodology manifestation.
5. According to RFED logic, adopting a re-composed version of HERMES, is the most suitable adequate option for this research. This detailed modified structure of the methodology was cross checked for further confirmation regarding accuracy of the proposed alterations and their effects on the research plan.

3.4 The applied version of HERMES

3.4.1 Adapting HERMES to this research

One evolved aim of this research is to introduce a holistic integrated Aviation Maintenance Monitoring Process (AMMP) that can be utilized collectively by operators, regulators and aircraft manufacturers to monitor and early detect potential existence of errors causal triggers associated with human factors during aviation maintenance. The process, comprising multiple strands, is to be practically applied and refined within industry.

To suit this research, some major alterations has been applied to the original HERMES structure in order to accommodate the research overall scope, while being loyal to the original main philosophy stream. These alternations included dropping of the accident/ incident investigation and the human factors training as end user terminal applications. In the other hand, safety auditing application is replaced in the new version with a proactive safety monitoring process. This monitoring process, mainly dedicated to aviation maintenance practices, includes safety enhancement both during aircraft and their parts design for maintainability, as well as for day to day operational life within MRO's. Details of the finalized research methodology are shown in Figure 3-4.

3.4.2 The methodology application: a brief overview

3.4.2.1 Fundamental Studies

The front end studies comprised a sophisticated literature review that focused knowledge of the field, and critically evaluated the previous contributions. Then a sociotechnical evaluation of the helicopter maintenance context was performed through detailed ethnographic studies based on observation, meetings, interviews, and visits to regulators, operators, manufacturers, and research centres. Maintainer task analysis was then performed. In a parallel line, a theoretical and conceptual knowledge base of the HMI systems and human behaviour taxonomies was built. By the end of this stage, the research problem was crystallized. Consequently, the research orientation was set and the associated research aim, objectives, and questions were furnished. The methodology processes roadmap was then set as the work's core structure.

3.4.2.2 Retrospective Backward Studies

For main data collection, a number of 804 helicopter safety occurrences were carefully scanned. Out of these, a sample comprising 58 of maintenance-induced fatal accidents and severe incidents was then thoroughly analysed using Human Factors Accident Classification System – Maintenance Extension (HFACS-ME) taxonomy (Schimidt et al. 1998,2001). Human error causal factors were first identified through the well established three classification orders of the taxonomy. Then a new more sophisticated fourth order of causal factors classification was introduced to raise the analysis resolution from 34 categories at the established third order to a total number of 197 new fourth order categories which are coded: 'Specific Failures' (SF's).

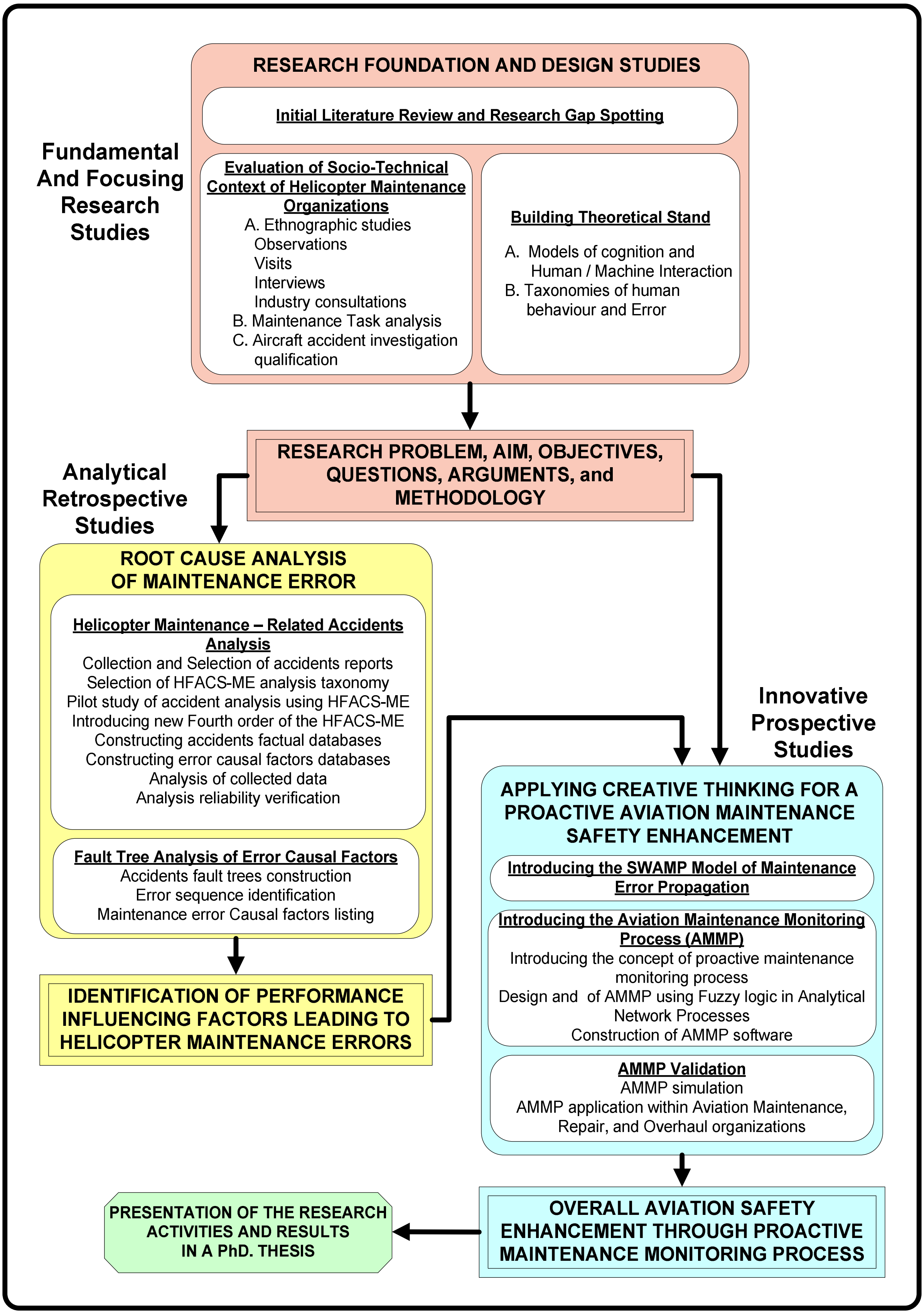


Figure 3-4 Research applied methodology structure based on HERMES methodology

Inter-rater reliabilities of 0.766 Cohen Kappa and 94.77% Percentage of Agreement were obtained during analysis. A further emphasis was given by applying FTA and Hierarchal Task Analysis (HTA) to identify probable mechanisms of helicopter maintenance errors. The end of this stage represented a major milestone by the identification of maintenance PIF's. PIF's are the factors and performance sequences leading to human maintenance errors.

3.4.2.3 Prospective Forward Studies

Using the outcomes of the retrospective research, a creative thinking process was conducted to set pace for the targeted maintenance proactive monitoring process. This was triggered by introducing 'The Swamp', a new human error model that explains the sequence and propagation of safety-related human errors through the behaviour of aircraft maintainer, supervisor, crew or other associated personnel. As a direct means to apply this 'Swamp' theory, the main AMMP project layout was introduced as well after a series of successive developments. The AMMP- as a holistic process- is a framework designed to join safety-oriented integrated activities within regulators, manufacturers, and most importantly, aircraft maintenance organisations. This communal process is to systematically collect maintenance performance safety-related raw data, analyse them and then design and apply any required new measures or modify those already in place such that any relative cited error causal factors can be proactively eliminated or at least positively treated.

3.4.2.4 Fuzzy logic: The core of the final product

The projected AMMP, as discussed previously, aims at assessing the existence of root causes leading to errors within 'real' uncertain and vague environments such as those witnessed within aviation maintenance industry. The usual subjectivity, always present within explorers' and experts' opinions when judging such existence, is yet another vital factor that led, with the first, to the selection of fuzzy analysis to be the main practice of the AMMP software programme (branded as ErroDetect). Kaufmann and Gupta (1988) wrote: "If our knowledge of the environment is imprecise, as happens in medical diagnosis, engineering, management decision-making, etc, the model must include the notion of the level of presumption. Fuzzy numbers have been created to reflect the vagueness of human perception and thus the notion of the level of presumption. These fuzzy numbers thus reflect the human cognitive process". New fuzzy logic algorithms are thus introduced within this research to further affectionate the established tactics in this regard, and to significantly reduce the need of complicated and costly systems of experts, thus setting a more industry-oriented product.

The AMMP model is built using fuzzy ANP theory. It comprised two fields of application:

- Design for maintainability continuum.
- Line maintenance performance continuum.

The concept is to continuously monitor existence of maintenance human error triggers that may initiate during aircrafts and other equipment design process, or during maintenance practices at the MRO lines. Having error triggers identified in advance, they can then be eliminated systematically. As a final part of the applied methodology, the AMMP process was subjected to simulation tests, field experts' evaluation, and direct application within real world settings.

3.4.2.5 Roadmap for methodology application

The adopted methodology was conducted through sequential stages that formed successive mile stones of a major roadmap dictated by the outlines previously illustrated as per Figure 3.4. Although detailed description, analysis, and application of various theories and models, discussed within this research, are given through the following chapters, nevertheless, a brief staged roadmap of the methodology activities can be indicated here as per Figure 3. 5.

3.4.3 Challenges to the methodology application

The application of HERMES in this research was faced by many challenges, the earliest of those was the need to modify the original methodology layout in order to accommodate the present research requirements. This was first suggested by this writer and then approved by Cacciabue, the methodology initiator, and his team at the European Union's Joined Research Centre-Italy. This modification consequently gave rise to a new challenge to the adapted methodology being the first to be thus implemented. Another difficulty was in-built within the methodology itself, in fact, the original methodology is a multi-teamwork-oriented protocol due to its well branched and diverse activities that need to be simultaneously addressed, thus it proved out to be very challenging for a limited number of researchers to cope.

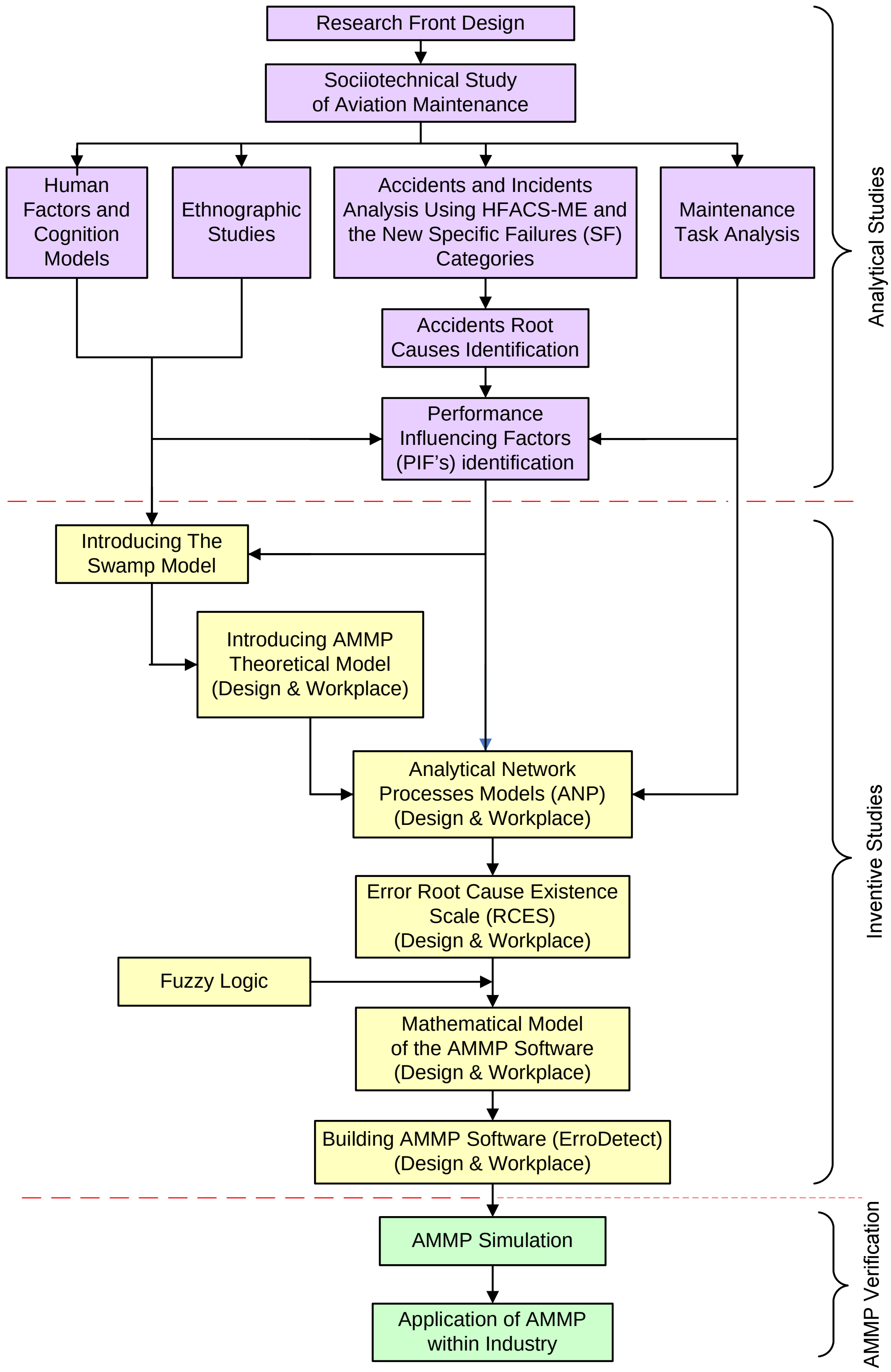


Figure 3-5 Roadmap for research methodology application

The most critical conundrum that faced the application of this methodology broke out at the phase of data collection. It was very difficult to get formal helicopter accidents reports that are written with satisfactorily reflection to human factors issues, consequently only 58 reports could be used for data analysis out of a total number of 804. The wide spectrum and diversity of the methodology sub-components necessitated serious upgrading and enrichments to the researcher's abilities and know-how such that those sub-components may be satisfactorily handled, for instance, a formal accident investigation qualification was obtained first in order to better understand accidents occurrence mechanisms and accident reports writing and analysis. A tactical problem faced the execution of the interrater reliability for the analysed reports. It was seriously difficult to allocate experienced co-workers with approved qualification in the yet new HFACS-ME taxonomy and associated report coding and analysis. Further more, a major challenge as well was the ability of selected aviation maintenance organizations to allocate the necessary provisions within their daily activities and staff workforce to practically apply the designed AMMP in the course of its verification within industry.

3.5 Chapter summary

HERMES is a much systematized methodology that provides strategic as well as tactical guidelines for a smooth flow of research sequential activities. The methodology is totally generic to accommodate different requirements of HMI treatment within safety-critical engineering systems. It has already been applied within various industries where it showed high rates of reliability. The current research, by adopting a modified version of HERMES, is ambitious to make the best out of its characteristics to address human error as seen in helicopter maintenance context, this will be of significant benefits for aviation safety in general. On the other hand, a sound application of the adopted methodology is hoped to give provision for the academic requirements of a PhD study to evolve, those undoubtedly encompass scientific scholarship, methodology practicalities, and a substantive contribution to the field knowledge pool.

Each of the afore-discussed challenges and the ways they were tackled represented an indispensable learning opportunity, the HMI models selection and application, the limited number of co-workers, the desperate data hunt, the required analysis reliability affordability, and the inventive introduction of new safety tools.

PART TWO

ANALYTICAL RETROSPECTIVE STUDIES

4 Evaluating the Sociotechnical Context of Aviation Maintenance

Science cannot solve the ultimate mystery of nature.
And that is because, in the last analysis, we ourselves
are a part of the mystery that we are trying to solve.
Max Planck

4.1 Introduction

4.1.1 Understanding the sociotechnical context

Contemporary research works, reports, and other publications that converse safety and / or reliability issues without genuinely referring to the term 'sociotechnical' are rare. To explore this term, the Collins English Dictionary (1995, P782, 850) defines 'sociology' as "the study of the development, organization, functioning and classification of human societies". Further, it defines things that are 'technical' as those "of or specializing in industrial, practical, or mechanical arts and applied sciences". Joining these two connotations, a conceptual frame that describes the existence and behaviours of humans within machine-driven environments can be understood.

Before the 1950s of the last 20th century, research and industry institutions often called for technological determinism where technology advancements and practicalities were taken to have the main direct effects on the production cycle. By then, terms standing for human presence were never added to the wheel-turning equation. It was only by Trist and Bamforth (1951) when an appreciation to the influence of human input within technical systems was introduced. The two writers argued that "human and organizational outcomes could only be understood when social, psychological, environmental and technological systems are assessed as a whole". This approach, which is defined as the 'sociotechnical system', was further developed and described by many works. Griffith and Dougherty (2001) showed that organizations constitute of "people (the social system) using tools, techniques and knowledge (the technical system) to produce goods or services valued by customers (who are part of the organization's external environment)".

Cacciabue (2004a) showed that HMS's are those realistic contexts in which humans operate machines through appropriate interfaces and controls. For him, these HMS are composed of two folds: The technical plant capital (interfaces) and the enveloping sociotechnical working environment. Sociotechnical fold, in turn, comprises four intermeshing elements:

a. Organizational processes: These are represented by strategic organizational decisions and the associated corresponding organizational culture. Both of which, when coupled together, play the vital role in setting the manner in which a technical system is - or should be - operated.
b. Personal and external factors: Personal factors are the individual's specific physical or mental describers that dictate his / her behaviour within the work context, while external factors are "all random physical or system contingencies" impinging on neighbouring working conditions including safety measures.
c. Local working conditions: These are the conditions affecting the implementation of tasks by influencing either the interface between operators and control systems or the cognitive powers of these operators or both. Maurino (1995) defined these local working conditions as "the specific conditions that influence the efficiency and reliability of human performance in a particular work context".
d. Defences, barriers, and safeguards: These are the structures and mechanisms, either substantial or societal, that are premeditated, programmed, and set within the human-machine system so as to provide for higher capable and safe running of a plant, both for planned or emergent operations.

Sociotechnical systems have always been challenging when it came to safety management perspectives. This is totally coinciding with the basic in-built characteristics of these systems: having humans, with all their potential reliability fallibilities, operating compounds of technology that are, by definition, significantly complex. Carayon (2006), Reiman and Oedewald (2007), and many other writers highlighted this juxtaposition of difficulties. They called for intense application of human factors techniques and ergonomic advancements to better handle such difficulties, expressly for sociotechnical systems that join work across multiple boundaries of many integrated, yet individual disciplines. In this regard, a "more proactive and predictive approach is needed, that is based on an accurate view on an organization and the demands of the work in question".

4.1.2 A unique dilemma of aviation maintenance

Patankar and Taylor (2004b) cited many works that showed aviation maintenance as a unique sociotechnical context. To such an understanding, safe and successful aviation maintenance and repair are not to be achieved solely through utilizing technology, contrary, technology 'users' are those who were found more responsible for such safety or success.

An aviation maintenance mechanic sometimes faces, in spite of all the precise technology around him/ her, some moments of uncertainty. Huge amounts of factors can play seen and hidden roles in crystallizing such uncertainties. Such situations, when there are no clear boarders between the right and wrong ways of completing a job, when no or only void supportive information are available, when he/ she is required to finalize a task while passengers are getting ready to board on the other side of the aircraft. Such situations, and so many similar ones, are the moments when human fallibility bounces out of control to set the trigger for a maintenance error.

"Maintenance personnel are confronted with a set of human factors unique within aviation maintenance" (Hobbs 2008). A large range of aviation maintenance activities are far hazardous to perform than most of the jobs within other labour roles in other industries. Tasks are to be successfully and safely completed in extremely high or low temperatures, open or closed workplaces, high locations and confined spaces. In aviation maintenance, preparatory and technical documentary work can actually resample higher weights than the actual physical activities on the aircrafts. At the gates, huge mental pressures are always there to be coldly absorbed by the mechanic who is, nevertheless, obliged to follow each and every detail. Huge brainstorming capabilities as well as supreme physical fitness are essential where faults diagnosis, decision making, remedy solution implementation, and technical measures execution are all to be handled together. What's more, communication and coordination margins are critical: With long distances between the job platforms at the far rear parts of an airliner and the controlling displays in its cockpit, high levels of noise, heat, and gas emissions from power plants and test rigs, working on semi-illuminated dark tarmacs, and so many other comparable scenarios, it is always hard to guarantee that the required levels of effective and efficient communication and team collaboration are secured.

Another completely separate category of overwhelming mental and psychological pressures, that aviation mechanics carry with them day and night, are those associated with the long-term influence of their momentary activities on aircrafts. An accident can suddenly explode out as a result of some 'sleeping' error within a maintenance job that was performed months or even years before. The mental and even spiritual loads on a mechanic whose maintenance activities once resulted in an accident are tremendously immense. Aviation maintenance, by all means, is such a sophisticated sociotechnical environment where both its 'socio' as well as 'technical' strings are stretched to their maximum limits.

4.1.3 This chapter

This chapter describes the activities performed during the preliminary stages of the adopted methodology execution. Ethnographic mapping of the aviation maintenance context is performed, maintenance task analysis is consequently conducted. As a result, detailed conception and deep understanding regarding the 'ins' and 'outs' of this sociotechnical system are achieved.

4.2 Ethnographic study of aviation maintenance

4.2.1 Ethnography

Ethnography, as a subset of anthropology, has been first introduced as a concept and a tool to explore the lives, behaviours and human production of other cultures (Garfinkel 1967). The main characteristic of an ethnographer is *'to be'* and *'not to be'* there in the same moments. The concept of ethnography, as a direct powerful way of learning about different human settings, is built on the idea that the information collector being totally immersed within the targeted population such that detailed knowledge on all life aspects within that population is acquired, and simultaneously being so contained, professional, articulate and light such that he / she has utterly no footprint impacting the original setting under investigation. Through ethnography, some pure exhaustive descriptive data pertaining to the community under analysis is planned to be obtained. Such set of 'thick data' usually converges-out free of any imposed external pre-conceptualities or influential ideas.

Ethnography, although first launched within research targeting social, racial, cultural, psychological and even philosophical contexts of the communal samples under light, but gradually it tends to accommodate other contexts as well. To this end, work contexts have recently become famous targets for ethnographers. Work establishments comprising man-technology settings often found nowadays to resemble true reflection of the surrounding local and national habits and cultures (Cacciabue 2004b). These are found to increasingly impact the active policies, implementation procedures, and the overall business attitudes set by a given organization. Ethnographic studies are featured by a set of properties that are thoroughly illuminated by several writers (Robson 2002, Wolcott 2005):

a. Ethnography is not only about collecting data describing behaviours, actions, events, and contexts of the community under investigation, rather, it is about understanding the meanings behind these attributes.
b. To obtain such an understanding, an 'insider's perspective' is essential.
c. Ethnography is a scientific paradigm, an applied procedure, yet it is *an art.* Sensitivity and sensibility of an ethnographer are but main inputs to the fieldwork, chiefly within situations when sheer quantifying scientific data is not required, or at least not the sole that is required.
d. Participant's observation is an essential ethnographic technique.
e. Data collection may take elongated periods through multiphase setting.

Casley and Kumar (1992) defined a participant observer as the one who "participates in the activities that are the subject of his study", however, this definition is progressively more used to cover lengthy inhabited observation with only minor definite participation. Direct observation is always supplemented by information gathered from interviewing key informants (Johnson 1990) as well as from analysis of documents, records, etc.

4.2.2 Objectives of the ethnographic investigations in this research

In accordance to the holistic methodology adopted by this research, the ethnographic study of aviation maintenance should work to push the knowledge envelope pertaining to safety culture, performance, and descriptive indictors there within. This study is targeting the following objectives:

a. Knowing the overall and detailed structures of MRO's, and understanding the procedures and legislations governing the sequence of work performance there within.
b. Understanding the social component, the human capital within MRO's, their qualifications, professional characteristics, work habits, norms, inter-personal relations including vertical and horizontal organizational relations.
c. Appreciating the impact of the 'cultural pyramid' (section 4.2.4) on the behaviours of maintainers, supervisors, and higher managements within MRO's.
d. Mapping locations of various MRO's within Reason's (1997) 'safety space'. Thus further understanding causes and reasons behind each anticipated location.
e. Understanding the role of technology, dark or bright, in work performance within MRO's.
f. Mapping the relations of MRO's, as self-contained context, with external influential organizations such as parent companies, aircraft manufacturers, suppliers, and regulators.
g. Using the above objectives to realize aviation maintenance errors, their hidden causes, momentary triggers, and propagation scenarios.

4.2.3 The scope of ethnographic study of aviation maintenance within this research

As genuine authentic part of this research, aviation maintenance worldwide has been ethnographically analysed through a strappingly-coupled series of activities. These activities were set to achieve the above listed objectives and simultaneously to satisfy the strict scientific requirements of an ethnographic research. The span of this ethnography extensively expanded to include rich *participant observation* that lasted for almost two decades prior to the formal start of this study. With 20 years of career within various direct aviation maintenance profession posts and other aviation-oriented duties, this writer has been endorsed with adequate amount of information, data, and practical hand-on experiences in this field. This expertise covered various aviation maintenance attributes including line maintenance tasks performance, hanger management, off-base 'dig-outs', technical storage, mass shipping of aircrafts and their components , aircraft overhaul, aircraft purchase contracting and technical acceptance checks, maintainers training, maintenance management, quality auditing, and others.

Table 4-1 Ethnographic studies of aviation maintenance within the current research

Activities	Brief descriptions
Participant Observation	Elongated participation in all aspects and levels of duty within aviation maintenance industry mainly devoted to rotorcraft. This is performed within multi-cultural, multi-location, and multi-roles settings. Observation located in Middle East, East and South Africa, and Russia. Details of findings from these participant observation activities are listed in section 4.2.4.
Key Informants Interviewing	Key informants were interviewed. Those are people who were in direct daily contact with aviation maintenance safety, human factors, and accident investigation issues. Their opinions were used to draw a picture concerning maintenance error causes, propagation, prevention barriers, and reactive investigation techniques. Interviewees were a selected sample from Air Accidents Investigation Branch (AAIB) - UK, Defence Aviation Safety Centre-UK, North Sea helicopter operators (Bristow, CHC), British Airways, Helicopter Manufacturers (Agusta Westland, Eurocopter). The overall located Time span was 3 years.
Surveillance Visits	Surveillance and exploratory organized visits were performed to various aviation MRO's within UK in order to further closely understand the influence of work environment, procedural contexts, and the interactions between maintenance personnel and technology on triggering maintenance errors scenarios, and accordingly to observe various safeguards put in place to withstand such potential errors. Visits were performed to North Sea helicopter operators (Bristow, CHC)-Aberdeen, British Airways advanced maintenance facility in Cardiff, and Eurocopter – UK. Allocated time spanned 3 years.
Documents Analysis	Documentation recounting to aviation maintenance management, regulations, safety, accident investigation, human factors, and related subjects were richly gathered and analysed for maintenance error causal factors, error propagation, breakable safety barriers, and other relative issues. This included over 800 helicopter accidents and incidents investigation reports, relevant research literature, regulatory publications, industry databases, aircrafts logs and maintenance manuals, specialized bodies reports (FEME, CHIRP, MEMS, etc.). Documents were analysed for maintenance human factors-based error and for other factual information. Allocated time spans 4years.
Experts Consultation	Experts in the fields of aviation maintenance, human factors, aviation safety and accident investigation, aviation regulation, maintenance error reporting schemes, and other relevant fields were consulted on the maintenance error initiation, propagation, and prevention aspects. The consultations aimed at filling any gaps in information and data obtained from previous ethnographic activities, and simultaneously, the consulted experts gave their opinions and evaluation of the current status of aviation maintenance, and draw guidelines highlighting best practices that

Table 4-0-1 Ethnographic studies of aviation maintenance within the current research (continued)

Activities	Brief descriptions
Experts Consultation (continued)	can be followed to enhance aviation maintenance safety. The consulted sample included experts from the following organizations: CAA-UK, CHIRP, MEMS, EU Joint Research Centre- Ispra (Italy), Bureau Enquêtes-Accidents (France), The allocated time spans for 3 years.
Research and Scientific Debate	Aviation maintenance safety enhancement has been the focus of numerous research works and on-going scientific debate.The current research deeply engaged in this debate and closely followed its progressive outcomes

This expertise witnessed multiple work environments and cultures in Sudan, Libya, Ethiopia, Iraq, South Africa, and Russian Federation in both civil and military settings. Complementary folds of information and data collection, different work settings appreciation, multi-cultural involvement and others aspects as well, are later added to the previous experiences. This fresh addition was obtained within the western aviation standards in Europe, USA, Australia, and New Zealand. An overall mapping of activities carried out as parts of this ethnographic study is presented in Table 4.1, while details of these activities and their findings are discussed in the following sections.

4.2.4 Participant observations: From hangar and office

The participant observation technique, as described in Table 4-1, resulted in a rich pool of data and know-how that can only hardly be categorized into five separate, yet closely inter meshing zones. A summery of the observed findings is revealed through the next following paragraphs.

4.2.4.1 Humans

Humans are all people having direct or indirect impacts on aviation maintenance. Consequently, any factors that can influence those humans, at any degree of intensity, will have their induced impact, on aviation maintenance. The following are some summarized findings regarding this orientation:

1. Maintenance personnel are very proud of their profession and of their abilities and skills that should set them capable of successfully completing their assigned tasks. They are further observed to be of even greater loyalty to their trades, lines, teams, and even shift groups.

2. Social intimacy and personal relations play major role in the workplace. This is a double-edged tool: Good social life and friendly environment, particularly in horizontal relations within an organization, can significantly push forward a given line's performance. However, too personalized work relations can badly influence the formal implementation of regulations especially for the vertical inter-organizational channels. This human-human interaction, with both its positive and negative impacts, also shapes the MRO's relation with its external related community of organizations and agencies.
3. Aviation maintenance has its own 'flavour' as a sociotechnical system. Further more, this flavour is, in turn, coloured in accordance to the compiled pyramids of cultures in which and through which a MRO performs. An observed *'cultural pyramid'*, a concentric regime of various influential cultures is always there. This starts when mechanics from one trade appreciate their trade's privileges over other trades. Engines/ airframe mechanics, for instance, sometimes feel some superiority over those from the avionic trade and vice versa. This is a pure human nature. The next outer envelope is the overall occupational culture that surrounds these local trade-wise interactions. Occupational culture is sequentially surrounded by the company and the national cultures. Figure 4.1 shows those observed cultural contexts critically shaping the human performance within MRO's sociotechnical system.

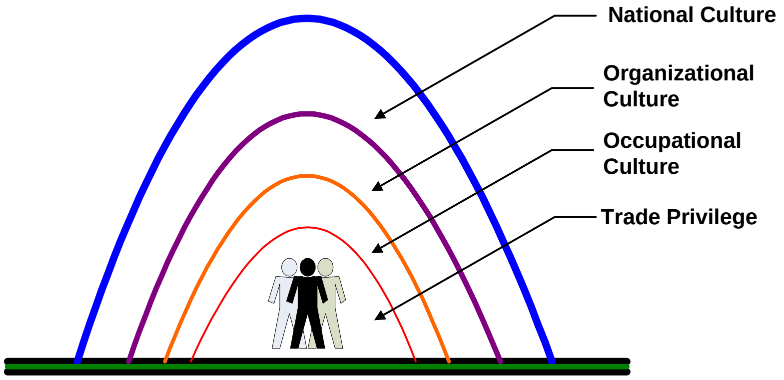


Figure 4-1 The cultural Pyramid: Influential Cultures on MRO environment

The national culture, as observed in this context, has its vital role in colouring the manners in which, even various international regulations, are handled locally. The implications of so close interpersonal connections within workplace, as discussed in paragraph 4.2.4.1/2 are just a simple illustration of this cultural impact.

4. Maintainers and supervisors are generally very adamant on having their assigned tasks successfully completed. The degree of such a success depends on a varying set of factors. Failure in completing a job is socially unbearable since it can easily be attributed to some personal skills and competence shortages especially for new comers. The peer pressures in this regard are huge. Thus the obligation to complete tasks, if coupled with any opposing factors, may drive maintainers towards some undesired behaviours such as shortcutting, shyness of seeking second opinion, waiving duties to next shifts if possible, or other similar conducts.
5. Organizational culture within MRO's is really varying between the two extremes: Totally blame and totally forgiving contexts. The majority of MRO's observed within this study are located generally some where in between the two limits and more tending to be at the 'blame' side. The blame intensity dramatically increases within more disciplined settings such as in military or even in some critical government-associated organizations. Higher are the blame features, higher are the pressures put on humans, and more susceptible are they to commit errors during various stages of task execution.
6. Each MRO is characterised by its unique in-work social life. As discussed earlier, very close personal connections can develop, within other leadership issues as well, sets of bad norms as the boarders between various employees and their specific roles get gradually diminished. In such cases, various supervisory problems may emerge such as their failure to inspect, deficiency in correcting persistent problems or controlling foreseen hazards, etc.
7. Communication between employees within ever changing contexts like that of MRO's are vital. Task instructions, feedbacks, explanations, etc. are either given - or essentially supported - verbally. Consequentially, the slightest miss matching in communicating any of this information will open all possibilities for maintenance errors.

4.2.4.2 Organisations and management

The organizational dimension plays critical role in the ultimate success of aviation maintenance industry, or inversely, in its failure. In fact, almost all of the maintenance related incidents observed within this sample could be back-traced to some shortage at a certain level in management of the MRO involved. The following are some main observations regarding this organizational impact:

1. Aviation maintenance worldwide stands on firm base of legislations, regulations, and rules. These cover very complex areas of personnel initial qualification and continuous development, workplace standards, aircraft technical standards, etc. The differences in performance between MRO's are direct mapping to how firmly and correctly these MRO's check-mate in compliance with these governing rules.
2. The overall level of performance efficiency and effectiveness within MRO's highly depends on the available provisions for continuous personal development training and other activities. This implies, from maintenance safety perspective, all relevant technical skills and competences-sharpening activities, human factor awareness, etc. The observed sample of MRO's revealed a fact that maintenance errors are significantly reduced as such personal development activities increased and vice versa. This is a direct impact of the MRO management behaviour.
3. The management of a given MRO leads the way to the work's safety up-keeping. The more correct, active, and effective is the role played by the management in this regard, the less are the witnessed maintenance errors. The roles of management spans widely in activities such as arranging for persistent morning briefings, appropriate manning and task distribution, quality control, quality assurance, etc. The observed sample showed direct relation between effective management performance and reduced number of maintenance errors incidents.
4. The observed sample showed varying levels of maintenance errors re-occurrences. Error re-occurrences are direct mapping of the overall organizational learning abilities of a given MRO. Employees and management both have their relevant roles in setting measures, individually and as a system, to prevent errors re-occurrences. MRO's with weaker management performance usually face greater rates of re-occurring maintenance errors or persistent unsafe behaviours.
5. The observed sample showed close coupling between level of information technology fluency of the working force members and the rates of safety-related maintenance incidents. For instance, maintainers who have more access to safety-related databases, human factors awareness information, workplace safety training, etc, are lesser vulnerable to error promoting conditions within workplace.

6. The observed sample showed that deficiencies in manning provisions, guidance, oversight, task design and work distribution, shift handover procedures, financial and / or technical resources, etc. can certainly impact the overall performance of maintainers and allow more room for maintenance error initiator situations.

4.2.4.3 Aircraft

1. An aircraft's design totally controls its maintenance. This control covers almost all aspects of the maintenance activities such as the overall maintenance programme of the given aircraft, maintenance cycle timings, parts operating and shelf lives, aircraft airworthiness provisions and limitations, essential maintenance facilities that, in turn, dictate maintenance locations, maintainers required skills and qualifications, maintenance task descriptions, maintenance materials, consumables, and tooling, MRO certification and associated regulatory conformity, and so many other inputs to the maintenance function. Thus it is totally of logic to observe that an aircraft's design can impact, positively or negatively, each one of the maintenance input assets whether they are human capital, software, environment, or hardware.
2. It is observed that poor *design for maintainability* of an aircraft, or any one of its components, can certainly form colossal potential for maintenance errors to be committed by maintenance individuals or teams. The most frequent of such drawbacks are poor for-maintenance accessibility, remote or confined working areas on aircrafts, complex parts design necessitating complex maintenance tasks, easy-to-incorrectly install parts, delicate or high technology sensitive components with special maintenance needs, etc.
3. The aircraft maintenance-related documentation and information exchange channels are vital in securing error-free maintenance. Any deficiency or malfunctions in these two attributes were observed to have led to critical maintenance errors. This involves the working aircraft logs, maintenance manuals, job-cards and other task-sheets, technical support publications and bulletins, feedback channels with aircrafts operators, manufacturers, and regulators, etc.

4.2.4.4 Operations and environment

1. A limited number of aircrafts within a given fleet of expanding duties will certainly induce higher demand on aircrafts availability. Thus higher serviceability

records are required usually within shorter intervals of time. This in turn induces huge workloads and work pressures on the maintenance workforce, a situation more prone to develop maintenance errors triggers. An airline company with higher aircraft redundancy would certainly have its internal or even contracting aircraft maintenance providers operating at lesser work pressures.

2. Overall climate settings and spontaneous weather conditions in which an aircraft is based and /or operated have significant influence on shaping types and frequencies of snags that that aircraft develops during operation or storage. Corrosion problems that sea coast-based jets suffer are larger in scales and severity compared to those suffered by Sahara-based ones for instance. Such variations in environmental conditions deeply influence types of maintenance jobs required and associated competences expected from the maintenance workers.
3. Environmental and operational conditions also impact the details of a given maintenance program and /or technical limitations allowed for components serviceability. The compressor wash frequency of a rotorcraft operating in rainy-cold weather in Europe for instance is far lesser than that frequency required for the same type operating at a dusty-hot environment near the Equator. Thus local conditions have their practically local consequences on the maintenance process regardless of the technical data given in manuals. This, if coupled with the pre-mentioned financial or political limitations, would certainly impose more hazards to the maintenance safety provisions.
4. Environment and weather also play critical roles in the correct completion of maintenance tasks by shaping the workplace environment. Windy, cold, hot, or dusty weather will totally state the cleanliness, ventilation, air conditioning, humidity, etc. of the workplace, and thus significantly influence tasks execution.
5. Operational requirements also influence safety of maintenance activities. A ‘dig-out’ maintenance mission usually applies certain lesser-firm technical activities to recover a defected aircraft when compared to the hub-based maintenance, where more adequate maintenance inputs are usually expected. Operational-induced shortcuts are dramatically observed to increase in the military setting or at more remote rural destinations. Maintenance errors are thus more expectedly fertilized within such scenarios.

4.2.4.5 Economics and politics

Aviation industry is a one that involves huge financial and statuary investments. Subsequently, aviation maintenance, as part of this industry, is greatly influenced by the economical and political environments surrounding a given MRO. The following observations are recorded in this regard:

1. Performance within a MRO is directly influenced by the surrounding economical environment. It is observed that MRO's existing within more stabilized to high levelled economies have, by nature of things, more access to financial resources that can guarantee more advanced technical assets and even higher qualified human capital. Better surrounding economy also indicates better established infrastructures that have their direct and / or indirect impact on maintenance activities execution. Stable energy supplies and efficient transportation networks are just only examples of such infrastructures. These observations are totally coinciding with the international reports indicating that regions of lesser economical power share greater rates of global aviation accidents and incidents.
2. Higher economical levels of living have their influence on the physical and psychological wellbeing of maintainers and even their higher management. Lesser life pressures greatly help maintainers to better perform their tasks at higher levels of accuracy and correctness.
3. Economics and politics have, collectively or in parallel, great impacts on the overall aviation maintenance functions. Restrictions or limitations superimposed by these two attributes can extremely hinder proper performance within MRO's. Flow of aircrafts components and spare parts, maintenance material, tools, and workplace assets, technical information and support, organizational learning and technology transfer, training and know-how enhancement, etc. are just some parts of the numerous maintenance inputs that can be damaged in this regard. For instance, a simple solution that a MRO can take, in a trial to overcome a political ban of aircraft spare parts, is to extend their life limits – usually without the necessary technical authentication, or even to re-use previously removed slightly-defective parts. Collecting major components of crashed aircrafts to be re-installed in operating ones is not unusual in such circumstances. The whole philosophy behind maintenance can thus be severely hurt.

4. Richer financial resources play the main role in better developing skills, competence, and overall technical fluency of the maintenance workforce. Human factors training, for instance, can be seen as some sort of luxury within MRO's that are starving to provide for the least operating inputs in the first place. Within the observed sample, the number and depth of the continuous development training sessions are directly related to the overall available financial funds.

4.2.5 Interviewing main aviation active informants

A major part of the ethnographic evaluation of aviation maintenance was performed through interviewing active experts and practitioners within this industry. Interviews, as briefly highlighted before in Table 4.1, covered colourful collections of aviation safety-related professionals in the accident investigation, operation, manufacturing, and regulatory roles. Detailed output accounts of these interviews can be presented here below.

4.2.5.1 Interviewing aviation accidents investigators

10 experts from the AAIB-UK and the BEA-France were interviewed regarding their reflection on aviation maintenance errors causes, consequences, and required measures for re-occurring prevention. Open-end questioning technique was basically adopted with some extended open discussion for deeper exploration of the field. The basic set of launching questions was as per Appendix A-1. The consequential output of these and other maintenance safety-oriented topics that were discussed with the investigators can be collectively summarized in the following account:

1. All interviewees declared that an aviation accident site or a certain condition of an aircraft that has witnessed an incident can not openly indicate the involvement of one or more maintenance errors. Only after thorough analysis of the collected related evidence when a maintenance malfunctioning can be concluded. Maintenance errors are generally of hidden nature and follow varying routs for propagation of consequences. This propagation of error consequences on the aircraft involved can take very long periods of time before a tangible indication for that error existence becomes observable, or before the incident or accident occurs.
2. Eight interviewees declared that aircraft documentation, operational logbooks, maintenance manuals with associated job cards, and maintenance history records are vital sources of evidence or information regarding the possibility of

maintenance malfunctioning involvement in a given accident or incident. Thus an appropriate handling and usage of such records has its crucial importance in the prevention of such maintenance shortages in the first place, as well as being decisive informing source during a substantial investigation.

3. A collective sum-up of all the interviews statements shows the most frequent types of maintenance errors that were involved in aviation incidents and accidents as:
    a. Incorrect installation of aircrafts parts and components.
    b. Incorrect sequence of component assembly.
    c. Forgetting open panels, loose parts, unfixed covers, etc.
    d. Omitting a step or more in the maintenance task sequence.
    e. Applying the wrong value of torques.
    f. Using the wrong type, calibre, part number, of spare parts.
    g. Forgetting tooling and other foreign items on aircrafts.
    h. Using the wrong type or quantity of gases, solvents, lubricants, fuels, etc.
    i. Incorrect data interpretation and / or entry in aircraft logs.
4. A collective sum-up of all the interviews statements shows the most frequent concluded causes of maintenance errors that led to incidents and accidents as:
    a. Lack of appropriate skills or aircraft knowledge
    b. Lack of close supervision or inconsistent self –certification
    c. Non-referral to maintenance manuals during tasks execution
    d. Failure to inspect.
    e. Poor aircraft design.
    f. Complex maintenance tasks or inadequate technical information /jobcards.
    g. Working during night or in inadequate conditions
    h. Task handover between shifts, or poor task distribution.
    i. Inadequate resources.
    j. Improper use and update of aircraft maintenance logs.
5. All interviwees stated that a maintenance error may not always be initiated at the individual maintainer level, and that a significant number of maintenance errors concluded had their initiating points (roots) emerging from higher levels within the given organization’s management. Six interviewees admitted that the concept of a ‘root causal factor’ is always referred to when meaning the very initiating

triggers of maintenance errors, these being usually deeply and latently existing within organisational scales. Thus, when the error is a direct consequence of the overall existing norms or other organizational culture issues, then the root cause is described as an organizational one, on the other hand, when the error is initiated due to the individual's malfunctioning, then such a shortage is either a personal active error or a violation.

6. All interviewees stated that the current frequently used maintenance errors investigation tool is the MEDA. Only four interviewees knew about other taxonomies such as HFACS-ME and Maintenance Error Investigation (MEI), they explained that such new taxonomies are yet to be introduced into aviation maintenance accident and incidents investigations. The depth to which human factors analysis is usually conducted during investigations depends on the complications and severity of each given accident in one orientation, and on the investigators' skills and fluency in human factors tools implementation in the other.
7. All interviewees stated that types of maintenance errors vary with the level of maintainers' technical skills and aircraft knowledge. Further explanations showed that while errors associated with poor skills or know-how shortages are usually committed by new inexperienced maintainers, it is noted that errors resulting from memory laps or procedural omissions are usually committed by highly experienced and qualified maintainers who, as part of the enveloping organizational norms, ignore consulting the maintenance manuals or other technical information sources.
8. Six interviewees stated that errors associated with inappropriate inspection or guidance failures are attributed to changes in oversight functions that followed the shift within industry from utilising independent quality control departments within the MRO to adopting self-certification of job performed.
9. All interviewees admitted that each of the fixed-wing and rotorcraft has its own distinguishing characteristics that directly influence their relative maintenance programmes and associated practicalities, but only three interviewwes clearly stated that there are no significant differences in maintenance errors committed in

both of the two types of aviation sectors in regard to error causal factors, propagation, and adverse consequences.

10. All interviewees stated that maintenance errors can be reduced by developing organizational learning from previous shortcomings. This is a totally reactive strategy with exceptionally high social and economical costs. Consequentially, the industry is looking forward to newer proactive measures to help further prevent errors re-occurrences. Some maintenance errors monitoring techniques, if introduced, may preserve such huge costs of the current organizational learning.

4.2.5.2 Interviewing aviation MRO's safety managers

To develop deeper appreciation of the aviation MRO industry perspective towards aviation safety and maintenance errors prevention, a series of interviews were held with active safety and quality managers of four different well established helicopter and fixed wings aircraft operators, those are: North Sea helicopter operators (Bristow, CHC), British Airways, and the maintenance facility of Eurocopter UK. A set of open-ended questions was carefully prepared to explore their and their organizations' perceptions of maintenance safety issues. Open concluding discussions were held at the end of each interview. The main pre-set interview questions are presented as well in Appendix A-2. The collective account of these interviews and the thorough discussions associated with them can be briefly summarized as follows:

1. All four interviewees showed that they had a type of safety management system already in place within the interviewed organizations in regards to maintenance safety and human errors prevention techniques, however, there are still areas of higher levels of risks that need to be addressed. These areas include further enhancement of individual's safety awareness, further involvement of maintainers to absorb newer concepts of workplace generative cultures, reporting schemes, etc.
2. All four interviewees emphasized the general need within industry to initiate major shift from the costly reactive safety measures to more proactive ones.
3. Three interviewees claimed that there is a general lack within industry of specific more scientifically-supported models that can help determining and verifying lists of duplicate inspection items within each MRO and for each given type of aircraft. It is further indicated that the current procedures in this regard depend mainly on the 'good will' and the accumulative experience of the personnel involved.

4. Two interviewees declared that there seem to be some persistent features within MRO's that continuously give rise to higher degrees of maintenance safety risks during day to day performance, such areas include high workloads and time tensions, tooling control, shifts handovers, and other points as well.
5. Two interviewees showed that although some safety-oriented devices and procedures are playing vital roles within the overall technical and procedural SMS's, but they have their drawbacks as well, for instance the HUMS, although being of critical value in assuring the overall aircraft integrity, but it involves very branchy and complicated implementation technical and administrative procedures, the thing that hinders the overall effectiveness and efficiency of the process.
6. All four participants indicated that generally they keep good information transfer channels with manufacturers. These involve a variety of folds covering the spare parts flow, technical support, technical documents, bulletins and other publications, and continuous maintenance programme updating. However, they all indicated that the areas of emergent technical consultation and determination of the local duplicate inspections are vital points needing more focussing.
7. The location of each MRO within the safety space depends on the values and work organizational culture. For the given interviewed organizations, all of them counted their location as to be of generative cultures where maintenance errors, as well as other safety concern initiators, are not totally assigned, as a blame responsibility, on individuals. Rather, some organizational learning process is taking place.
8. The overall appreciation for safety-oriented regulatory programmes, such as the various confidential voluntary reporting schemes, vary significantly between the interviewed MRO's: Whilst two organizations are totally accepting and participating in these schemes, other organizations still doubting any positive output of these programmes and thus they are not so keen to take part there within.

4.2.5.3 Interviewing helicopter manufacturers

Safety and quality responsible officials from Agusta-Westland and Eurocopter, two major rotorcraft manufacturers, were interviewed in the course of further examining the overall sociotechnical context of aviation maintenance. The interviews explored the helicopter manufacturers' perception and implementation of various design for maintainability concepts and other relative issues such as the position of human factors considerations in design, various procedures and basics of a given aircraft type maintenance programme, the determination of vital points and safety-sensitive maintenance lists. A list of pre-prepared questions for the interviews can be seen as per Appendix A-3. Main outputs of these interviews can be presented in two deterministic points that were favoured by both organizations:

1. Human factors understanding and practical considerations are being gradually introduced as part of the design for maintainability. However, a lot is still to be introduced in this regard.
2. There are no specific scientifically-approved mathematical or other models that are systematically utilized to determine the duplicate inspection items for each type. Pure reliance on previous experiences is the usual practice in this area.

4.2.6 Other ethnographic study activities

This stage of the research comprised as well other ranges of interlinked activities that worked to further enrich the stocks of both scientific information, and this writer's personal appreciation of the subject matter variables within numerous settings. As listed in Table 4.1 before, some of these activities are:

- Performing multiple planned visits to different MRO's. These included visits to both light and heavy maintenance lines of both fixed and rotary-winged aircrafts.
- Comprehensive studying of different types of aviation maintenance related documents. These included regulatory documents and reports, aircraft manuals, research publications, industry reports, etc. All types of documentary formats were consulted.
- Consulting industry experts and research centres practitioners. This included continuous discussions with current and ex-aviation maintainers, safety training providers, regulators, theorists and co-researchers, and a number of aviation maintenance and human factors lead experts.

The complete accumulative outputs of these and other activities as well are widely spread through out the successive stages of this research, and thus they are totally covered or referred to through various chapters of this thesis.

4.3 Maintainer context identification

This research's methodology calls for exhaustive understanding of the working context enveloping people under investigation, aviation maintainers in this instance. According to Cacciabue (2004a), the SHELL model is a recommended tool in such approach due to some major considerations:

- SHELL is the reference model adopted in many domains that are strongly affected by human factors issues, such as aviation, for accidents and incidents analysis. For example the Accident / Incident Data Reporting system (ADREP 2000) of ICAO and MEDA of Boeing are both based on SHELL.
- SHELL has been validated and widely applied in other working contexts for many decades.

Based on SHELL model, and using the previous accumulated knowledge, a sociotechnical relations chart of the maintainer and supervisor within a maintenance organization context was prepared in details as part of this sociotechnical initial study, the chart is given in Appendix B. The chart is an advanced step towards an overall perception of the work nature within MRO's. This is totally required as a base for the next prospective studies of this research.

4.4 Aviation maintenance tasks analysis

4.4.1 Defining tasks analysis

Seamster et all (1997) defined the Task Analysis (TA) as the analysis tool that "specifies the primary job tasks and their criticality, frequency, and difficulty, the performance objectives, and the behavioural requirements for the job". Annett and Stanton (2000) edited another definition for TA as "Methods of collecting, classifying, and interpreting data on human performance in work situations".

Sandom and Harvey (2004) showed that TA covers a range of techniques to describe, and sometimes evaluate, the human- machine and human-human interactions in a system. One of the best known TA tools is the HTA where a task is broken down in terms of goals and sub-goals and their associated plans. The end result can be a pictorial representation, often in a form of flowchart, showing the actions needed to achieve a successful completion of the task. On its own, this type of breakdown of the task can be useful in demonstrating where the problems are.

4.4.2 *Conducting maintainers task analysis*

According to the adopted methodology roadmap of this research, detailed analysis of maintainer tasks within work place was conducted using the HTA techniques. Maintenance activities were divided into two categories representing both maintainer and supervisor jobs. No previous works could be found that show exactly, or even in broader format, the various steps a MRO maintainer employee may take in order to have an autonomous aircraft maintenance job performed as standardized from the start to completion. Consequently, referring to maintenance manuals of many aircraft types, and to other associated technical documentation as well, and recalling all previous accumulated information through the previous stages of this research, including the elongated participant observations as per section 4.2.4, a basic TA of the aircraft maintenance activities is performed.

In this research, the maintainer job was typically sub-divided into twelve basic blocks of main tasks. These start by receiving the job notification and end by signing the helicopter (or aircraft as general) as serviceable or unserviceable. Each of the twelve blocks was in turn set into sub-tasks, which were further refined into partial sub-tasks and so on till all basic activities of the job were obtained. Similar approach was conducted for the supervisor activities. Appendix C shows brief parts of the first levels of the maintainer typical task analysis diagram.

4.5 Chapter summary

As a major approach to evaluate sociotechnical context of safety and human factors within aviation maintenance organizations, in particular those maintaining helicopters, a series of activities were conducted: These included organized visits to related manufacturers, operators and regulators, official databases reviewing, interviews and consultations with maintenance engineers, safety managers, accident investigation experts, regulators, human factors practitioners and detailed observation of written, verbal, and behavioural protocols within maintenance workplace. As a result, an all-inclusive awareness of the hazards, risks, and malfunctioning inherent within the overall maintenance system and its various components and activities was reached. Simultaneously, a parallel interpretive theoretical milieu was built encompassing various models of cognition, and working taxonomies within HMI settings.

5 Root Cause Analysis of Aviation Maintenance Errors

Science is wonderfully equipped to answer the question "How?"
but it gets terribly confused when you ask the question "Why?"
Erwin Chargaff

5.1 Introduction

5.1.1 Root cause analysis: The basic concepts

Human errors in aviation maintenance are generally discussed through two main approaches: HRA and HEC. The later mentioned approach has always been described as behavioural, contextual, or conceptual in nature. The most obvious response to a human error is to identify its causal mechanisms and consequentially altering the system such that that error is not repeated (Latorella and Prabhu 2000).

Root Cause Analysis (RCA) was firstly originated within the nuclear industry when accidents and incidents investigators discovered the need to go beyond the ‘what’ happened to accommodate a far wider scope of ‘why’ it happened, thus providing spacer room for real organizational learning. RCA thus facilitated an important way-out of the shortages in abnormal occurrence investigations which were usually terminated in the past without the ‘real’ cause of the mal performance, technical or human, being determined. The terminology governing the definition of ‘what was wrong’ or ‘what went wrong’ that induced an undesired occurrence or phenomenon are very precise. Many works tinted, collectively, a set of definitions concerning such conceptualities:

Causal Factors:

- Causal Factors: “The human errors and/or equipment failures that, if eliminated, would have prevented the incident or would have substantially reduced the consequences of the incident” (Kiihne 2008).

Root Causes:

- Root Cause(s): “the most basic cause that can be reasonably identified and that management has control to fix” (Paradies and Busch 1988).
- Root Cause(s): “A condition which is necessary for an accident such that if it had not been present, the precise accident would not have happened” (Kinnersley and Roelen 2007).

- Root Causes: “The most basic causes. They are almost always the absence, deficiency, or neglect of the management systems that control human actions and equipment performance” (Kiihne 2008).

Contributing Factor:

- Contributing factors: “Other factors (than causal factors and root causes) that were present and contributed to the accident occurrence and/or its severity” (Kinnersley and Roelen 2007).

It is clearly understood that there are no definite sharp boarders between these categories, such that a contributing factor in a given occurrence can be a direct causal factor in another. This is natural since “accidents are rarely clear-cut”. Identifying root causes of a given undesired occurrence effectively set the track for the necessary remedies to be put in place. To boot, it is always potential to systematize a set of databases of root causes which tackle individuals, paraphernalia, and organizational quality faults, thus allowing for closer determination of root cause trends for the given field. Understanding such trends, even more effective preventative recommendations can be designed not only to prevent reoccurrence of the given specific undesired events, but also to handle so may of the surrounding associated incident initiators.

Regardless of the exact types, depths, and efficiencies of the practical techniques that a safety-related investigation process follows, it is found that such investigation characteristically spans through three major sequential phases. These phases must all be covered communally and effectively if the investigation is to achieve its seen and hidden aims. These three phases are (Livingston et al. 2001):

a. Sequencing of events: This is the immediate stage after the safety-related occurrence. It comprises “obtaining a full description of the sequence of events which led to the failure”. All types of physical evidences, witness interviews, etc are utilized to freshly obtain and arrange the available pool of data into an understandable sequence of events.
b. Identification of causal factors: This is a later stage in which investigators ascertain the most critical events and / or actions from amongst the general sequence. Then direct cause (s) of each of these critical events is identified. Thus the overall causal factors of the safety occurrence are obtained. Many organizations usually stop their investigation probes at this stage due to the wrong anticipation that knowing the direct causes of the given occurrence is sufficiently enough for the overall organizational learning process.

c. Identification of root causes: This is much deferred stage in which direct causal factors are further re-visited such that their underlying promoting conditions, known as root causes, can be determined. Enquirers are tasked to use suitable tree structures or other relevant tools to identify these root causes which are often expected to be some pre-existing underlying conditions or contexts that first set the pace for the causal factors to exist and line-up.

5.1.2 This chapter: Investigating the investigations.

In this chapter, a detailed data-mining process is described. As a complement to the understanding of the overall sociotechnical context of the aviation maintenance, a thorough statistical analysis of a sample of 58 helicopter maintenance-induced safety occurrences is conducted to study helicopter accidents and incidents' survivability and the severity distribution of such occurrences. The sample is obtained out of reviewing 804 formal finalized investigation reports of previous maintenance related helicopter incidents and accidents worldwide Analysis is carried out to identify helicopter main and sub-systems mostly exposed to maintenance errors and to determine various types of such errors. Expected inherent relations between rotorcraft components affected and types of associated maintenance errors are investigated. Human factors – based triggers of these accidents and severe incidents are explored. The concept of 'Specific Failures' that immediately precede each of such occurrences is newly introduced for more detailed representation of the last breached individual and organizational safety barriers. Root causes of these safety occurrences were then sought utilizing the HFACS-ME taxonomy with a refined focus on its third order categories list. The influence of rotorcraft characteristics on MRO's and the maintainers overall on-the-job behaviour is discussed on the light of the root cause investigation results.

5.2 Investigating root causes of aviation maintenance errors

5.2.1 Data for factual and root cause analysis

804 formal helicopter accidents and incidents reports from Australia, Canada, New Zealand, UK, and USA were screened as per Table 5.1.

Table 5-1 Helicopter accidents / incidents reports selection

Country Of Events	Reports Issuing Body	Screened Reports	Analyzed Reports
Australia	ATSB	56	7
Canada	TSB of Canada	79	10
New Zealand	CAA of New Zealand	13	1
UK	AAIB	368	16
USA	NTSB	288	24
	Total	804	58

From these, a set of 58 safety occurrences were selected according to the following criteria:

1. Occurrences were exclusively maintenance-related.
2. They covered the period from 1995 to 2005.
3. Occurrences were from similar contexts regarding standards of provided training, human and materials resources, and overall technical performance. This formed a homogeneous sample of occurrences regardless of the country of event.
4. Occurrences involved modern helicopters currently utilized worldwide.
5. The associated formal reports were written with accepted reflection to human factors issues.

The selected sample of occurrences, listed in Appendix D, was then subjected to two separate stages of analysis:

1. General statistical analysis of accidents' factual data.
2. Human factors-based analysis to explore the root causes of these occurrence (having causal factors already been concluded within reports).

Findings of these two stages of analysis are thoroughly described and discussed through the following sections 5.3 and 5.4 respectively.

5.3 Factual analysis of helicopter safety occurrences

5.3.1 Objectives of factual analysis

The selected sample of helicopter maintenance-initiated safety occurrences is first analysed for factual data, this analysis targeted the achievement of the following objectives:

a. Drawing detailed appreciation of the severity level of maintenance-induced helicopter safety occurrences.
b. Recognition of helicopter most critical parts or systems in regard to maintenance sensitivity. Exacting emphasis is to be paid to smaller-sized fixations and power transmission elements.
c. Establishing recognition of various types of maintenance errors associated with different helicopter systems and parts.
d. Investigating existence of inter-relationships between helicopter hardware design and maintenance errors.

5.3.2 Constructing actual databases of safety occurrences

A fully detailed database was first constructed to analyze the general data of the selected 58 helicopter maintenance related safety occurrences. Each accident or serious incident was analyzed regarding severity, main helicopter systems involved, helicopter sub-systems or sub- components involved, and types of maintenance errors committed that led to the associated occurrence. The research was then focused to identify any correlation between helicopter affected hardware systems / components and the nature and types of errors committed by maintainers at various levels. Factual analysis database is given in Appendix E.

5.3.3 Analysis of factual collected Data

5.3.3.1 Safety occurrences severity

The given accidents and incidents population, as indicated by Figure 5.1, comprised various degrees of outcome severities, these included 6% of accidents that led to ‘minor injuries’, ‘serious injuries’ of 7%, ‘no injury’ incidents of 31%, and dominant 57% of ‘fatal’ accidents.

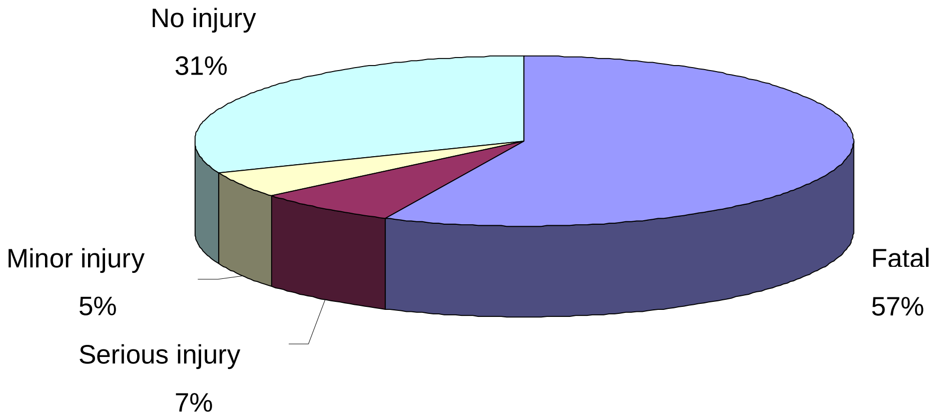


Figure 5-1 Severity distribution of the analysed helicopter safety occurrences

It is clear that helicopter accidents are highly critical and mostly of fatal consequences. Low occupant survivability (Hessmer 2001) of helicopter crashes necessitates more efforts to be focused on helicopter safety including maintenance practice issues.

5.3.3.2 Main helicopter systems involved

Analysis is required to identify helicopter systems that are most frequently affected by maintenance errors. Figure 5.2 shows the main rotor system as one of the most critical helicopter parts. 32% of the total cases of the given population involved main rotor system maintenance errors, this should be taken in contrast to the fact that work on the main rotor system usually involves a significant amount of the total maintenance activities (Eurocopter 1999). Given the criticality of this system with major moving parts rotating under the main load and manoeuvres of the aircraft, then all maintenance, inspection, and duplicated inspection activities on this system are naturally expected to be performed at high levels of perfection, however, this is not always the case here. This is attributable to the overall complexity of the system. Further explanation may be also furnished by emphasizing that human factors play huge role in causing maintenance and inspection errors for this system in particular, for instance, the usual high and compact location of the main shaft and rotor hub components give significant rise to errors such as those induced due to personal reach, handling, liquids level reading, and accessibility limitations or restrictions.

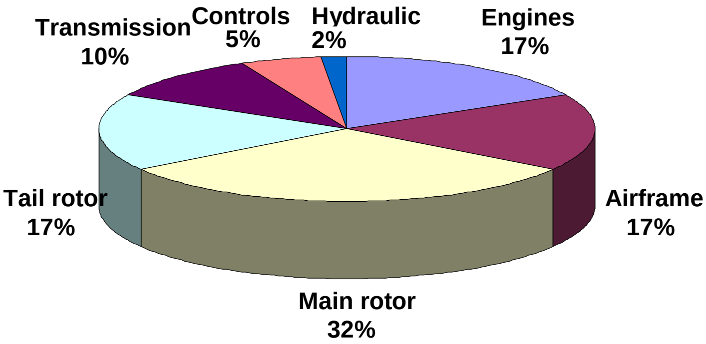


Figure 5-2 Helicopter systems involved in safety occurrences for the given population

Similarly, it is highly impractical to achieve error-free visual inspections for the mid sections or far tips of the cantilever-hanging main blades. Such visual scanning is in fact required by most of the maintenance procedures to be carried out on the upper and lower blades surfaces by having the maintainer climbing to the aircraft top or by standing on ground. Both of the positions are frequently impractical for high detailed inspection reliability (Melloy et al 2000, Floyd and Schurman 1995). Figure 5.2 also shows that the tail rotor assembly, engines, and load- bearing airframe components (e.g. tail boom, stabilizers, under-carriage) are the next frequently affected systems by maintainer's errors, each with 17% of the total accidents and incidents cases given. This again emphasizes the relation between system location, complexity, and accessibility and its being more exposed to maintenance errors. Transmission, flight controls, and hydraulic systems come next with lower occurrence percentages of 10%, 5%, and 2% respectively.

5.3.3.3 Helicopter sub-systems, components, and parts involved

Further details were obtained concerning sub-components of helicopter that were mostly maintained in wrong ways. Again a clear relation can be highlighted between the purpose, nature, shape, location, and fixation of a component or part and its potentiality to suffer a maintenance error. Analysis, as indicated by Figure 5.3, showed that two major groups of mechanical components were the most critically involved with total percentage of occurrence equal to 13% each: The first group, which comprises bolts, nuts, screws, and rivets, are found to be maintenance error - critical due to their small sizes, easiness to be mixed with similar parts, critical values of tightening torques required, confined work areas, difficult handling and / or visualization angles, and many other human factor-induced issues. The other group which similarly attracts maintenance errors comprises dynamic load carrier components that require precise detailed removal, installation, and complicated alignment procedures, these include gears, drive shafts, couplings, and spindles. ‘Tension –torsion straps’ (T-T’s) come last with only 2% of the total occurrence population, this is attributable to the significant number of helicopters that do not utilize these T-T straps, their low frequencies of maintenance / inspection cycles, and the usually rigid ‘preventive maintenance’ procedures applied on them (Dhillon and Liu 2006).

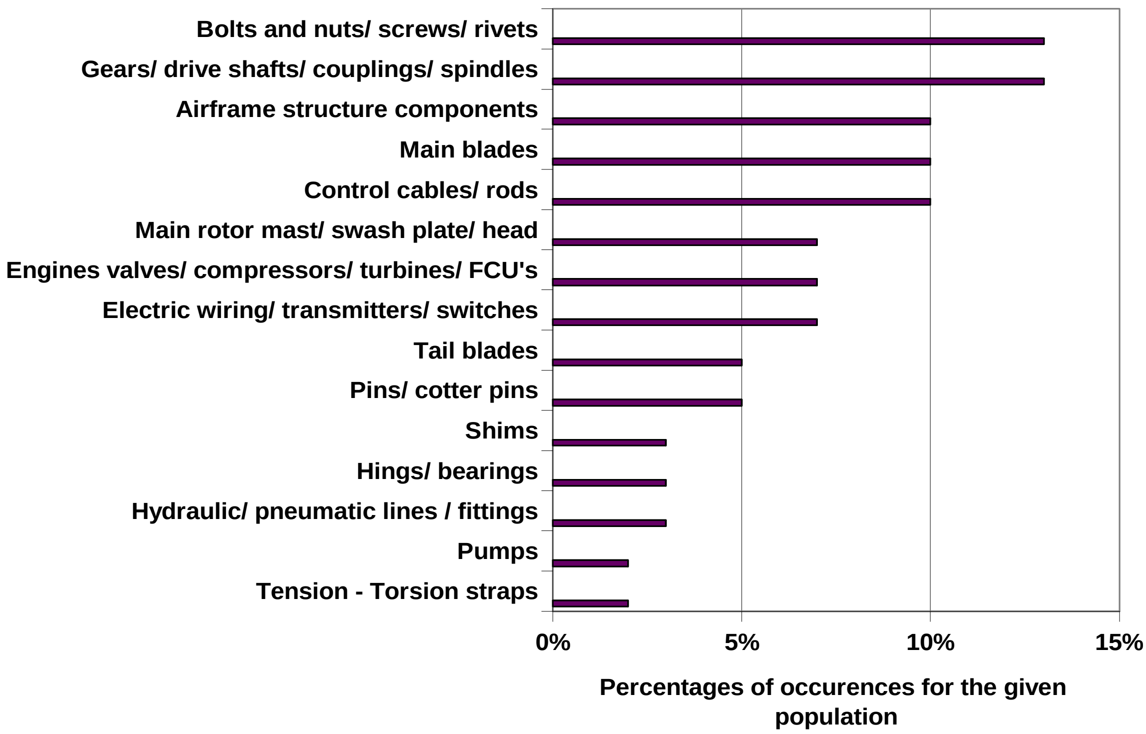


Figure 5-3 Helicopter parts and components involved in accidents and incidents for the given population

5.3.3.4 Types of maintenance errors committed

Analysis of the sample population gave clear identification of the types of maintenance errors that led to those safety occurrences. The significance of determining such types of errors stem from the fact that they, being the answer to the question ‘what had happened’, represent at the same time clear indications for the answer to the ‘ why it happened’ question. In other words: listing of these ‘errors types’ is a strong tool to help identify their causes. It is found that the most frequent maintenance error committed for 23% of the given sample is the usual combination of ‘No or improper inspection’ that led to the ‘defect(s) not detected’ error. The next most frequent error of 18% is the ‘skipping of maintenance procedure steps, Airworthiness Directives (AD), or Service Bulletin (SB) requirement’. ‘Incorrect installation’, ‘parts/material omission’, and ‘improper fitting/ torque values’ are the next most frequent errors with 14%, 12%, and 6% of the total occurrences. A total of fifteen types of errors committed within the whole given population of occurrences are represented in Figure 5.4. It is worth emphasizing that Figure 5.4 denotes direct listing of errors types as factual events before applying the human factors-based analysis during causal factors investigation in the next stage of this study.

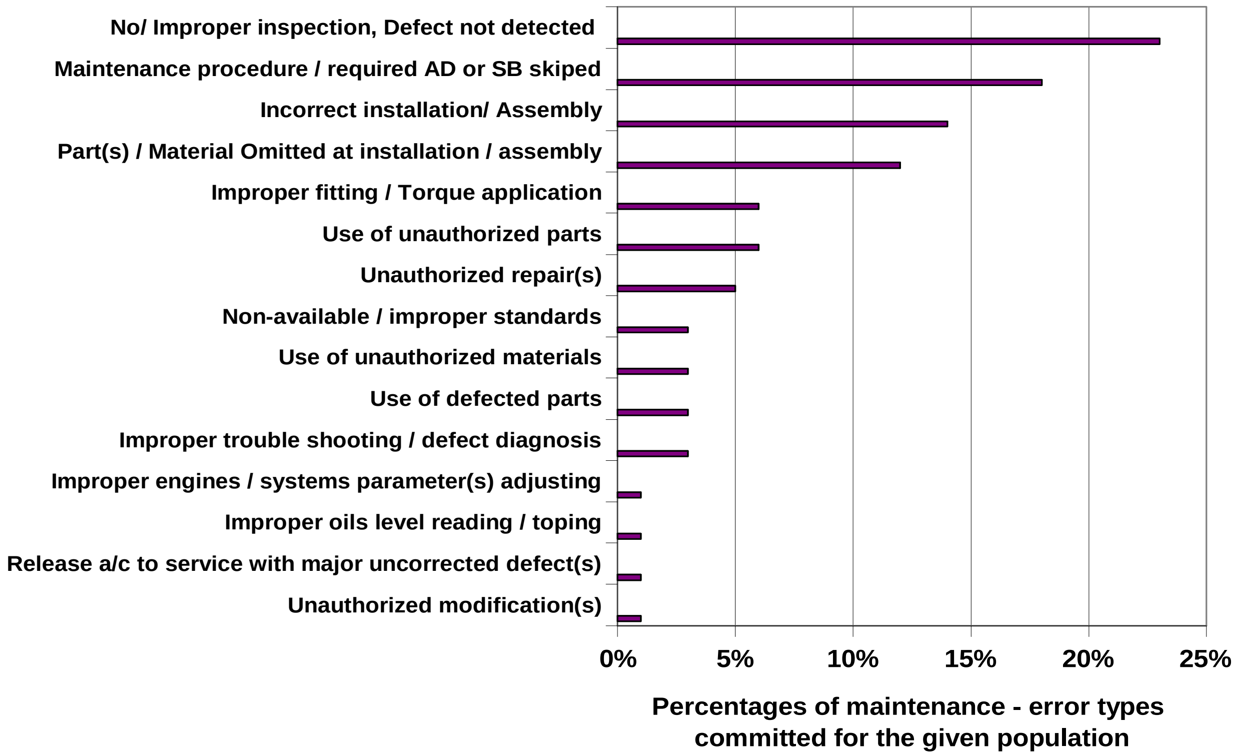


Figure 5-4 Types of maintenance errors committed in the given population of safety occurrences

Further, an interesting relation can be identified between helicopter systems, components, or parts and the types of maintenance-error committed. This can be best appreciated by considering the most frequently affected helicopter parts as indicated in Figure 5.3, in conjunction with the most frequent types of errors as per Figure 5.4. In view of the first two groups of ‘fine smaller-sized’ mechanical components that comprised bolts, screws, rivets, gears, couplings, and spindles, as given in Figure 5.3, and considering the amount of detailed procedures, critical orientations, sophisticated alignments, and torque values associated with their more frequent removals and installations, then it is obviously logical to coincide these activities with the second and third ranked types of errors committed, namely: ‘skipping procedures or technical requirements’ and ‘erroneous installation’ as indicated in Figure 5.4. Similarly, the next frequently affected helicopter parts given in Figure 5.3 are the major airframe components such as tail boom, stabilizers, main blades, and control cables. These ‘large’ parts are of very low frequency of removal and installation. They are mostly visually inspected or hand-touched / judged during daily or even most of the scheduled maintenance. This sort of inspection / judgment is also applicable to the ‘fine’ parts as well, the thing that gives rise to the number of overall visual inspection / hand judgment applications. Thus it is totally perceivable to observe that such inspections are the most frequent erroneous activities with often associated ‘undetected defects’ as recorded in Figure 5.4 (First category of improper inspections and undetected defects). An overall conclusion of this point is that: smaller frequently removed and installed parts are always affected by procedures mal-application or improper installation errors, while the rarely removed large airframe components are mostly exposed to improper inspection types of maintenance errors.

5.4 Human factors-based analysis of helicopter safety occurrences

5.4.1 Objectives of human factors-based analysis

The selected sample of helicopter maintenance-initiated safety occurrences is then further analysed from human factors perspective. This analysis aimed at achieving the following objectives:

a. Appreciating the influence of human factors on maintenance safety.
b. Appreciating the shares of organizations as well as individuals in maintenance errors causation.
c. Determination of human-factors based root causes of aviation maintenance errors.
d. Recognition of various scenarios of maintenance errors propagation.

e. Appreciating the exact nature of pre-conditions that promote safety occurrences.
f. Assessing the overall human reliability of aviation maintenance.
g. Listing of main performance shaping factors of aviation maintenance.

5.4.2 Flow of investigative human factors analysis

Reason (1997) introduced the 'Defences in depth' model of organizational accidents in which the combination of improper organizational latent conditions and unsafe acts performed by individuals usually leads to accidents. Having an organizational accident occurrence, investigation can follow an opposite flow direction from the last active failure that produced the immediate accident down to its roots in a wider organizational concept, and that is how this model can be utilized as a human factor analysis tool in organizational accidents perspective. The whole concept is illustrated in the previous Figure 2.7. Accordingly, the given 58 helicopter safety occurrences were analyzed starting from the most immediate individual failures and down to the initiating roots of the maintenance errors that were pre-present within the organizational level.

5.4.3 Introducing the 'Specific Failures', a proposed fourth order for HFACS-ME taxonomy

The published powerful HFACS-ME taxonomy (Schimidt et al 1998, Schimidt et al 2001, Crotty 2002, and Krulak 2004) gives detailed analysis for causes and factors that contribute to maintenance-related accidents and incidents regarding human factors concepts. The most detailed presentation of such an analysis goes down to the 34 list scale of the third order categories as shown in Table 5.2. In other words, the *immediate* causes and factors contributing to maintenance related safety occurrences are detailed to a scale of 34 categories which describe all the expected latent or active failures. Considering any of these third order categories, for instance 'Inadequate Organizational Processes' or 'Inadequate Documentation', it is arguable that there are many factors or conditions that can go wrong with the organization processes or aircraft documents. This gives rise to the question whether there is any means for finer resolution that shows further details regarding the immediate failures that exist prior to aviation maintenance-related safety occurrences. As an answer, the following simple theory has been developed:

In fact, each of the 34 third order categories can be illustrated by a limited number of examples. For instance, Schmidt et al.(1998) wrote: *" A manual omits a step in a maintenance procedure, such as leaving out an O-ring that causes a fuel leak is a case of (Inadequate documentation)"*. So if the most frequent case examples such as the one given above are gathered for each third order category, then these cases can be seen as a set of most frequent and logic sub-divisions of this category. For instance, 'Inadequate Documentation' category can be further specifically detailed into the following sub divisions:

1. No / limited documentation available.
2. Documents not updated.
3. Alerts/ Service bulletin not provided.
4. Documents / CD's unusable.
5. Documents contain conflicting information.
6. Documents contain insufficient information.
7. Documents not understandable.
8. Practical procedural step(s) omission.
9. Incorrect maintenance procedural sequence.
10. Required information / response delayed.

For more compactness, these "sub-divisions'' are to be known - for the purposes of this study – as Specific Failures (SF's).The same concept applies to all the 34 third order categories. SF's can either be latent conditions or active failures that immediately precede maintenance-related safety occurrences, they represent greater detailed definition of the causal factors leading to such occurrences, thus higher resolution of analysis can be obtained. Following such an understanding, 197 specific failures were only just introduced as per Table 5.2. These SF's have been either inspired from literature or genuinely introduced after thoroughly scanning sequences of the given population occurrences. These SF's are taken in this research to resemble a newly introduced fourth order set of categories, which were then utilized (as bottom line) in the first stage of the human factors –oriented analysis to determine the most frequent immediate factors and conditions that 'specifically' preceded each of the higher third order categories.

Table 5-2 Breaking down HFACS-ME 3rd Order categories into Specific failures

1st Order	2nd Order	3rd Order	Specific Failures
Management Conditions	Organizational Conditions	Inadequate Processes	Fail to enforce regulations Fail to provide oversight Fail to track performance Inadequate guidance Poor planning Task complex/ confusion Procedures incomplete Non existing procedures
		Inadequate Documentation	No/ poor documentation Documents not updated Alerts/ Service B. not provided Documents/ CD's unusable Conflicting information Insufficient information Documents not understandable Practical step (s) omission Information not available Procedure sequence Delayed informing response
		Inadequate Design	Purchasing failure Deficiency not corrected Modified equipment Unserviceable/ deformed component Design error Poor layout/ Configuration Poor/ no accessibility Easy to be incorrectly installed
		Inadequate Resources	Organizational improper manning Lack/ constrains of funding Lack of parts/ equipment Inadequate facilities/ materials
	Supervisory Conditions	Inappropriate Operations	insufficient operational resources Inadequate brief times Supervisory improper manning Inadequate schedule Improper task prioritization Non useful information Unrealistic expectations
		Inadequate Supervision	Failure to provide guidance Failure to provide oversight Failure to provide training Failure to track performance Failure to track qualifications Failure to inspect Task planning / organization Task delegation / assignment Amount of supervision
		Uncorrected Problem	ıgnoring risks Failure to enforce rules/ SOP's Use of unsafe equipment Use of untrained personnel Failure to follow rules/ SOP's Assigned unqualified worker
		Supervisory Misconduct	No corrective actions Documents not updated Unsafe condition not reported Parts/ tools incorrectly labeled Known hazards not controlled Corrective action delayed

1st Order	2nd Order	3rd Order	Specific Failures
Maintainer Conditions	Maintainer Medical Conditions	Maintainer Mental State	Complacency Distracted Mental fatigue Life stress Misplaced motivation Task saturation Channelized attention Peer pressure vulnerability
		Maintainer Physical State	General health Medical illness Physical fatigue Circadian rhythm
		Maintainer Limitations	Hearing limitations Visual limitations Insufficient reaction time Incompatible aptitude Physical capability/ strength Physical reach/ size
	Crew Coordination	Crew Communication	Terms not standardized Hand signal not standardized Documentation/ log failure Documentation delays Equipment failure (radio) Equipment use (light / whistle) Inadequate brief / pass down Inadequate shift turn-over
		Crew Assertiveness	Maintainer new in group Fail to brief / make suggestions Fail to correct discrepancy Fail to confirm messages Inattention to feedback Waiver when confronted Peer pressure
		Crew Adaptability / Flexibility	Maintainer emergency response Maintainer response to system failure Changes to routine Different from similar tasks Team member changes Disregard of constraint
	Maintainer Readiness	Maintainer Training / Preparation	Not trained for task Inadequate knowledge Unrealistic training Insufficient On Job Training Inadequate skills New for task
		Maintainer Certification / Qualification	Not certified in task Not certified in model Qualification expired Not licensed to operate
		Maintainer Infringement	Intoxicated at work Hung over Inadequate rest Drug / medicine use Night shift/ work

Table 5.2 . Breaking down HFACS-ME 3rd Order categories into Specific Failures (Continued)

1st Order	2nd Order	3rd Order	Specific Failures
Working Conditions	Working Environment	Lighting / Light	Night visibility Inadequate workspace illumination Inadequate flashlights Inadequate natural light
		Weather / Exposure	Extreme temperatures Ice on equipment/ precipitation Visibility in rain/ snow / fog Equipment / manning changes Inadequate clothing Wind
		Environmental Hazards	High noise level House keeping/ cleanliness Hazardous/ toxic substances Trip/ fall hazards
	Working Equipment	Equipment damaged / Unserviced	Equipment is of limited usability Eqpmnt unusable (damaged, unserviced) Equipment gauge/ calibration error Unsafe equipment (brakes / electrical) Unreliable / faulty equipment Inoperatable/ uncontrollable equipment
		Equipment Unavailable / Inappropriate	Equipment used elsewhere Equipment not in inventory Equipment unusable (inappropriate) Power sources inadequate
		Equipment dated / Uncertified	Calibration expired Open purchase / uncertified Extended beyond service life
	Workspace	Confining Workspace	Insufficient workspace Constrained position Constrained equipment use Insufficient maneuverability
		Obstructed Workspace	Vision obstructed (fog / smoke) Vision blocked (obstacles) Not directly visible Maintenance hindered Not easily seen/detected
		Inaccessible Workspace	Inadequate aircraft design Inadequate support equipment Workspace totally inaccessible Workspace partially accessible Workspace not directly accessible

1st Order	2nd Order	3rd Order	Specific Failures
Maintainer Acts	Maintainer Errors	Attention / Memory Error	Maintainer missed communication Loss of situational awareness Maintainer distracted / interrupted Maintainer fail to recognize condition Maintainer procedural mistakes Maintainer sequence errors Maintainer omitted procedural step
		Judgement / Decision Making Error	Maintainer exceeded ability maintainer poor decision Maintainer misjudgment /misperceived Maintainer misdiagnosed situation Maintainer improper procedures
		Knowledge / Rule-based Error	Maintainer inadequate task knowledge Maintner inadequate process knowledge Maintner inadequate aircraft knowledge
		Skill / Techniques Error	Maintainer delayed response Maintainer overuse of controls Maintainer inadequate skills Maintainer poor techniques Maintainer improper cross check
	Maintainer Violations	Routine / Norm Violation	Maintainer did not follow brief Maintainer bending of regulations /SOP's Use of incorrect equipment (as norm) Maintainer violated training rules Maintainer doesn't utilize checklists Maintainer skipped procedures Use of incorrect parts/ materials
		Infraction (Isolated) Violation	Maintnr violated single event to safe time Maintainer violated to expedite mission Use of incorrect equipment (isolated act) Maintainer skip publication cross check Use of incorrect parts / materials
		Exceptional (Severe) Violation	Maintainer falsifying qualifications Maintainer falsifying inspections Maintainer not using required equipment Maintainer violated under pressure Maintainer signed off without inspection Critical procedure skipped
		Flagrant (Blatant) Violation	Maintnr falsifying qualification (blatant) Maintnr falsifying inspections (blatant) Not using required equipmt (blatant) Maintainer other blatant violations Maintainer thrill seeking

5.4.4 Constructing error causal factors databases

Two complementary overlapping sets of databases were constructed regarding the selected 58 safety occurrences. These database constructions resembled a first step of a deep and comprehensive secondary data-mining process as pre-highlighted in Chapter 3. This was accomplished by revisiting the formal reports of maintenance-initiated helicopter safety occurrences in a more human factors-oriented and specified manner. It is an authentic feature of the HFACS-ME taxonomy to enable such belated reviewing of formal concluded reports as long as they contain the actual description to 'what happened' and the overall information of the 'associated contexts' that accommodated that happening. The databases were constructed in the following sequence:

a. The 58 Helicopter accidents and serious incidents reports were re-analysed using the upgraded HFACS-ME taxonomy of four orders. Each and every detail within each of the reports was measured by comparing it to the list of the fourth order 197 SF's in order to determine whether that detail fits with any of the SF's. Vast more improvement of analysis resolution was thus guaranteed if compared to that which would have been obtained if the analysis was started just by the 34 third order categories.
b. Detailed spreadsheets were then constructed to statistically analyse frequencies of occurrence of each of the SF's and whether there were any correlations between them that may show any specific patterns or grouping. This is illustrated in Appendix F.
c. The analysis was then taken one upper level to the collective 34 third order categories of the HFACS-ME. A second set of spreadsheets database was similarly built to investigate these categories. A benefit of this stage was to compare its outputs with those similar analyses of other very rare works (Schimidt et al 2001, and Krulak 2004) that only stopped at the resolution level of maximum 34 entries. The second set of databases is given in Appendix G.
d. The constructed spreadsheets of both the databases were used to statistically determine the root causal factors and other influential human factors that participated to the given safety occurrences under re-investigation.

5.4.5 Analysis of human factors –based databases for identification of aviation maintenance root cause factors

The secondary data analysis was continued by further investigating the occurrence frequencies of various upgraded-HFACS-ME categories. In almost every case of the 58 safety occurrences re-visited, it is found that the concluded causal factor(s) in each report were not the root ones. The data mining process showed clearly that deeper underlying factors or conditions were always there that initially set the track to the undesired event to take place. This is a genuine target of this research, to recognize deeper root causes of human errors that are usually committed during aviation maintenance.

The analysis was conducted in an opposite route to the sequence of events that preceded the occurrences as recommended by Reason (1997) and many other publications. Thus immediate specific failures were investigated first, then they were collectively classified to construct the third, second, and then first order higher management set of causal factors. This can be further detailed as per the following sections.

5.4.5.1 Most frequent Specific Failures (Proposed fourth HFACS-ME order categories)

To answer the question 'why' regarding helicopter maintenance errors, the first stage of the human factors-based analysis utilized the set of 197 Specific Failures as per section 5.4.3 to determine the most frequent immediate factors and conditions that specifically preceded each of the 58 analyzed safety occurrences. It is found that the most frequent Specific Failure associated with the given population is 'Required information not available in relative documents' with 5.1% of the total specific failures entries of 493 that directly precede these 58 helicopter accidents and serious incidents. 'Maintainer failure to recognize condition', 'no / poor documentation', 'non-existing organizational procedures', and ' maintainer inadequate skills' are the following four specific failures with 4.3%, 3.9%, 3.9%, and 3.7% respectively. Figure 5.5 shows the most frequent 30 Specific Failures observed. The first 5 specific failures represent 20.9%, while the total 30 top listings represent 70.4% of the total sample entries found. This is further illustrated through Figure 5.5.

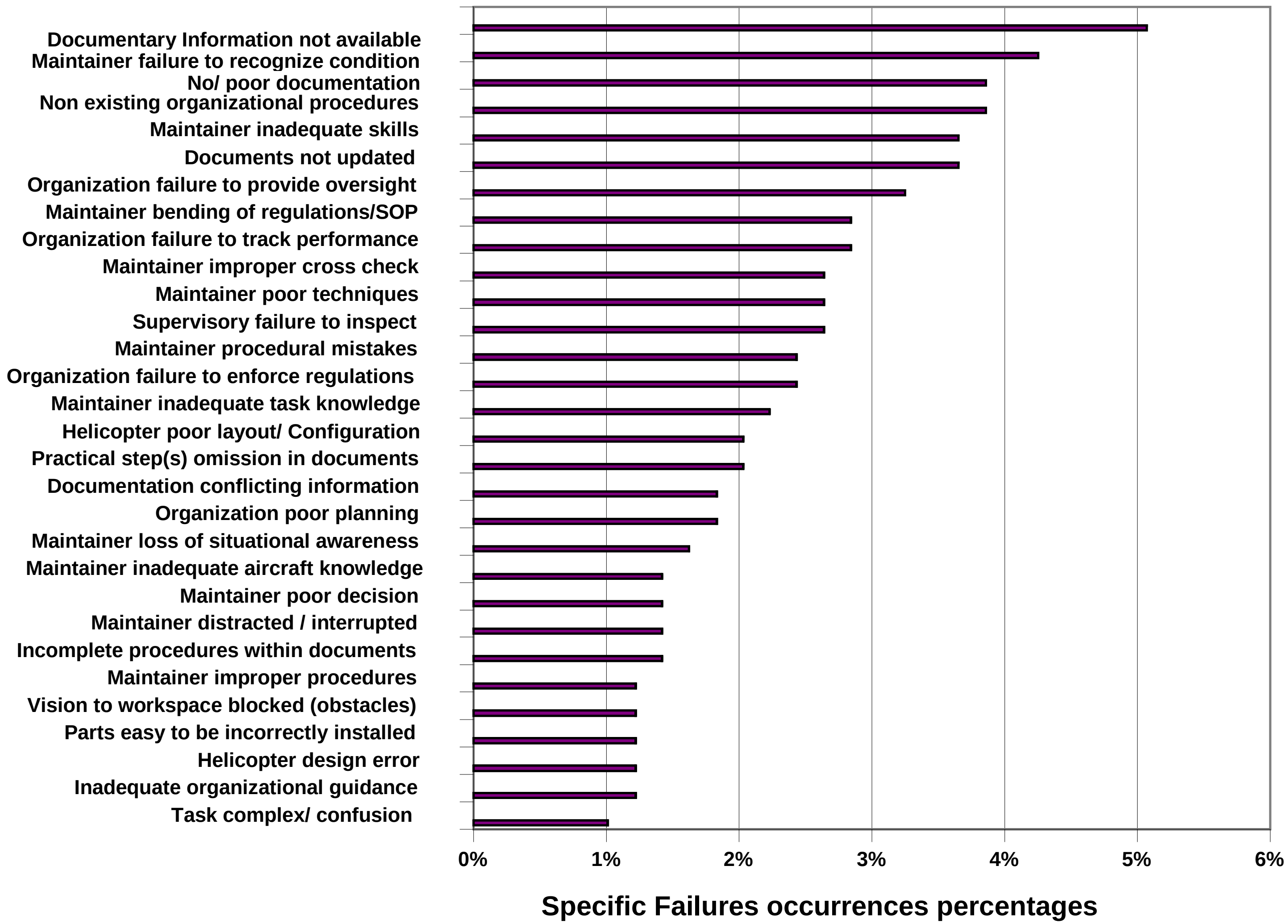


Figure 5-5 Most frequent 30 Specific Failures within the analysed 58 Helicopter safety occurrences

Further study of Figure 5.5 provides more focused resolution as per exact failures that led to the occurrences. The observed listings vary between management, supervisory, workspace conditions, and maintainer erroneous acts. Maintenance reliability can benefit from such specific listing by initialising the preparation and implementation of specific solutions to each of the revealed exact short comings. In another hand, a systematised organizational safety culture assessment can be derived referring to the *number* and *nature* of the recorded specific failures for each case.

The total 493 entries were un-evenly distributed between the 58 population cases. Figure 5.6 shows that only one occurrence took place due to a single specific failure. On the other end, very high numbers of Specific Failures are similarly witnessed in very few occasions as well. The most frequent cases that represent 65.5% of the total population comprised between 3 and 9 specific failures for each case. It is thus seen that the vast majority of the cases occupies the intermediate portion of the spectrum. This coincides with Reason's (1997) organizational safety space theory where the position of an organisation within the safety space is a plain resultant of the interaction between its intrinsic resistance and vulnerability to its operating hazards. Reason indicated that most of the organizations are located within an intermediate position of the safety space.

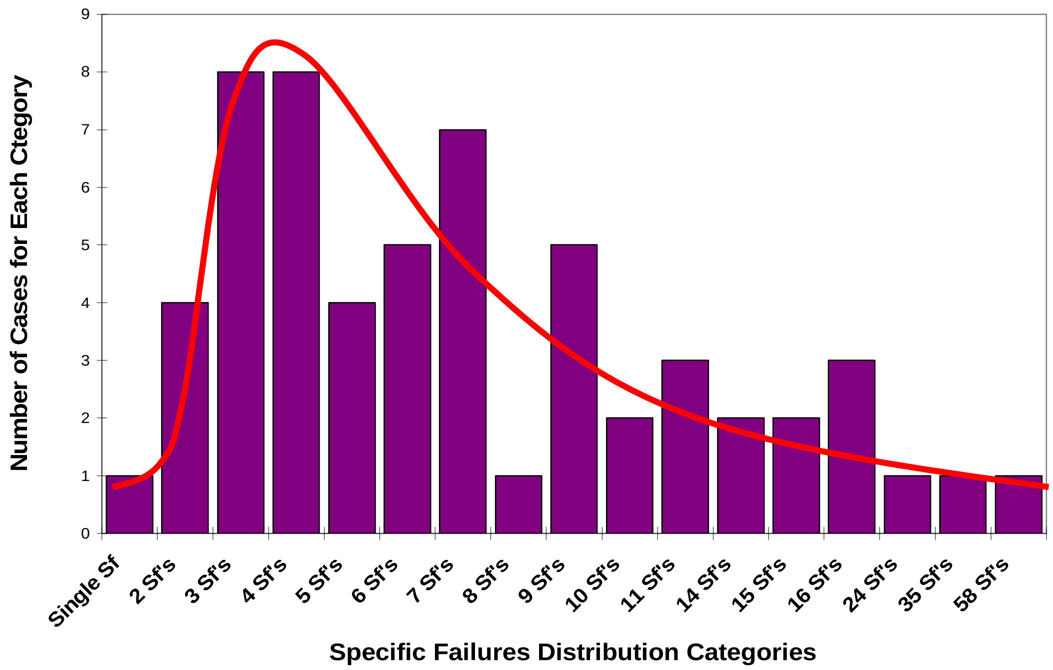


Figure 5-6 Specific Failures distribution for the given population

5.4.5.2 HFACS-ME third order analysis

The 34 third order categories were then used to analyze the given population in the search for their root causes. Specific failures were studied for each occurrence to indicate existence or non-existence of each relative third order category. A complete third order classification was then identified for the whole population. Figure 5.7 highlights the 'inadequate organizational processes' as the most frequent causes of maintenance errors at this level with 12.9% of the total selected sample. The next frequent categories are 'Inadequate documentations' with 11.1% and 'Maintainer attention / memory- based errors' at 10%. 'Maintainer skill / techniques- based errors' and helicopter 'inadequate design' groups come in the fourth and fifth ratings with 7.9% and 7.5% respectively.

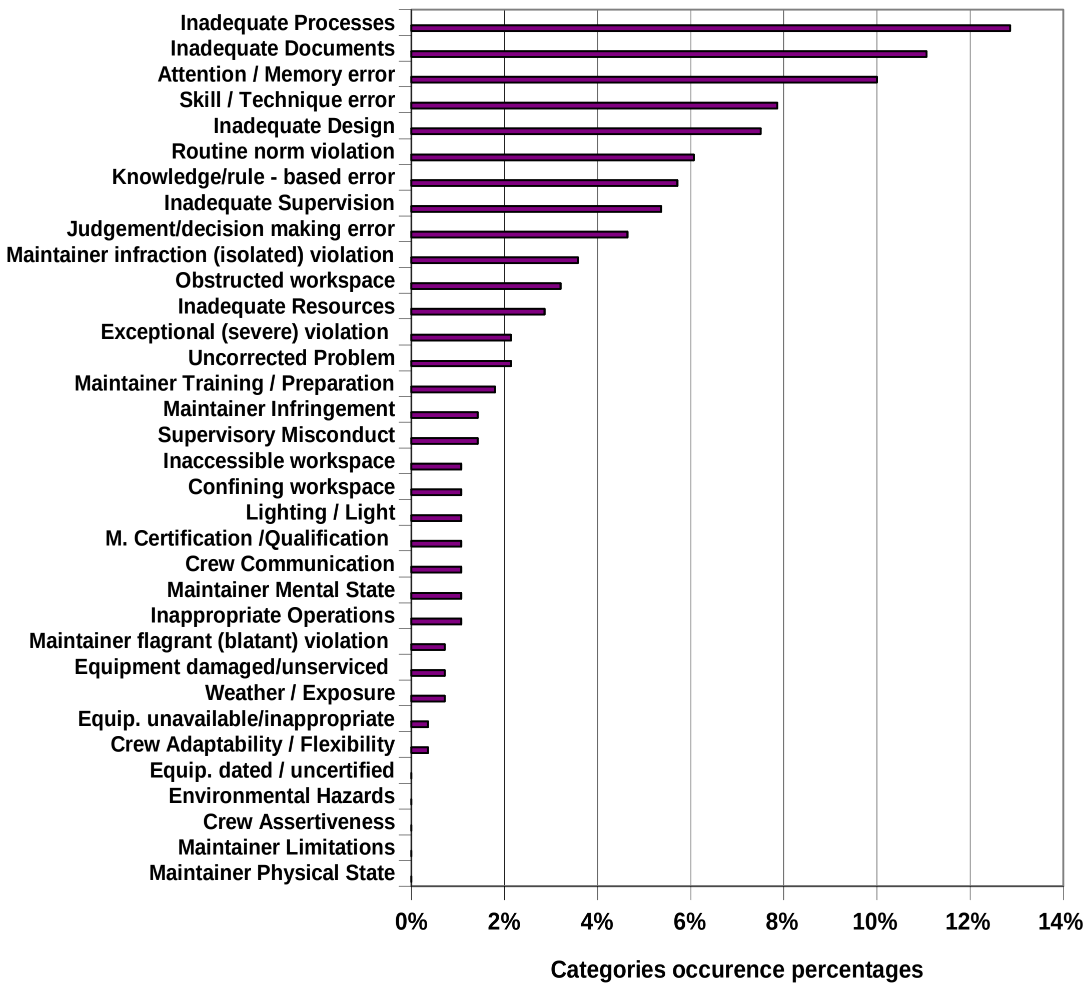


Figure 5-7 HFACS-ME third order root causes classification of the given sample

The obtained results (frequencies of occurrence) were passed, at the third order level, through reliability assessment for coding and analysis accuracy. The same HFACS-ME tool was used for a second independent rating, and then both 'Cohen's Kappa' and 'percentage of agreement' methods of inter-rater reliability assessment were applied.

5.4.5.3 HFACS-ME second order analysis

Tracking the root causes upwards in both individual and managerial folds, the obtained third level results were assembled systematically to indicate only 10 categories at the second order level of the taxonomy as given in Figure 5.8. A clearer picture indicating high presence of organizational malfunctioning can be observed: Logically, the collective contributions of inadequate processes, documentation, design, and recourses formed a dominant inadequate 'Organizational conditions' covering 35% of the total second order level causal matrix. Next come the 'maintainer errors' category with a 28% weight, those included memory, decision making, knowledge, skill, and rule-based maintainer shortages. It is also clear that the measures applied at the MRO's covered by the given population are reasonably effective regarding the 'working equipment', 'crew coordination, and 'maintainer's health conditions'. Each of these appears only at the low rate of 1%.

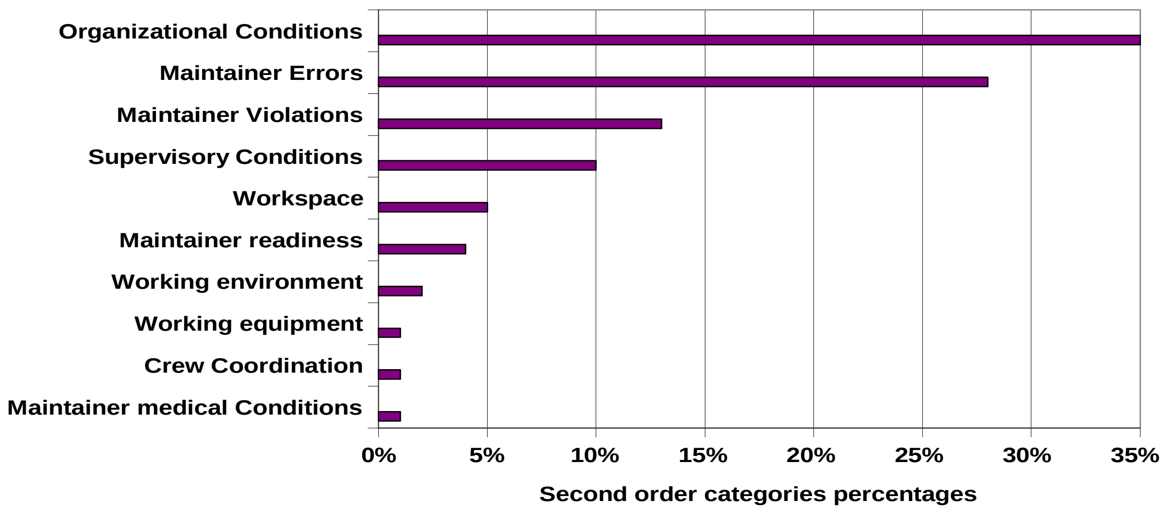


Figure 5-8 HFACS-ME second order root causes classification of the given sample

5.4.5.4 HFACS-ME first order analysis

Analysis was further taken upwards to identify weights of causal factors deeply rooted in upper management level or within maintainer's conditions and behaviour. It is found that 44% of the total causal factors involved in the sample occurrences have their roots originated within 'management' sectors, this is concluded by joining the 'organizational' and 'supervisory' contributions from the previous second level. These are mainly latent conditions of the system since almost all of the 'organizational' conditions and most of the 'supervisory' behaviour were always there for long times within the MRO establishments involved. The next share of causal factors were rooted within individual maintainers acts which are mostly active errors or violations that immediately brought about the undesired outcomes, these acts cover 41% of the total causes observed. 'Working' and 'maintainer' latent conditions represent origins for 8% and 7% of the total sample cause factors involved respectively as per Figure 5.9.

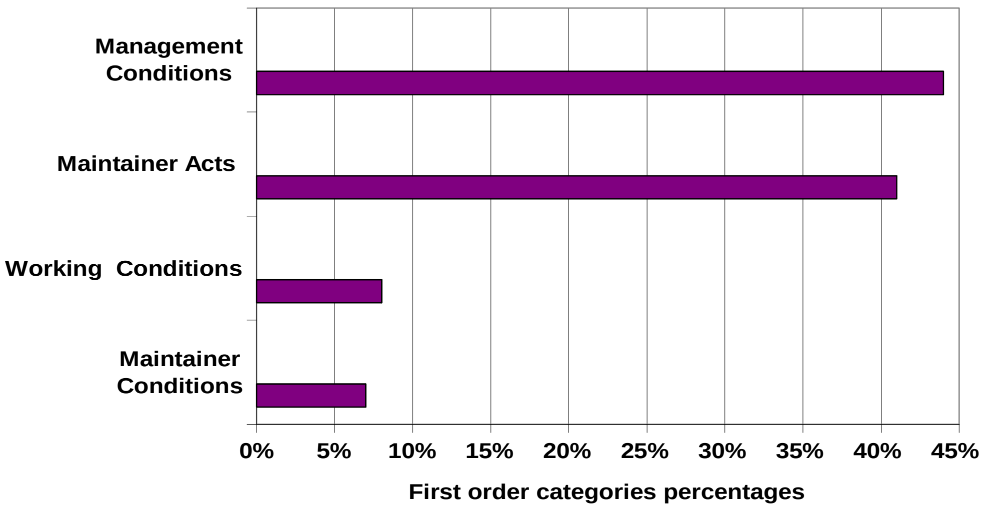


Figure 5-9 HFACS-ME first order root causes classification for the given sample

5.4.6 Verification of the human factors-based analysis reliability

5.4.6.1 Basic concepts of inter-rater reliability analysis

Many writers have discussed theory and techniques of Inter-Rater Reliability (IRR). Cohen (1960) discussed that in some situations in the clinical–social– personality areas of psychology, it frequently occurs that the only useful level of measurement obtainable in nominal sealing i.e. placement in a set of K unordered categories. Because the categorization of the units is a consequence of some complex judgment process, it becomes important to determine the extent to which these judgments are reproducible, i.e. reliable. The procedure which suggests itself is that of having two (or more) judges independently categorise a sample of units to determine the degree, significance, and sampling stability of their agreement. Gwet (2002a) showed that evaluating the extent of agreement between two or more raters is common in social, behavioural and medical sciences. He gave a reliability experiment where two raters (A and B) must classify N subjects into one of two possible response categories i.e. (1 or 2) , (True or False), (Yes or No) etc. The categories are assumed as disjoint (no overlap). The only possible out come of such categorization can be illustrated in the following Table 5.3.

Table 5-3 Distribution of subjects by rater and response category (Gwet 2002 a)

	Rater A		
Rater B	**Yes**	**No**	**Total**
Yes	a	b	B(Yes) = a + b
No	c	d	B(No) = c + d
Total	A(Yes) = a + c	A(No) = b + d	N

Where, a: Total number of subjects classified as (Yes) units by both raters.

b: Total number of subjects classified as (Yes) units by rater B and as (No) units by rater A.

c: Total number of subjects classified as (Yes) units by rater A and as (No) units by rater B.

d: Total number of subjects classified as (No) units by both raters.

Adopting similar tabulation, many other writers (Harris 1994, Hsu and Field 2003, Huddleston 2003, Gwet 2002b, Ludwig 2005, Chin Lee and Harris 2005) gave detailed formulations and examples for inter-rater reliability in the two frequently used methods, namely, Cohen–Kappa (K) and percentage of agreement (%). General formulation can be given, referring also to the above Table 5.3, as follows :

A. Cohen's Kappa method

$$K = (F1 - F2) / (N - F2) \qquad , K = 0.00 \text{ to } 1.00$$

Where,

$$F1 = a + d$$

$$F2 = [(a + b)(a + c) + (b + d)(c + d)] / N$$

$$N = a + b + c + d$$

The various degrees of agreement indicated by Kappa value K are given in Table 5.4 below.

Table 5-4 Degree of agreement between raters a according to K values (Huddleston 2003)

K Value ranges	Degree of Agreement between raters
0.08 – 1.00	Almost Perfect
0.60 - 0.79	Substantial
0.40 - 0.59	Moderate
0.20 - 0.39	Fair
0.00 - 0.19	Slight
≤ 0.00	Poor

B. Percentage of agreement method

Percentage of agreement = [(a + d) / N] * 100 %

The levels of agreement indicated by the percentage of agreement between raters are given in Table 5.5 as follows:

Table 5-5 Level of agreement between raters a according to percentage of agreement (Huddleston 2003)

Percentage ranges	Level of Agreement between raters
91- 100	Very high
81 – 90	High
71 – 80	Moderate
61 - 70	Fair
51 - 60	Slight
≤ 50	Poor

The obtained results of the 34 third order categories discussed in the previous section 5.4.5.2 were passed through reliability assessment for coding and analysis accuracy. The sample reports were re-coded and analyzed by a second independent experienced rater to assess these above obtained results. The same HFACS-ME tool was used for the second rating activities, and then both 'Cohen's Kappa' and 'percentage of agreement' methods of inter-rater reliability assessment were applied. Details are given in Table 5.6. The Kappa value for this inter-rater reliability assessment ranged between 0.483 and 1.0 with an average value of 0.766, similarly, percentages of agreement between the raters ranged between 72.22% and 100.0% with an average of 94.77%. Both the scales indicate substantial to very high rates (Cohen 1960, Gwet 2002a, Huddleston 2003) of coding and analysis reliability.

Table 5-6 Inter-rater reliability verification for the HFAC-ME analysis

Serial	Third Order Categories of HFACS-ME	Frequency of Occurrences for the given Population	Inter rater Reliability	
			Kappa Value	Percentage of Agreement
1	Inadequate Processes	36	0.483	72.22
2	Inadequate Documentation	31	0.778	88.89
3	Inadequate Design	21	0.667	83.33
4	Inadequate Resources	8	0.769	94.44
5	Inappropriate Operations	3	0.609	88.89
6	Inadequate Supervision	15	0.609	83.33
7	Uncorrected Problem	6	0.640	94.44
8	Supervisory Misconduct	4	N.a	100.0
9	Maintainer Mental State	3	1.00	100.0
10	StateMaintainer Physical State	0	N.a	100.0
11	Maintainer Limitations	0	N.a	100.0
12	Crew Communication	3	0.640	94.44
13	Crew Assertiveness	0	N.a	100.0
14	Crew Adaptability / Flexibility	1	N,a	94.44
15	Maintainer Training / Preparation	5	0.640	94.44
16	Maintainer Certification / Qualification	3	1.00	100.0
17	Maintainer Infringement	4	N.a	100.0
18	Lighting	3	N.a	94.44
19	Weather / Exposure	2	N.a	100.0
20	Environmental Hazards	0	N.a	100.0
21	Damaged / Unserviced Equipment	2	N.a	100.0
22	Unavailable / Inappropriate Equipment	1	N.a	100.0
23	Dated / Uncertified Equipment	0	N.a	100.0
24	Confining Workspace	3	N.a	100.0
25	Obstructed Workspace	9	1.00	100.0
26	Inaccessible Workspace	3	N.a	100.0
27	Maintainer Attention / Memory Error	28	0.778	88.89
28	Dated / Uncertified Equipment	13	0.852	94.44
29	Maintainer knowledge / Rule-based Error	16	0.557	83.33
30	Maintainer Skill / Technique Error	22	0.753	88.89
31	Maintainer Routine Violation	17	0.778	88.89
32	Maintainer Infraction Violation	10	N.a	94.44
33	Maintainer Exceptional Violation	6	1.00	100.0
34	Maintainer Flagrant Violation	2	1.00	100.0

5.5 Fault tree analysis to identify maintenance errors causal factors

5.5.1 Fault Tree Analysis: The basics

Fault trees are used to graphically represent system failures and their causes (Stanton et al 2005). Kirwan and Ainsworth (1992) indicated that a fault tree is a tree-like diagram which defines the failure events and displays their possible causes in terms of hardware failure or human error. This method was originally developed for the analysis of complex systems in aerospace and defence industries and they are now used extensively in PSA. They also indicated that typically within a fault tree diagram, the failure event is placed at the top of the fault tree and the contributing events are placed below. The tree is held together by AND / OR gates, which link contributory events together. An AND gate is used when more than one event causes a failure i.e. when multiple contributory factors are involved while an OR gate is used the failure event could be caused by more than one contributory event in isolation. Sandom and Harvey (2004) illustrated that fault trees trace backwards from the undesirable event to identify all the potential causes that might contribute to it. The complexity of the tree diagram is influenced by complexities of failures under analysis.

5.5.2 Objectives of building accidents Fault Trees in this research

In this research, fault tree analysis was performed on some helicopter maintenance-induced safety occurrences to facilitate achieving the following objectives:

a. Focusing understanding of maintenance error initiation and propagation scenarios.
b. Verifying the results of the HFACS-ME human factors-based analysis in regard of the determined root causes of each safety occurrence. This in fact represents genuine case of research ‘triangulation’ as discussed in chapter three. The firstly concluded maintenance errors root causes would be further emphasized via applying other parallel analysis techniques such as fault trees.
c. Appreciating various possibilities for ultimate prevention of safety-events reoccurrences. This is achievable by recognizing various critical intervention opportunities within the sequence of errors propagation that can be addressed in order for these sequences to be stopped.
d. Enriching the researcher’s scholarship by developing more skills of both fault tree theories as well as the associated practical software programmes.

5.5.3 Conducting Fault Trees analysis

Analytical Fault Trees were built for a selected range of accidents and incidents from the selected population of safety occurrences to further emphasise the concepts of maintainer errors mechanisms and sequences that they follow. Accidents and incidents were selected to various degrees of complexity. Maintainers' performance procedures that led to the safety occurrence were evaluated and compared against actual job cards from the Eurocopter (2000) Maintenance Manual, being a typical recommended reference manual for the helicopters involved in some of the occurrences under analysis, these are short listed as per Table 5.7.

The analysis was carried out using the reliability software Relex Reliability Studio 2006. An illustrative sample Fault Tree diagram of G-PUMH helicopter case over the North Sea is given in Appendix H. Results and analysis of these fault trees are further discussed in chapter 6.

Table 5-7 Short list of helicopter safety occurrences analysed using Fault Tree technique

Manufacturer	Type	Model	Code	Location	Date
Aerospecial	S. Puma	AS332L	G-PUMH	North Sea	27/9/1995
Aerospecial	S. Puma	AS332L	G-PUMA	S. F.G. Oil rig	06/3/1997
Aerospecial	S. Puma	AS332L	G-PUMB	Aberdeen airport	20/7/1998
Aerospecial	S. Puma	AS332L	H-BHY	Karratha/Australia	24/5/2004

5.6 Chapter summary

A total of 58 helicopter maintenance-induced safety occurrences were analysed both statistically and on a human factors basis. Helicopters are found to be more vulnerable to accidents and severe incidents such that they are mostly of fatal consequences. Investigation yielded that main rotors, tail rotors, transmission systems, and engines of rotorcrafts are the most critical and yet most exposed components to maintenance errors. Furthermore, parts requiring higher cognitive or intellectual concentration during assembly, installation, alignment, or adjustment are found more potential to suffer problems that lead to major consequential undesired outcomes. Many types of maintenance errors were listed, the most common one is improper execution of various inspections with higher risks of associated defects being left undetected.

During the human factors-based investigation, more affirmation of the nature of immediate causes directly foregoing the analysed occurrences is obtained. This was achievable by introducing an organized list of specific failures resembling each of the HFACS-ME taxonomy third order categories. This analysis also concluded that a large proportion of the studied accidents and incidents were brought about due to causal factors that were deeply rooted within organizational and managerial levels. Individual maintainer erroneous acts also gained major scores of such causal factors.

Finally, it is discussed that helicopter MRO's and their workforce are different in significant number of aspects to those of fixed wing airliners organizations. This is quite tangible regarding the clear differences in types of maintenance errors committed which are, in turn, subject to the different physical and operational natures of both types of aircrafts. Similarly, the differences between MRO's for fixed and rotary wing aircraft were discussed.

6 Retrospective Studies Finalization: Learning from Past Errors

We work because it's a chain reaction, each subject leads to the next.
Charles Eames

6.1 Introduction

6.1.1 The concept of organizational learning

Many writers who were involved in organizational safety and human reliability fields highlighted the crucial need of various organizations to embark on some levels of practicing Organizational Learning (OL). OL, which is increasingly approached by both academics and practitioners, is universally being furnished in two fashions:

- Reactive OL, comprising adaptation of new organizational settings or work contexts in reaction to previous events. This process is always observed as being more involuntary in nature and is usually established after paying very high social and economic penalties.
- Proactive OL, suggesting and adapting enthusiastic future-oriented changes of organizational settings or work contexts in search for better performance. This is a more cognitive process that calls for developments to be invented from the scratch.

These two folds of OL have been discussed in literature under multiple notions: single loop and double loop, lower and higher, tactical and strategic, and lately, adaptive vs. generative learning. The concept of single and double-looped OL was first introduced by Argyris and Schon (1978,1996) who saw the proactive orientation as being of higher mental activity that overpasses the single loop of the reactive learning. This is given in Figure 6.1.

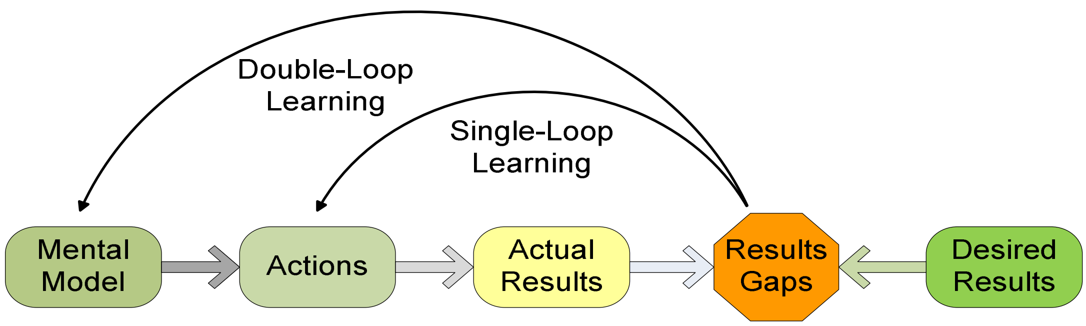


Figure 6-1 The single vs. double loop organizational learning model (Argyris and Schon 1978, 1996)

Carroll et al (2002) further utilized this thinking to develop a 4-staged OL model that form a spectrum of processes, with extreme limits located at absolute reactive and proactive ends. Figure 6.2 tells all about this.

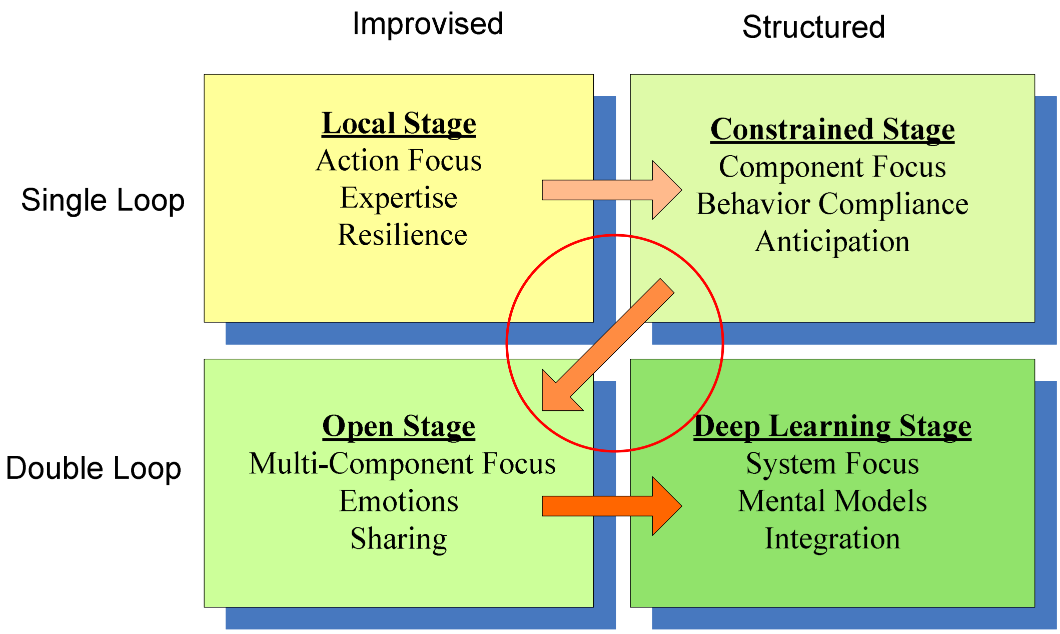


Figure 6-2 The 4 - Staged model of organizational learning (Carroll et al 2002)

Carroll et al. called for more work to be accomplished towards enriching the OL processes through more sophisticated overseeing-studies of organizational systems. This would be achievable by investing deeper intellectual capital, thus leading to the introduction of higher profile models.

This writer sees that Cacciabue (2004a) went a further step forward by introducing the HERMES model. HERMES is the 'matter-of-fact' manifestation of the overall pre-introduced concepts. The methodology sets practical procedures that join the understanding of previous lessons (reactive, single looped, tactical, etc) to the planning of future performance (proactive, double looped, strategic, etc).

This research, as a practical implementation of HERMES, captures the full sprit of this expanded OL conceptualization when being dedicated to aviation maintenance. The current work targets the digestion of past experiences (as discussed in the previous chapters) and then utilizing the product to set solutions for the future (as will be discussed within the following chapters).

6.1.2 This chapter

This chapter is the intermediate junction between the two backward and forward-oriented parts of this research. Graphically, this can be represented by the 'in-purpose encircled' directive middle arrow of Figure 6.2 above. The chapter comprises the transitional stage of summing up outputs from the retrospective studies which are, in a parallel fashion, the starting initialization of the directions for the following prospective studies. The chapter lists various deep causal factors of aviation maintenance, their accountability as performance influencing factors, and their associated patterns and scenarios of propagation. The chapter then sets the pace for the required future treatment of these outputs.

6.2 Maintenance error initiators and promoters

6.2.1 Performance influencing factors, root causes, and the Specific Failures within aviation maintenance

In addition to the accumulative results obtained through the sociotechnical studies as well as root cause analysis, a comprehensive set of Performance Influencing Factors (PIF's) present at various degrees within aviation maintenance can further be identified.. This set of PIF's, being direct mapping of past and current organizational situations, represents supplementary guidelines for future interventions development.

PIF's are generally referred to as "the conditions that influence human performance in a given context" (Kim and Jung 2003). These conditions are known in literature in various terminologies such as PSF, context factors, performance affecting factors, error producing conditions, common performance conditions, and some others as well. They generally describe the overall interaction between human, technology, and the surrounding organizational environment. The interlinking between these three inputs within aviation maintenance is so complex and overlapping such that it becomes of logic to take the PIF's within this industry in a holistic collective manner.

Referring to the concept and definitions of error root causes as discussed in section 5.1.1, it can be observed that the PIF's are actually a complementary part that form, with the root causes, the overall spectrum of human error initiators and promoters. In other words, the human error within complex sociotechnical systems is initiated as a result of a certain setting of root causes, then it is further catalyzed into a higher stage of seriousness and severity due to the presence of a certain setting of PIF's. The utilized

HFACS-ME taxonomy in Chapter 5 works to identify these collective sets of root causes and PIF's. The associated fault tree and task analyses aim at further reinforce these mechanisms of error initiation and propagation. Further in this orientation, it can be seen that the list of 197 Specific Failures introduced also in Chapter 5 (re-presented as well in Appendix I) thoroughly cover all the basic error-initiating and promoting acts and conditions within aviation maintenance. The mentioned taxonomy addresses all elements of the managerial, technical, and human ingredients of the industry. In fact, these listed SF's are either error root causes or PIF's shaping the performance within MRO's. As discussed previously in section 5.1.1, the distinction between these two categories in most cases is difficult due to the fact that a genuine root cause within a given case can be a clear PIF within another and vice versa. A schematic illustration relating the SF's, root causes, and PIF's is given in Figure 6.3.

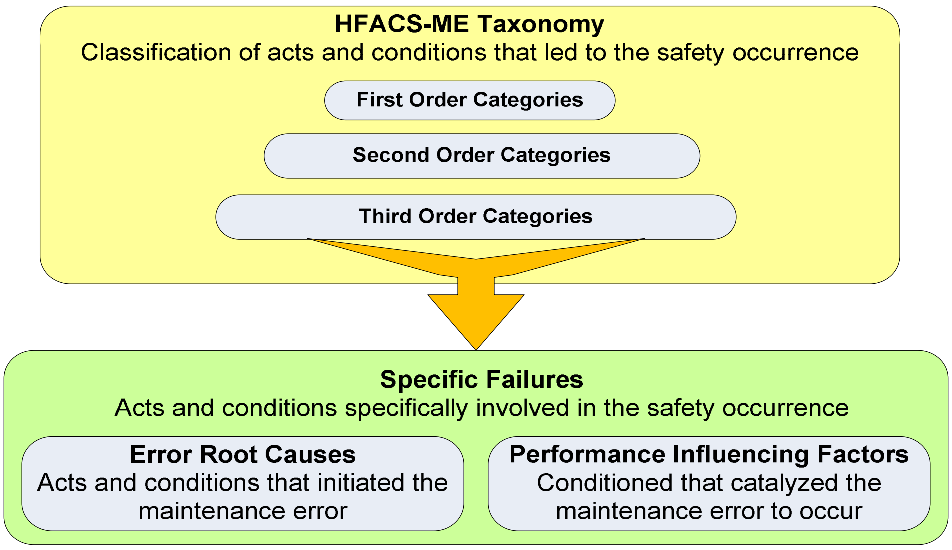


Figure 6-3 Corelation of Sppecific Failures, Root Causes and PIF's

By this final stage of the retrospective study, the initial SF's listing of section 5.4.3 is accordingly accepted as the actual holistic mapping of all the root causes and PIF's, prevailingly found within MRO's. These identified SF's will thus be utilized for the next prospective part of this work in accordance with the general requirements of the applied methodology. To this end, only a compact set comprising the upper most recurrent 30 SF's is found to be of most critical dominating influence on performance within MRO's. Consequently, mainly these top 30 SF's, re-listed in Table 6.1, will be considered for the next prospective part of this research.

Table 6-1 Concluded 30 SF's for the rotorcraft maintenance industry

Serial	Most Frequent SF's concluded by the retrospective study (as recognized by rotorcrafts MRO's)
1	Technical or other type of information is not available to maintainers
2	Maintainer's failure to recognize condition of a/c, workplace, task, etc.
3	Non or weak existence of organizational procedures
4	No or only poor technical documentation is available
5	Documents not updated
6	Inadequate skills of maintainers regarding their assigned tasks
7	Organization failure to provide oversight
8	Organization failure to track performance
9	Maintainer bending of regulations or standard operating procedures
10	Supervisory failure to inspect work done or other maintainer's duties
11	Maintainer poor techniques followed to carry tasks
12	Improper cross checks performed by maintainers to validate jobs
13	Organizational failure to enforce regulations
14	Maintainer procedural mistakes when following task sequences
15	Maintainer inadequate task knowledge
16	Practical step (s) omission in technical manuals, job cards or others
17	Aircraft poor layout or configuration
18	Poor organizational planning
19	Conflicting information provided within available documentation
20	Maintainer's loss of situational awareness
21	Incomplete procedures within documents
22	Maintainers are distracted or interrupted during their work
23	Poor technical or other decisions taken by maintainers or supervisors
24	Maintainer's inadequate aircraft knowledge
25	Inadequate organizational guidance
26	Aircraft design error
27	Aircraft parts are easily to be incorrectly installed
28	Vision to workspace is blocked (obstacles)
29	Maintainer's improper procedures within workplace or on aircrafts
30	Maintenance tasks are complex or confusing

The above listing, based on occurrence frequency, tells again about the intermeshing nature of the PIF's within MRO's. For instance, a condition that stems from an individual's perspective often indicates some organizational shortage at a higher level. Similarly, drawbacks in designing an aircraft or any of its parts, or even having defective technical documentation provisions, are coupled, in most cases, with obvious maintainer's mal functioning, or at least confused decision making.

6.2.2 The special case of rotorcraft

It is of great interest to investigate whether the special characteristics of helicopter have any influence on the managerial and individually-originated types of maintenance errors compared to fixed wing aircrafts. In fact, it is found that helicopter MRO's and maintainers are significantly different, in many aspects, from the fixed-wing aircraft maintenance personnel and organizations. Many factors leading to such an understanding can be highlighted. These include the criticality arising from the single load path to failure regarding the rotors and transmission systems, lack of redundancy, and low chances of emergency survivability manoeuvres. Such issues and other similar ones should undoubtedly influence the on-the-job personality, concerns, cautiousness, and general behaviours of helicopter maintainers. The relatively small size of helicopters limits the overall man-hours required compared to large aircrafts, particularly during major scheduled maintenance, thus smaller sizes and numbers of teams are logically expected. This should reduce all types of errors normally associated with crew coordination, teams formation, shifts handovers, task assignments, and supervisory and leadership shortages. Further, smaller groups of workers usually develop more tight personal relationships, mutual trust, and easier adopted professional and organizational qualities including-unfortunately- norms. The critical helicopter systems also influences the overall capacity of technical paper work and maintenance manuals procedures which are -in turn- usually critical, so any deficiency in such procedures will give higher potential to error generation. Maintenance cycle frequencies are higher for helicopter, nevertheless for its critical rotating components, thus more exposure to errors is expected. In fact, a helicopter, not like a fixed wing airliner, is naturally expected to suffer a number of snags after each flight, this is usually due to its tough operational conditions. Hence, helicopter corrective maintenance lines are always busier. These arguments may be firmly backed up by quick comparison between Krulak's (2004) results, mainly of fixed wing airliners as represented in the previous Figure 2.1 in Chapter 2, and by the findings of this study as given in Figure 5.8: Both analyses utilised HFACS-ME third level classifications for safety occurrences in coinciding periods and within similar overall organizational cultures. Concise information extracted from the two figures is reproduced here in Table 6.2.

Table 6-2 Most frequent causal factors of maintenance errors for fixed and rotor-wing aircrafts

Rank out of 34 categories	Fixed wing causal factors (From Krulak 2004)	Helicopter causal factors (This study)
1st	Inadequate supervision	Inadequate processes
2nd	Judgement / decision errors	Inadequate documentations
3rd	Attention / memory errors	Attention / memory errors
4th	Inadequate processes	Skill / technique errors
5th	Knowledge / rule-based errors	Inadequate design
6th	Inappropriate operations	Routine norm violations
7th	Inadequate documentations	Knowledge / rule-based errors
8th	Inadequate communications	Inadequate supervision
22nd	**********************	Inadequate communications

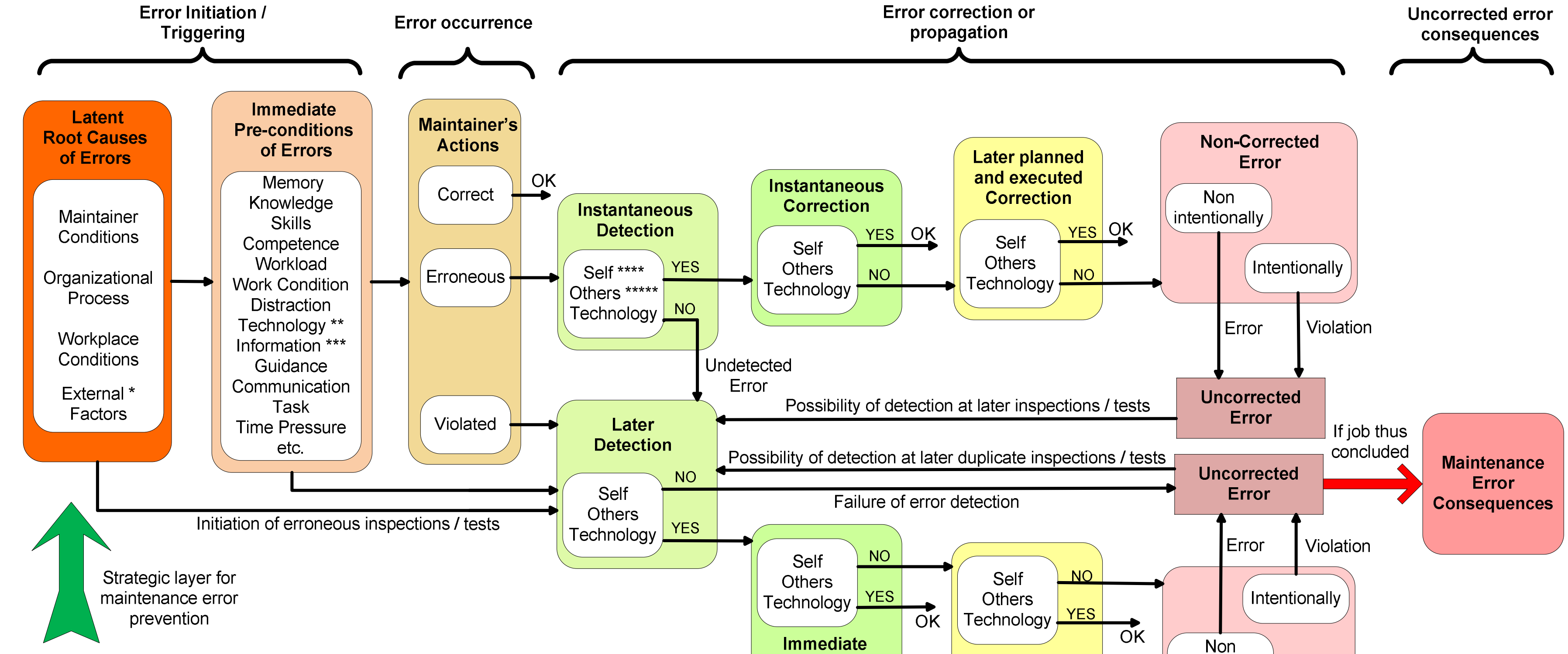
It is noticeable that the supervisory problems are the main error causal factors for the sample of majority fixed-wing airliners of high man-hours demand and large numbers of workers, whereas such supervisory malfunctioning comes only at a late 8th stage of importance for helicopters. In similar fashion, crew communication comes in the 8th and 22nd stages of importance as causal factor for fixed wing and helicopter maintenance workforce respectively. Conversely, while documentations problems are of higher concern for helicopter, it comes only at a similar late 7th stage of importance for the fixed wing aircraft maintainers. Also while Judgement and decision making represents the second important causal factor for fixed wing maintenance errors, but it does not show any major importance in the helicopter context as indicated by this study. Helicopter maintenance primarily suffers from inadequate organizational processes as dominant causal factors, these include inadequate regulations, oversight functions, guidance, planning, tasks, and procedures. These same inadequate processes come at a later 4th stage of importance for fixed winged airliner maintenance. Skill-based errors are seen here only for helicopters as an indication of job criticality and/or complexity, these errors also raise questions regarding the existence and effectiveness of relative training programs and their available funds. Finally, it is further interesting to notice that maintainer attention and memory errors are of typical weights as causal factors for both groups, this is quite expected since memory shortages are common human nature aspects.

6.3 Maintenance errors initiation and propagation scenarios

The first comprehensive reactive part of this study concluded sophisticated analysis of various scenarios that maintenance errors may follow during their causation, initiation, occurrence, and propagation. Consequently more accurate understanding of these and other points was obtained within the holistic branchy context of aviation maintenance. A newly introduced Maintenance Error History (MEH) model, as illustrated by Figure 6.4, summarises such an understanding, and describes various stages of maintenance errors and the close intermeshing between them.

Studying the model in Figure 6.4, although significantly simplified, it can be evidently seen that there are limitless numbers of variations in which a single aircraft maintenance error can initiate, occur, and develop. The possibility of any of the four here-listed collective error root cause categories to embrace an error initiator is always open, and such possibility dramatically multiplies if more than one root cause category is involved. The overall complexity in such a case becomes more tangible by recalling the fact that each root cause category classifies limitless numbers of individual unique root causes. Furthermore, again unlimited numbers of various combinations from the immediate causal factors before each error occurrence can be assigned for each setting of root causes combinations, thus the overall number of possible causation scenarios is again infinite. Things get further complicated and varied by considering the diverse chances of a committed error to be spontaneously detected and corrected, detected with remedy delayed, delayed in detection, and the undesired cases when errors surreptitiously propagate forward undetected at all.

It can thus be readily concluded that '*aviation maintenance error scenarios of initiation, occurrence, and propagation are infinite*' such that it is almost impossible to accurately measure or practically predict when, where, and how a 'next' maintenance error will take place. Consequently, this writer sees that it is totally non-logic as far as it is impractical to invest huge efforts of backward and/ or forward organizational learning capital trying to set future maintenance error occurrence predictors, instead, some other innovative applicable solutions must be sought.



Key

*	External	:	Exta-organizational factors that influences maintainer performance like family, financial issues, regulations, etc.
**	Technology	:	Aircrafts, aircraft parts, maintenance materials, devices, equipments, facilities. etc.
***	Information	:	Aircraft documents, manuals, technical CD, films, bulletins, links with manufacturers, etc.
****	Self	:	Activity carried out by the maintainer who first committed the error.
*****	Others	:	Activities performed by other maintainers, supervisors, quality controllers, etc.

Figure 6-4 Maintenance Error History (MEH) model of aviation maintenance error causation, occurrence, and propagation scenarios

The aptitudes of ordinary human reliability methods, mainly built on tough extended mathematics and probability calculations, seem questionable in providing true practical solutions that a busy safety responsible employee of a MRO can readily and trustfully apply to reduce and prevent his / her day o day threatening maintenance errors trends.

6.4 Possible intervention attack points

A truly natural question that an analyser of Figure 6.4 may develop in mind, after having digested all the complexity of the real world situations that that figure tries to resemble, would be: ‘ What is the best optimum point that an innovative solution may aim at to prevent or at least reduce aviation maintenance errors?’. A first glance will show that if error initiators, namely root causes, could be eliminated, then that would mean the logical possibility of having error-free aviation maintenance.

More precisely, huge efforts are always exhorted on developing tougher measures for inspection validation, or investing big amounts of money to persuade maintainers to concentrate more on their jobs. These and others as well have continuously been considered and could undoubtedly be further applied, but nevertheless, maintenance errors are still existent facts. The real answer would thus better be to eliminate the errors’ fertilizing swamps (Reason 1997), the root causes that vaguely, yet tangibly and uniquely exist within each and every MRO, or else within the rest of the industry sectors. Targeting the root causes implies firm and willing-full adaptation of strategic profile thinking:

- Acknowledging that root causes are out there, within each MRO.
- Acknowledging that by eliminating root causes, error-free performance can be achieved.
- Developing theories classifying, assessing, and modelling these root causes.
- Building practical scientifically-approved applicable tools that work to eliminate root causes in daily practice within industry.

These root causes, although very complex, but they are approachable. They are the simple, normally obvious, continuing, hazardous, lived with, yet un-noticed conditions and facts within a given maintenance organization. *They are so close such that they are not seen*, at least by the ‘home people’, the management and other staff and employees. A MRO may have employed the wrong lesser number of maintainers for many months or even years without noticing any of the continuous everyday risks that are associated with such poor manning. On the contrary, every thing might have been taken as ‘normal’ in accordance with the daily ‘normal’ work records. The deadly fact in this particular case, which organizations need to appreciate, is that ‘normal’ doesn’t imply ‘safe’. To conclude, they are the root causes of maintenance errors that must be challenged, not their generated consequences, in order for any intervention strategy to be successful.

6.5 Characteristics of the required corrective measures

Building on the above, a successful set of corrective measures that can effectively and efficiently influence preventing maintenance errors or at least reducing them may unavoidably incorporate a handful of features that can satisfy the complexity, dynamism, and randomness of the problem. The performed socitechnical research that was discussed earlier, in particular the ethnographic part of it, showed the real industry need for practical tools that can fill the gaps in this regard. For instance, the duplicate inspection items lists usually issued by manufacturers, regulators, and MRO’s organizations are still being finalized referring to mere previous almost habitual experiences in most cases. No mature scientifically-supported methods could be spotted as standing out in this orientation. The new generation solutions, consequently, should ensure appropriate provisions for the satisfaction of the above and other concerns through a number of ‘must have’ characteristics, a brief listing of which can be presented as:

- Proactive solutions are needed, no further social or economical penalties are allowed.
- Scientifically approved
- Such solutions must be practically applicable.
- Integrate-able within current SMS systems, no new infrastructures are required.
- Fight the root causes in the first place
- Free of complexity, no deep mathematics, overbearing paper work, or highly sophisticated expert systems are involved.

- Accommodate previous theoretical limitations and practical drawbacks like uncertainty handling, subjectivity of analysis, transformability of models into user tools, capital expert systems, complicated training plans, inter-industry communication, finance, etc.
- Must be dynamic, upgradeable, comprehensive and yet suitable for each individual organizations
- Can handle the problems given by the four categories of root causes (and their sub-lists) in addition to aircraft design and error-prone features.
- Can handle all possible causal factors and all problem associated with job validation and inspection.
- Make sound representation of OL at its higher (double loop, strategic, generative) patterns
- Give theories, models in scientific background then set practical tools
- Economical, time saving
- Starting from current situation and goes gradually towards zero errors
- Help developing universal databases and standard of safety monitoring
- Joins manufacturers, regulators, MRO’s, as well as academia and other research institutions.
- Etc.

These and other characteristics are taken as dictating guidelines for this research work in its second prospective part as will be discussed through the coming chapters.

6.6 Chapter summary

This chapter is the intermediate channel between the two major parts of this research. It lists the chief findings of the elongated retrospective studies and uses them to predict and provide needed guidance for the following proactive research to be furnished on those findings. The chapter showed that the scenarios for aviation maintenance errors initiation, occurrence, and further propagation are infinite. Thus it is concluded that only eliminating the basic root causes of errors will lead the way for a successful error-free performance.

PART THREE

INVENTIVE PROSPECTIVE STUDIES

7 Creative Modelling of the Aviation Maintenance Monitoring Process

A thought is an idea in transit.
Pythagoras

7.1 Introduction

7.1.1 Thinking proactively

The emerging philosophy of ‘Proactive Safety’ has been called for by many writers, after the habitual treatment of reactive accidents and incidents investigations with their expected safety recommendations that usually follow (Braithwaite et al. 1998, Liou et al. 2007, Edwards 2007, Shyur 2008). High-reliability organizations need to espouse more ‘resilient’ orientations in their safety improvement plans, especially when addressing critical complexity or uncertainty problems (Mearns 2009, Grote 2007a). Such organizations are called upon to demonstrate proactive awareness towards minor performance fluctuations that could indicate wider potential failures. It is now well understood by the industry that human error can never be utterly prevented, nonetheless, it can widely be confronted and reduced by acting proactively through multiple options (Kontogiannis and Malakis 2009). “Reacting proactively means taking a more comprehensive look at the human factors of supporting safe operation” (Burns 2006) as a genuine improvement over the saturated simple error analysis procedures or performance efficiency enhancements.

Building on the overall outcomes of the retrospective part of this research, the next part of it will thus focus on developing tools that can be used by the industry to further enhance aviation maintenance safety. According to the conclusions of Chapter 6, two major requirements must be fulfilled by such tools:

- They must be proactive, to spare social and economical losses definitely associated with reactive treatments.
- They must work to eliminate root causes of maintenance errors.

These two main objectives can be fully satisfied by introducing a proactive scheme to continuously monitor existence, thus, furnishing the way to the elimination of errors root causes. Figure 7.1 conceptualizes this thinking. Such proactive process can take place within two intermeshing cycles: The first one ensures the practical execution of root causes detection, elimination, and thus performance improvements within MRO's, aircraft design offices, or during aircraft and other equipment manufacturing processes. The other wider loop comprises all the scientific-based research and development activities that produce tools for the industry to utilize. Hence, the current research can be seen as a part of such collective industry-scientific movement.

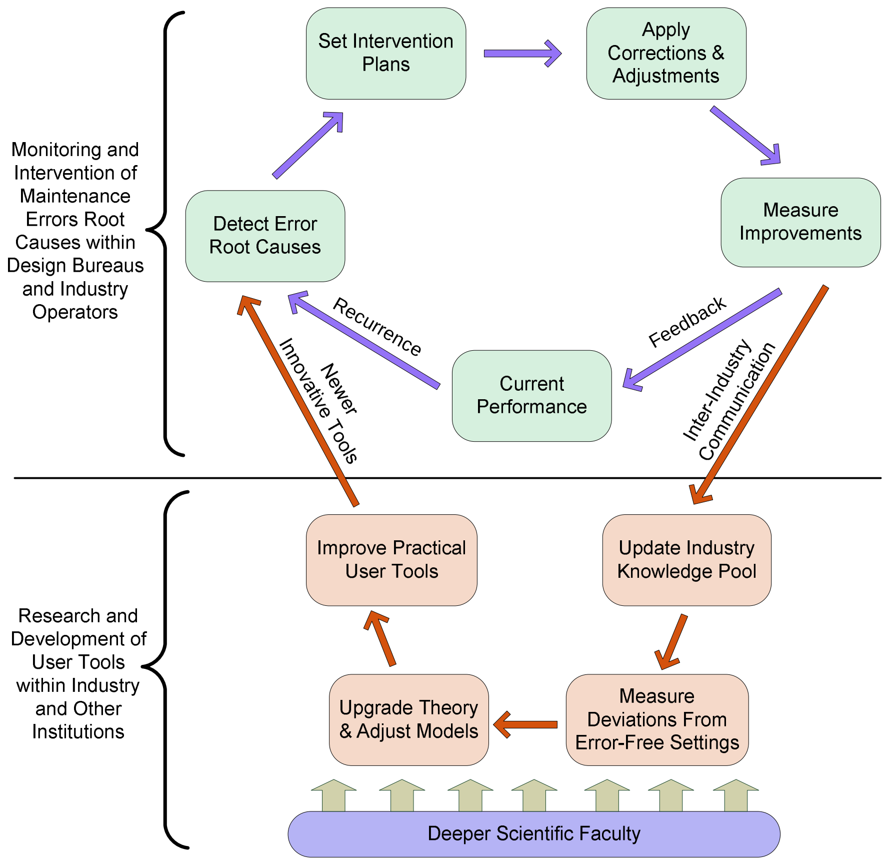


Figure 7-1 Conceptualization of proactive aviation maintenance safety by eliminating maintenance errors root causes

A second glance to the main categories of aviation maintenance errors root causes, as also discussed in Chapter 6, will assist the understanding of root causes as being of two main foundations:

- Human-based root causes: Those which are directly induced by individuals or collective teams or groups. These are root causes found within maintenance lines, workplaces, hangars, factories, or initiated within management, legislators or regulators offices.

- Machine-based root causes: Those which are directly found / induced by hardware including aircrafts, equipment, tools, material, etc. To this point, it can further be seen that an indirect remote human influence can still exist within these hardware groups of root causes, for instance, during design or manufacturing processes.

Accordingly, proactive intervention scenarios aiming at eliminating maintenance error should strategically be designed to address these two main groups of root causes.

7.1.2 This Chapter

In this chapter, a new set of hypotheses, models, and practical tools are introduced to proactively address the accumulation of crucial maintenance human error causal factors within the aviation maintenance environment. The chapter discusses the existence of root causes and the best strategies to eliminate them. This is the first part of the prospective stage of this research.

7.2 Introducing the SWAMP Model of maintenance error propagation

Experts have already compared human errors within safety-critical industries as mosquitoes. This is quite reasonable since no one can ever tell when or where would be their next 'bite'. In fact, huge efforts have already been paid to produce an answer to this simple, yet challenging question: *What would be the scenario leading to the next incident or accident within a given safety-sensitive organization? And consequently, what measures can be taken to prevent such scenario?* For the case of mosquitoes, many protective methods, barriers, and sophisticated vaccinations are already in place, but drying the insects' initial fertilization and breading swamps will always remain to be the optimum solution. It is high time now to think same-wise for the prevention or at least reduction of human error-caused safety occurrences within high reliability industries. We should try to proactively eliminate the 'situations' leading to human error rather than trying to treat the human nature itself.

Based on both the well known Swiss Cheese and SHELL models of accident causation and HMI (Reason 1997, CAA 2002b, ICAO 2005), a new human error propagation model is introduced, in this research, as 'The Swamp' model which explains the sequence of maintainer and supervisor errors initiation and propagation (within a MRO) that always precede maintenance-related aviation incidents and accidents. The model is given as per Figure 7.2.

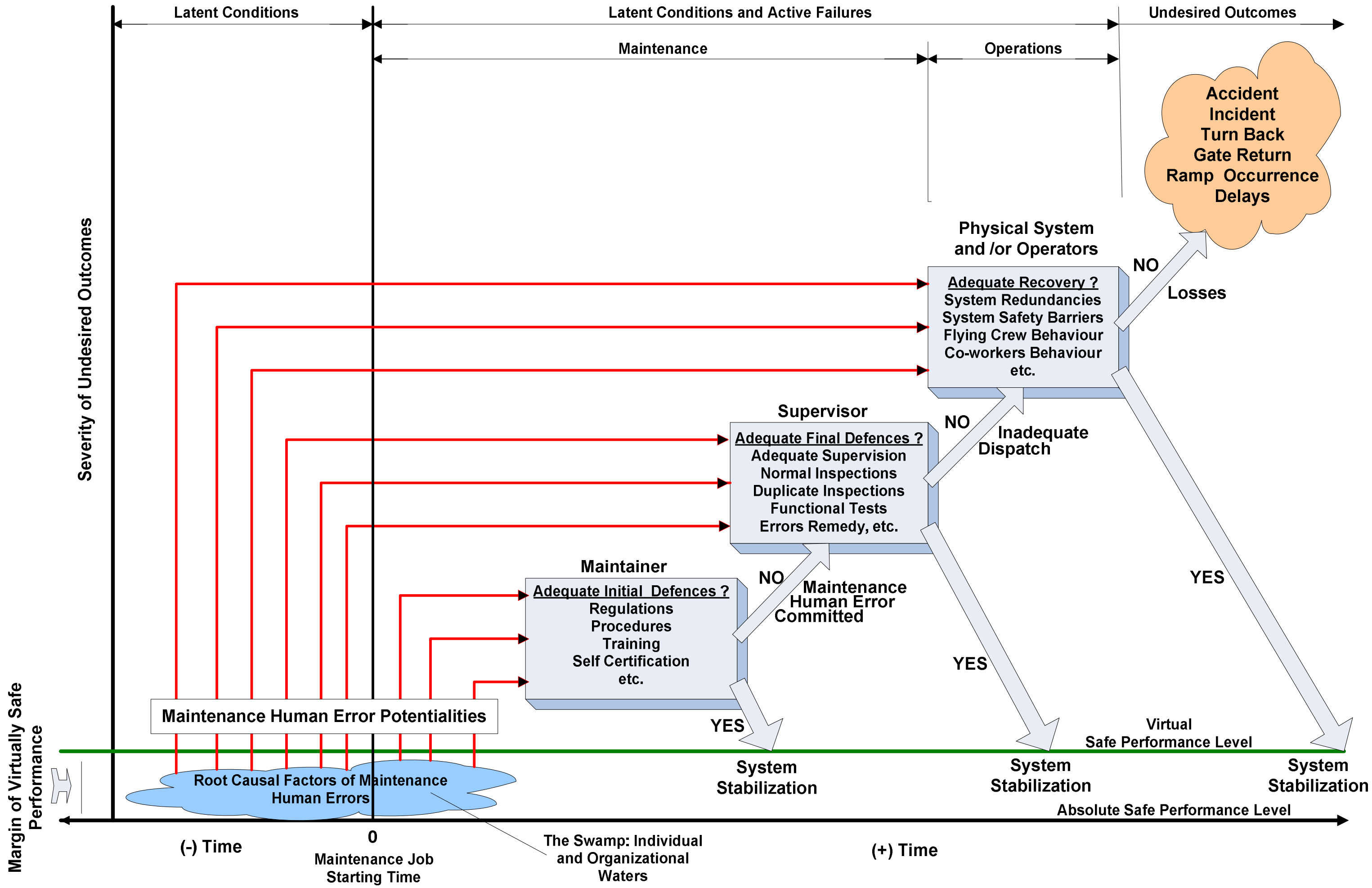


Figure 7-2 The 'Swamp' model of maintenance human factors- related error propagation

This ‘Swamp’ model shows the sequence and propagation of safety-related human maintenance errors through the behaviour of aircraft maintainer, supervisor, crew or other associated personnel. The main component of the model being the ‘Swamp’, a persistent situation of latent conditions (intermittently disturbed and exaggerated by some active failures) within the MRO that form a source of root causal factors for human errors during aircraft maintenance activities. The existence of this swamp is some where underneath the normal safety level of everyday practice (given in Figure 7.2 as ‘ virtual safe performance level’) such that the dominant perception within the MRO would always be: ‘everything is safe’ while it is actually not. The swamp, being a mixture of numerous mutually interrelated error root causes, represents the basic source of maintenance human error potentialities that can randomly and abruptly develop into actual maintenance errors which produce incidents and accidents. The influence of this swamp environment is continuously threatening the maintenance process through its various stages: initial maintenance preparation, actual maintenance practices, self-certification, supervision, advanced inspections, functional tests, and even through to the operational phase.

A maintenance error can always exist, unseen, un-recovered, for short or even long times after the aircraft is signed-off. Barriers and safe-guards already established within each maintenance stage are always expected to trap any emerging errors and directly eliminate them, thus setting the process to the ‘virtual’ safe level of performance again. In case of non-existence or improper functioning of these barriers, the committed maintenance error would propagate such that it can only be faced by the next stage of defences (including those from operational and / or technical sides). However, this would always be at the cost (risk) of exposing the aircraft to more severe undesired outcomes if these errors in question failed to be captured once more. On the other hand, if such errors are ‘hopefully’ trapped in this later stage, then more complicated efforts would expectedly be required to re-establish the whole process to its ‘safe’ level again.

A major philosophy of this model is its conceptualization of the critical margin between the daily accepted (familiar / normal) current level of safety practice (given in figure as ‘virtual safe performance level) and the targeted absolute safety bottom line with nil undesired outcomes (shown as ‘absolute safe performance level’). This margin is created due to the presence of the 'swamp'. The swamp width in the illustration is directly proportional to the real swamp's size and influence within a given MRO in reality. A direct result of this specific interrelation would be: *If the swamp is dried up, then this margin would ultimately vanish and the organization would perform (at least theoretically) at the level of 'absolute safe environment'.*

Building on the previous Swamp theory, and recalling the two machine-based and human-based families of error root causes, the following two hypotheses can further be proposed as detailed materialization of the first research's Hypothesis 1 stated previously in Chapter 1 of this thesis:

Hypothesis 2:
'An aviation maintenance task can be executed at a significantly higher level of safe performance such that human-induced undesired outcomes would almost be nil if possibilities of human error that can be initiated due to any design features associated with that task are eliminated'.

Hypothesis 3:
'An aviation MRO can operate at a significantly higher level of safe performance such that human-induced undesired outcomes would almost be nil if the existing unseen accumulation of mutually-interrelated root causes that lead to human maintenance errors are eliminated'.

The objectives of this research work, in its prospective fold, is to introduce the necessary models and tools that can satisfy these two hypotheses originated from the above 'Swamp' model.

7.3 The Aviation Maintenance Monitoring Process (AMMP)

7.3.1 Introducing AMMP

To explore validity of the aforementioned hypotheses, a new hybrid retrospective / prospective safety process is introduced: Aviation Maintenance Monitoring Process (AMMP). The strategic AMMP concept, illustrated in Figure 7.3, is an intermeshing coordination between various industry bodies, the major of these being manufacturers and MRO's. Nonetheless, other actors such as regulators and other safety-oriented institutions can have their shares too. The concept is to continuously monitor existence of human error triggers that may be rooted during design process, as well as during maintenance practices at the MRO lines.

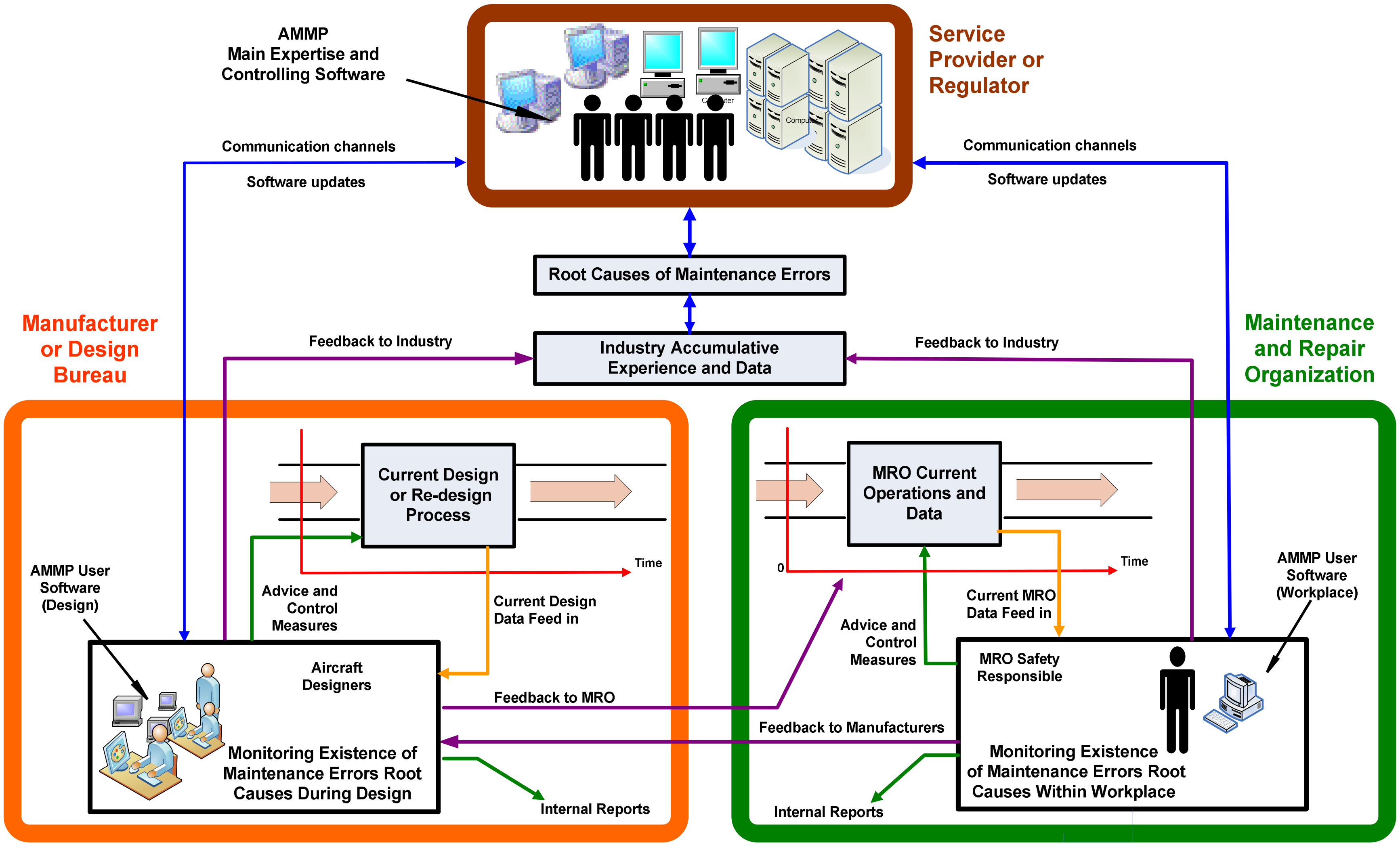


Figure 7-3 Strategic layout of the Aviation Maintenance Monitoring Process (AMMP)

Having identified the root causes in advance, they can then be eliminated systematically, thus causing the aforementioned 'Swamp' to simultaneously shrink down throughout the various sectors of the industry. The AMMP strategic proposed layout is composed of three inter-linked industry stakeholders: The main AMMP provider, aircraft design offices, and the MRO's.

7.3.1.1 The main AMMP provider

This is intended to be a specialized body of high expertise, deep scientific research capacity, and genuine skills in analysing past and current industry data that describe aviation maintenance errors and their initiators. The body may be initiated and launched independently or as a part of the current industry settings, for instance, within a regulatory authority. This provider is tasked to methodically analyse and comprehend the industry's pool of data, theory, and professional knowledge in this field, and use the overall thus digested information to build a set of user software packages that can be used by both design and maintenance houses, with a main target of eliminating maintenance errors root causes. The process is designed to be of a dynamic generative nature, continuously tracking and upgrading the software packages and their application zones. *The current research is temporarily fulfilling this role of the AMMP provider.*

7.3.1.2 The aircraft design offices

Using furnished inter-industry channels of information exchange, these offices can make use of feedback from MRO's, as well as other industry sectors, to ensure the freedom of new designs (or those being upgraded) from any in-built error prone features when seen from a maintainer human factors perspective. This can be achieved by applying the AMMP proposed software in its design-oriented version. In fact this task is a forward improvement by further capturing deeper maintainer human factors aspects to be added to the well established 'design for maintainability' portfolios.

7.3.1.3 The MRO's

By applying the proposed workplace version of AMMP software, quality officers and other safety-oriented staff within a given MRO can directly measure the existence of any of the maintenance errors root causes within their organization, thus setting the pace for instantaneous remedies to be introduced thus eliminating such root causes.

7.3.2 AMMP Practicality

The AMMP, as a tactical process, as indicated by Figure 7.4, operates in two simultaneous orientations: Design for maintainability and workplace safety. This can be discussed as follows:

7.3.2.1 Design for maintainability continuum

The dilemma of promoting safety as a genuine part of complex safety-critical systems designing processes has been the focus of many works (Kinnersley and Roelen 2007, Hale et al 2007). The proposed AMMP theorizes that, as a part of design (or re-design) for maintainability, an aircraft designer needs to ensure that maintenance tasks can be performed with ultimate smoothness, effectiveness, and freedom of human error initiators with regard to human factors such as: access to job area, space limitations, exposure and visibility, restriction to hand tools usage, angle of view to job area, human body location during job execution (e.g. human body reach, tilting, or bending possibilities), ventilation, temperatures, visual or audible caution indicators (e.g. labels, signals, warnings), aircraft parts influence (e.g. in respect to weights, and sizes), etc.

These human error-promoter factors and hundreds of others as well, are to be considered and to have their potentials of occurrence numerically identified as per each and every subtask that a maintainer is expected to do. Identified risks are then sequentially evaluated against sets of accumulative recommended reliability levels. Aircraft design features that show high risk potentialities during expected maintenance subtasks execution must be re-visited and necessary adjustments must be secured. Design should only be finalized when such risks are brought under control for the given subtasks.

Summing to a larger scale, each main maintenance task can then be evaluated for risks of design-inherent human errors promoters by considering the accumulative risks of its forming associated subtasks. Thus each maintenance task can be cleared when such risks are collectively controlled as well. Consequently, by having all expected maintenance tasks – as per the relative maintenance manuals – cleared in regard to risks of design-induced human errors, the overall potentialities triggering such errors will be reduced if not eliminated. The process is expected to continue such that accumulative AMMP databases within industry will gradually lead to lower and lower risks potentialities starting from current levels of safety performance.

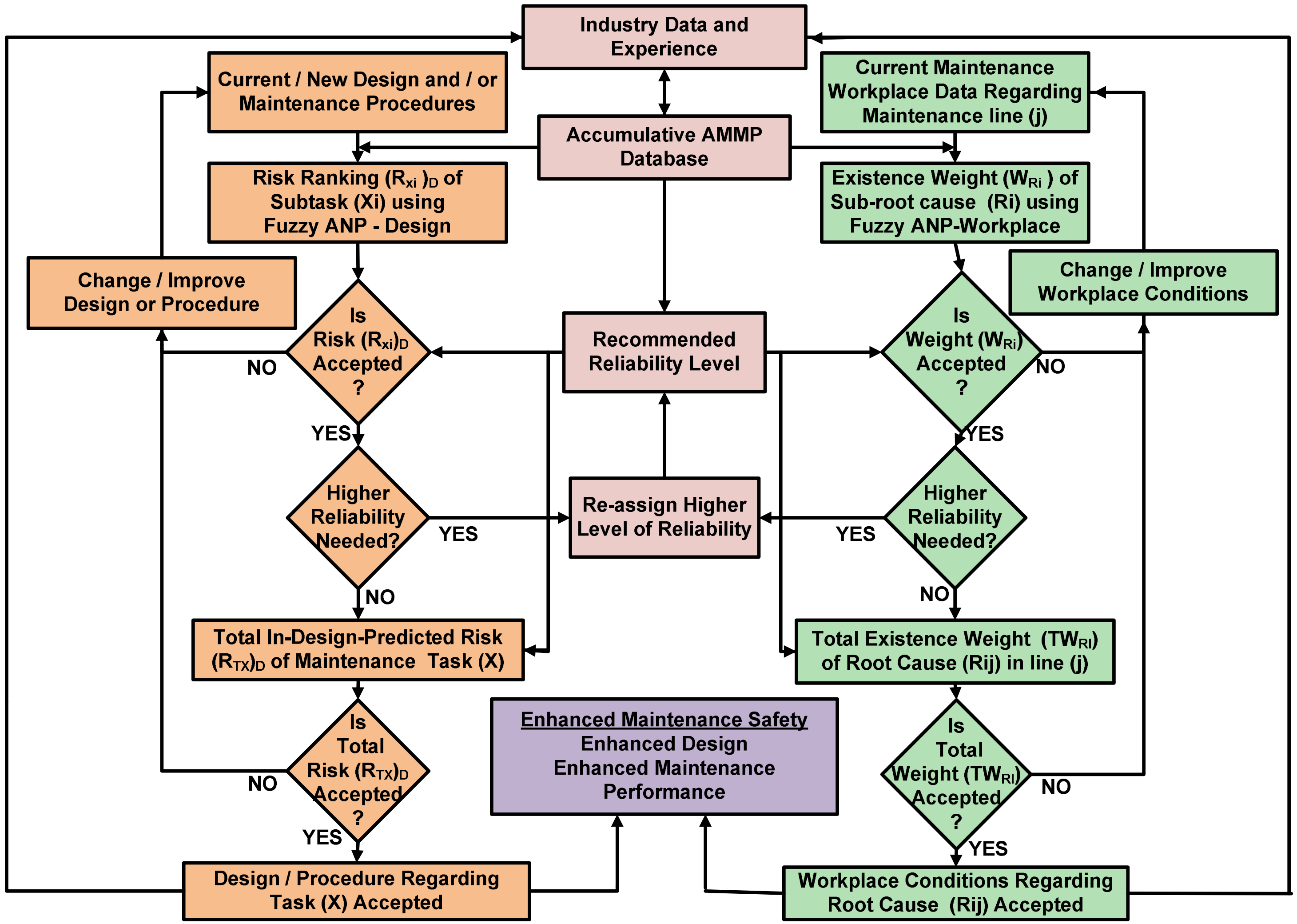


Figure7-4 Tactical layout of the Aviation maintenance Monitoring Process (AMMP)

7.3.2.2 Maintenance line performance continuum (workplace)

Complementary to the concept within design regime, the factors that influence human performance within a MRO line are considered in this continuum. These factors, taken here as human-error causal factors, are direct manifestation of all individual and organizational shortages and malfunctioning predictable within the given MRO. Each causal factor is intelligently subdivided into a set of intermeshing sub-factors that are individually evaluated for risks of promoting human error during maintenance practices. Risks identified for each sub-factor are evaluated in contrast to a required level of performance reliability. Sub-factors with high risks of initiating or exaggerating human errors must be addressed for each given maintenance line within the MRO. Root causes are then collectively evaluated for risks of existence within that MRO line. Necessary measures are expected to be set to address those risks and gradually eliminate them.

7.3.3 Selecting fuzzy logic for AMMP

The concept of ‘fuzziness’, first introduced by Zadeh (Zadeh 1965), was developed to facilitate accurate decision-making within uncertain environments. Modern complex and dynamic systems within engineering, medicine, finance, management, and others are all environments which are usually full of uncertainty and subjective understanding. All are full of moments of ‘vagueness’ when critical decisions are to be made depending mainly on flows of data that are neither certain, nor objective. The critical constraint in this sense is that such data, although imprecise, ill-separable, and vague, nevertheless, contains great amounts of useful information that can never be put aside. Previously, in such cases, it was usually left to humans to, subjectively and uncertainly, decide on issues of critical consequences depending merely on their own merit and perceptions. Fuzzy logic and fuzzy mathematical tools were thus introduced to eliminate the shares of uncertainty and subjectivity that used to accompany the human cognitive processes when deciding within ‘fuzzy’ settings, thus providing for better more accurate decisions. Kaufmann and Gopta (1988) wrote: “In human sciences, data and processes may or may not be vague, may or may not be measurable, may be subjective or objective. However, when a mathematical model is used in decision-making process its validity must be questioned, especially if the actual model must be reduced to one that is deterministic even when environment is fuzzy. If our knowledge of the environment is imprecise, as happens in medical diagnosis, engineering, management decision-making, etc, the model must include the notion of the level of presumption. Fuzzy numbers have been created to reflect the vagueness of human perception and thus the notion of the level of presumption. These fuzzy numbers thus reflect the human cognitive process."

Coming back to the fact that aviation maintenance, with all its dynamic complex inputs (most of them are far from being precisely measurable or even truthfully predictable), is a real uncertain environment especially when it comes to the assessment of safety performance or freedom from errors. It is thus appropriate to adopt fuzzy logic and its tools for the purpose of proactively and accurately measuring the potentiality of committing maintenance errors within the fuzzy aviation maintenance environment.

Through the two continuums of the proposed AMMP as described in the previous section 7.3.2, actual data and processes concerning details of aircraft design and manufacturing practices, as well as daily data, conditions, and performance terms pertaining to MRO's contexts are analysed utilizing a newly developed comprehensive sociotechnical user software – coded as ErroDetect.

7.3.4 Analytical Hierarchy Processes vs. Analytical Networks Processes

Saaty (1980) first introduced the Analytical Hierarchy Processes (AHP) as an effective tool to solve decision-making problems in complex multi-criteria settings, where such problems could be structured in hierarchies. The main assumption here being the clear functional independence of the upper levels of the hierarchy from the lower ones, and thus from the more specific local criteria that govern each of these levels. With such independence secured, the AHP inter-relations between various levels and criteria are, by definition, unidirectional without any interdependence linking between various ingredients in the upper and lower parts. This is typically indicated by Figure 7.5. The AHP techniques are used for treating many decision-making tasks (Chang 1996, Tolga et al 2005). However, lots of decision-making problems cannot practically be structured in pure unidirectional hierarchies due to the presence of genuine interactions between upper and lower parts having various higher factors depending, in any way, on some of the factors from the lower sections. In these later cases, the dependence between factors must be considered.

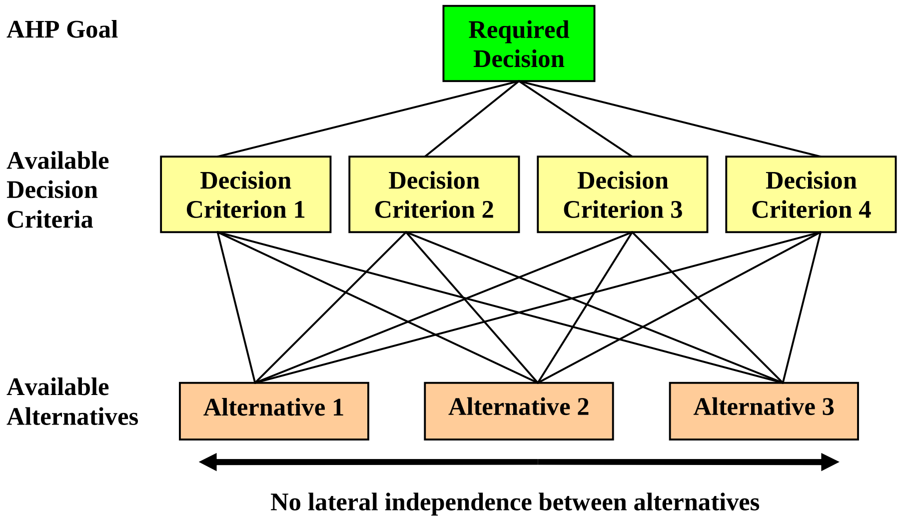


Figure 7-5 Typical simple AHP diagram to select one of three independent alternatives

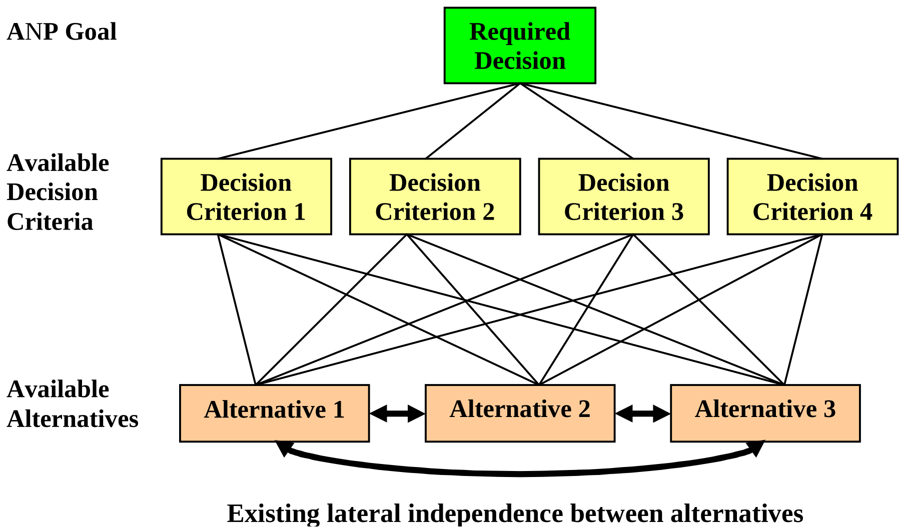


Figure 7-6 Typical simple ANP diagram to select one of three interdependent alternatives

Saaty again introduced the Analytical Networks Processes (ANP) as a generalized setting of the AHP, to accommodate inter-dependence between various factors influencing the decision-making process (Saaty, 1996). This is schematically illustrated by Figure 7.6. The ANP's are used when it is difficult to specifically determine whether any of the various levels and criteria involved in the decision making process are of higher or lower importance, of dominant or following nature, or of direct or hidden influence. In such complex cases, normal hierarchical frames with linear vertical relationships are vague. Only ANP approaches are of exact suitability to build inter-related frames that support proper decision making in fuzzy environments.

A typical application of fuzzy ANP methodology was conducted by Dagdeviren et al (2008) who used the ANP approach to assess safety performance in a work system setting by determining the Faulty Behaviour Risk (FBR) of workers within given organizations. They concluded that complex work systems should generally be analyzed from a holistic perspective where all influential attributes must be acknowledged, especially those involving qualitative concepts like “safety cultures, sensory adaptation, tendency of risky behavior, competition, management–worker relationships”, etc.

For this research purposes, the pre-mentioned developed software: ErroDetect, forming the core of AMMP application, is based on fuzzy ANP’s as described by Chang 1996, Deng 1999, Kahraman et al. 2006, and Dagdeviren et al 2008. Necessary mathematical formulations of the model are structured building on the fuzzy philosophy and arithmetic as indicated by Zadeh 1965, Kaufmann and Gupta 1985, 1988, and Cox 1999). The full mathematical model adopted for this research will be analysed in details in the next chapters. The software can be used most expectedly either by aircraft designers, or by safety officials in MRO’s. Regulators can further use some audit-oriented versions of ErroDetect as universal design and performance tools in the future.

7.3.5 What is to be monitored?

As indicated before, AMMP works, in its two complementary continuums, to effectively monitor the seen and / or inherent existence of maintenance human errors root causes. Variables that are exactly monitored are briefly illustrated through the design and workplace ANP models given in Figures 7.7 and 7.8. By implementing AMMP, many varieties of information and situations can be scanned for hidden root causes and causal factors. This starts from the design for maintainability inputs and downstream to MRO’s data including manpower, team formation, training sessions, qualifications control, work flow (performed work jobs per given period of time), material flow, hangar specifications, material and tool control, etc.

As indicated in section 7.3.4, ANP’s are typically formed from three or more levels of influential constraints that govern the decision-making activity. For the design for maintainability continuum, as shown in Figure 7.7, the ultimate goal of the ANP structure, shown in the first level, is to determine the error potentiality during execution of a given task (X) that can be committed by maintainers due to root causes associated with aircraft or supporting equipment design. The second level of the structure comprises the nine main tasks that are partially or collectively included within every maintenance activity.

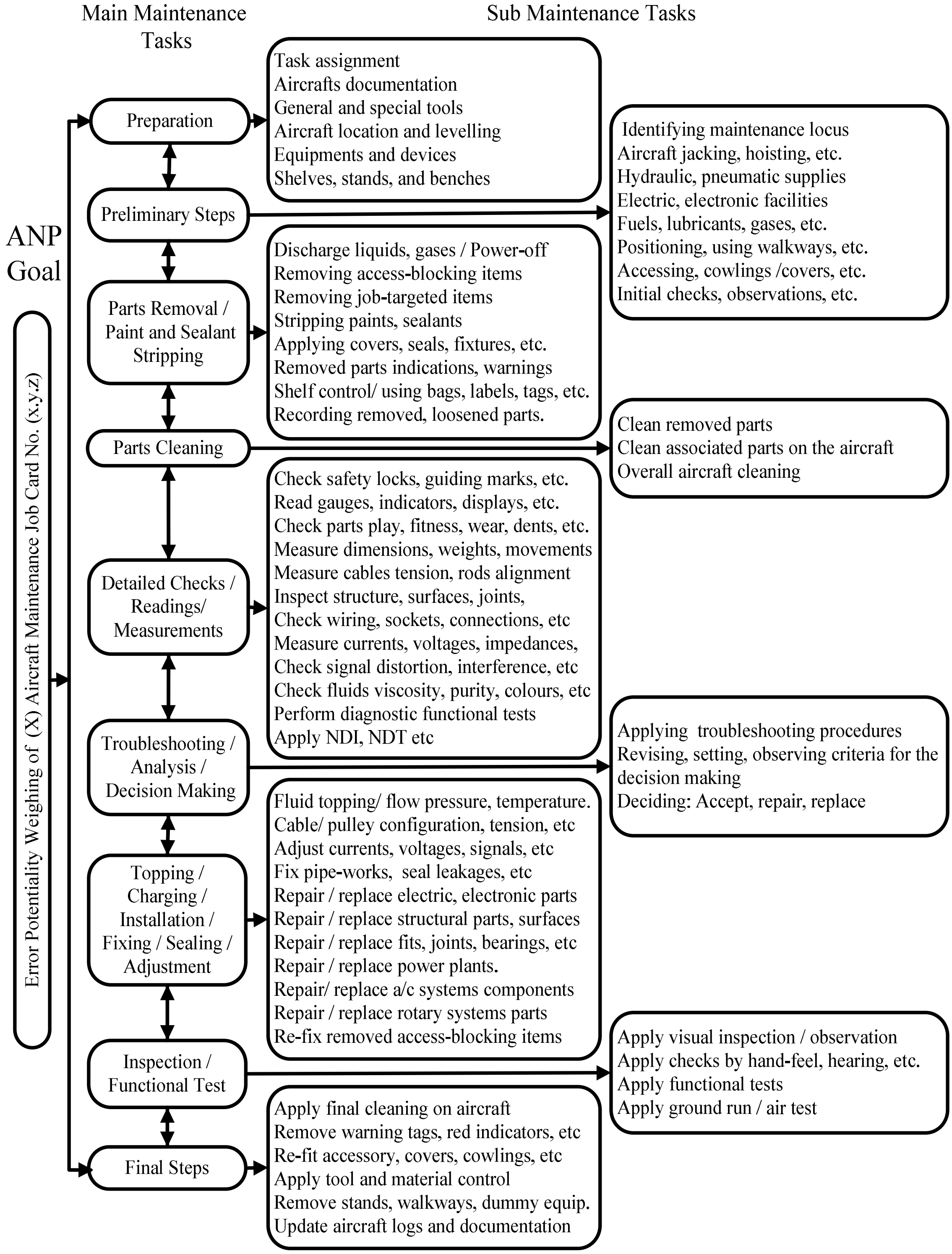


Figure 7-7 Fuzzy ANP - Design and manufacturing: Assessing the existence of potential maintenance errors root causes inherent within design as a part of 'design for maintainability'

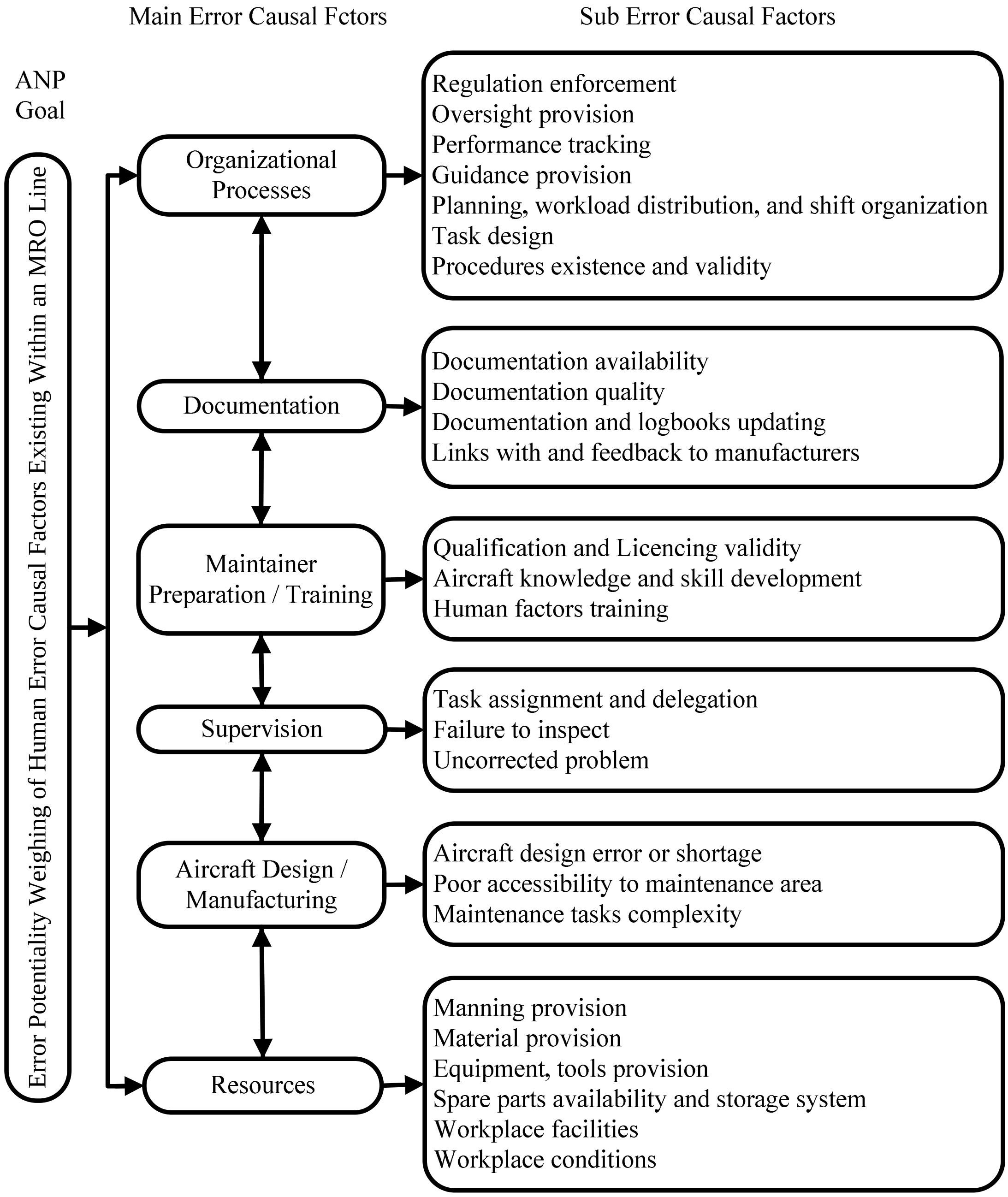


Figure 7-8 Fuzzy ANP-Workplace and maintainer: Assessing existence of potential maintenance errors root causes inherent within MRO workplace or maintainer conditions

These main tasks are significantly inter-related within each other in one side, and of total influence on the first goal level on the other. Then each main task is further subdivided into a number of sub-tasks which form, again in collective or partial settings, the third raw of the ANP structure. The sub-tasks, in turn, have three folds of inter-linkages: Each set of sub-tasks stemming from a single given main task are mutually dependent within each others. Thus they are globally inter-dependent with other sub-tasks from the rest eight other main tasks. Finally, these sub-tasks influence the overall main goal as well. It can thus be seen that this ANP structure is holistically addressing the overall inter-dependence of various tasks and subtasks in forming potential environments in which design-induced maintenance errors root causes may exist.

Similar understanding can be observed from Figure 7.8 in which the second part continuum of AMMP, namely the workplace and maintainer continuum, is represented by another ANP. Here the main goal is to determine the potentiality of existence of root causes associated with MRO's workplace conditions and maintainers' behaviors. The second level comprises main root errors, indicated here as main causal factors, that might be present, and the third level is formed by a list of sub-root causes as well. The two previous Figures 7.7 and 7.8 indicate all the error root causes that were concluded from the previous retrospective part of this research, which must be monitored for existence. Accordingly, suitable remedies may be sought.

7.3.6 How were the Fuzzy ANP's constructed?

The two fuzzy ANP's shown in the previous Figures 7.7 and 7.8 were obtained as a result of two main features of the applied methodology:

- The methodology instructs to apply brainstorming and free inventive thinking at the crucial intersecting stage just between the two retrospective and prospective parts of the current research. This thinking should make ultimate use of the obtained theoretical and practical pool of knowledge in the subject matter in order to scratch new structures that provide solutions for the spotted gaps.
- The first part of the research study provided sufficient data and information in regard to maintenance error root causes, error propagation, task analysis, PIF's , an overall understanding of the problem and the expected remedies.

It was thus natural to construct the two ANP's referring to the above notions. In fact, literature showed importance of freely establishing the ANP's, in cases like those handled by the current research, from the scratch so that they form bases to build future solutions on. Practically, the current ANP's were constructed according to this roadmap:

- The 197 SF's that led to helicopter maintenance-related accidents and serious incidents were identified. The importance of the top 30 of them was emphasized as major root causes.

- These SF's (root causes) are found to practically form the overall PIF's that shape the performance within MRO's.
- The maintenance task analysis simultaneously conducted showed various stages of maintenance activities and their hierarchal dependencies.
- Integrating the obtained knowledge regarding the maintenance PIF's with the task activity hierarchies resulted in the construction of the required ANP's diagrams.

The overall sequence of these stages within the applied methodology has already been illustrated before through Figure 3.5. This figure as well shows the next steps after the determination of the ANP's, namely: the construction of the RCES, building ErroDetect, and finally the practical verification of the AMMP within industry.

7.4 Technical framing of AMMP software

7.4.1 Building the Root Causes Existence Scale (RCES)

Practically, ErroDetect is based on the Root Causes Existence Scale (RCES) which is a systematic combination of 870 different assessment criteria for checking the existence of maintenance human errors root causes. RCES is designed, with direct reflection from the retrospective analysis findings, and then in-built within the software, thus significantly mapping large spectrum of the expected scenarios of human error initiation and propagation that can be triggered by any of the design, manufacturing, or maintenance workplace conditions malfunctioning.

Having set the two ANP's, a comprehensive sophisticated set of fuzzy mathematical logic operations are formulated as per the pre-mentioned references. Table 7.1 shows the overall scheme used to build the RCES.

Table 7-1 Building scheme of aviation maintenance human errors RCES

Comparators	ANP- Design	ANP- Workplace
Goal	Detection of error initiators in design as per each job card	Detection of error initiators in MRO as per each maintenance line
Main triggers for errors	Main maintenance tasks (9 within each job card)	Causal factors (6 within each MRO line)
Partial triggers for errors	Sub maintenance tasks (total of 61)	Sub-causal factors (total of 26)
RCES assessing criteria	Each sub-task is weighted by 10 assessing criteria (total of 610)	Each sub-factor is weighted by 10 assessing criteria (total of 260)

7.4.2 Sample assessing criteria: design and work place perspectives

Tables 7.2 and 7.3 show samples of the criteria inbuilt within ErroDetect for both design and workplace perspectives respectively. Wider informative sets of these criteria for the design practices are given in Appendix J as well.

Table 7-2 Samples of the criteria in-built within ErroDetect for design perspective

Main maintenance task:	**Installation or repairs**
Sub maintenance task:	**Install or repair mechanical fits, joints, fixers, brackets, couplings, bearings, etc.**

Associated assessing criteria for the exact given subtask:

1. Potentiality of error if subtask involves critical alignment, orientation, or critical joining (especially for bearings, couplings, etc.)
2. Potentiality of error if sub-task involves composite structure repairs, integration, or joining techniques.
3. Potentiality of error during repair works within this sub-task due to compactness, poor accessibility to work area, or if this area is greasy, oily, hot, dark, or remote.
4. Potentiality of error during cutting exact shapes including rounded corners of sheet metal, metal bars, or composites. Or during applying anti-crack techniques.
5. Potentiality of error if the subtask involves riveting (rivets part numbers, distribution, application techniques, sealing), or during welding (for approved applications).
6. Potentiality of error during applying required torques (low or high) due to work area compactness, location, or the need to use wrench extensions.
7. Potentiality of error during applying shrink fits, pressing fits, or piercing techniques (bearings) (e.g. When heating and cooling processes are involved within very short period of application).
8. Potentiality of error when applying adhesives, sealants due to part shapes, location, access, compactness, inclination, etc.
9. Potentiality of installing a part in the wrong orientation if it can easily be installed either ways, or possibility of cross wiring, or wrong cable orientation.
10. Potentiality of error if similar but different components (different part numbers) can easily be applied (rods, brackets, bolts, nuts, screws, rivets, safety locks, guiding marks, sheet metals, windscreens, etc.)

Table 7-3 Samples of the criteria in-built within ErroDetect for workplace perspective

Main causal factor:	**Organizational processes**
Sub causal factor:	**Task design**

Associated assessing criteria for the exact given sub-factor

1. Lack of the overall understanding of the importance of proper task design (within middle and high management).

2. Potentiality of error because not all necessary elements regarding task design are considered (i.e. maintenance procedural sequence, multi-trade jobs, man-hours needed (possibility of multi-shifts), tooling and equipments, materials, degree of job precision, worksheets issuing, applying relevant service bulletins, airworthiness directives, or safety letters, etc).

3. Potentiality of error due to complexity of maintenance procedures (e.g. if complex jobs are not given proper consideration during task design and / or worksheet preparation).

4. Potentiality of error due to non-clarity of worksheets or wrong (confusing) sequence of maintenance steps.

5. Potentiality of error because no additional consideration are given during task design for high-precision jobs such as 'shrink fits with few microns of precision' (e.g. associated worksheets of such jobs are not given in different (emphasised) format, or proper quality assurance measures are not set within procedures of these jobs).

6. Possibility of error re-occurrence due to lack of recording, analysing and learning from previous task design shortcomings, using such experiences to improve performance, and to monitor such improvements.

7. Potentiality of error because task design is not assigned as a definite responsibility to a definite unite within the MRO

8. Potentiality of error due to non-conformity of operational worksheets (job instructions) with general approved maintenance procedures (e.g. if instructions are confusing, conflicting, or practically-inapplicable).

9. Potentiality of error due to improper consideration of long-jobs requirements (e.g. multiple shifts handovers) in task design.

10. Possibility of error due to lack of feedback channels (formal and informal) from maintainers to management concerning task design, workloads, and shifts (e.g. weak or no provisions for suggestions or complaints).

7.4.3 Why a user software?

The overall strategic philosophy of the AMMP is to integrate the knowledge gained on aviation maintenance error causation and development into the daily live-world within aircraft design bureaus and busy MRO's hangars. This integration is a major requirement of the regulator and a keen demand of the industry practitioners (ARP5150 2003). One major way to achieve such integration is through the innovative introduction of user software that covers all the possible error initialization scenarios, thus illuminating the way leading to their elimination.

The factors that dictated the introduction of ErroDetect as an interactive user program can be briefly discussed as follows:

- The AMMP, as a newly introduced concept, stands on the establishment of a software that is readily applicable by designers and safety officers within MRO's to help them proactively detect maintenance error root causes, a user computer-based package is thus needed, not a single-run localized problem solver.
- The code must be a practical one, with industry users kept in mind when it is being structured and built.
- The package is a daily data register, thus it is expected to generate multiple settings of databases describing maintenance error generation industry wise.
- User software better provides for the continuation of the AMMP process even after this current research is concluded. This is a major objective of this work.

7.5 Chapter summary

It is high time to further enrich the human factors knowledge pool further thinking proactively for the prevention, or at least reduction, of human error-caused safety occurrences within high reliability industries like aviation maintenance. A new set of hypotheses was then formulated that led to the introduction of the industrial proactive AMMP. AMMP is a holistic hybrid retrospective/ prospective integrated process that may be simultaneously and collectively implemented by main industry stakeholders.

The suggested AMMP is a new concept with practical industry-oriented tools that work to fill the challenging need of proactively identifying scenarios leading to next probable incidents or accidents within a given safety-sensitive organisation. and thus support setting measures that can hinder such scenarios. The suggested concept can be directly adopted by aircraft designers, manufacturers, as well MRO's. The aim is to proactively monitor the existence of human error root causes that are initiated during design practices, manufacturing processes, or at later stages due to workplace or workforce conditions. As a result, such causal factors can be gradually eliminated to reduce the overall risk of maintenance errors. The process is based on a Root Causes Existence Scale (RCES) and a comprehensive socio-technical user program built applying the fuzzy analytic network process. A total of 870 different assessment criteria were designed and then in-built within the software thus mapping the outcomes of the retrospective error causal factors investigative studies.

8 Mathematical Formulation: Design of AMMP Software using Fuzzy Logic Analytical Network Processes

"Essentially, such a framework provides a natural way of dealing with problems in which the source of imprecision is the absence of sharply defined criteria of class membership rather than the presence of random variables"
L. A. Zadeh-Fuzzy logic introducer

8.1 Introduction

8.1.1 The importance of Fuzzy Logic

In response to the ever increasing complexity of modern life, the world is becoming less and less predictable. Consequently, our perception of uncertainty is growing day after day. Human reliability within aviation maintenance context is an obvious case where such uncertainty persistently exists to various degrees of intensity. This uncertainty, vagueness, or fuzziness is most encountered when it comes to human reliability assessment within a given maintenance line, or during executing a specific maintenance task. Fuzzy sets theory and arithmetic (Appendix K) are now considered as promising tools to provide for such assessment to be accurately and effectively performed. As discussed in section 2.6.1 before, a major drawback of current works in human reliability assessment and enhancement is the recurrent dependence on experts' interpretation of sociotechnical work contexts, with all the expected subjectivity and uncertainty that frequently accompany such analyses. The importance of fuzzy logic thus stems exactly from this point: The ability to provide analysis and decision-making tools that are free, both of subjectivity and vagueness of the decision-making criteria.

Although fuzzy logic has received high attention recently, as a result of the booming fuzzy logic-based products that filled a big gap in technology, nevertheless, this emerging science is increasingly gaining access to the expert and informed decision making systems. Cox (1999) wrote: "Coupling fuzzy logic with expert system technology provides a mechanism for producing fuzzy models that address important classes of problems in information decision support. Fuzzy expert systems model the world in terms of the semantics associated with the underlying variables, thus providing a much closer relationship between real world phenomena and computer models".

8.1.2 Fuzzy Logic vs. Probability

Although some works in literature, as well as so many scientific faculties, take the fuzzy logic to be a *form* of probability, or consider them both to represent and measure the same uncertainty phenomena, or at least think of them both as having some common origin, but nevertheless, the clear fact is that *fuzzy logic is not probability*, nor has any joined origins with it. Cox (1999) again attributed this common confusion that many people develop between the two concepts to a set of similarities that both the concepts share. Another major reason for such confusion is the "long formal history" of probability when compared to the "short and rather obscure history" of fuzzy logic, a fact that leads many scientists and mathematicians into that confusion, especially, for instance, when comparing fuzzy logic with the subjective Bayesian probability.

The current research adopts the fuzzy logic concept since it is a closer representative of the real world of human reliability within aviation maintenance, rather than the well known probability inputs to this and similar fields. This can further be clarified through Table 8.1 that lists various similarities and differences between the two concepts (Zadeh 1965, Kaufmann and Gopta 1986 and 1988, Cox 1999).

Table 8-1 Brief comparison between probability and fuzzy logic

Probability	Fuzzy logic
Similar Features (Externally seen properties)	
Measures a form of uncertainty	Measuring a form of uncertainty
Encodes the degree of uncertainty with a metric scale between (0) and (1)	Encodes the degree of uncertainty with a metric scale between (0) and (1)
Describes event spaces utilizing sorts of Gaussian functions distributions	Describes event spaces utilizing sorts of Gaussian functions distributions
Differences (actual distinguishing properties)	
Measures a specific kind of uncertainty in which the likelihood of an outcome of a discrete event is tested. This event outcome either happens or not.	Measure a different kind of uncertainty in which the degree or extent to which an event occurred is looked for.
The outcome happens clearly and unambiguously	The occurred event may involve some ambiguity and uncertainty
Deals with randomness in a large population. The uncertainty here is in respect to the occurrence of an event within this given population	Involves the ambiguity coupled with the actual description of an event. These ambiguities are usually continuous valued criteria where the boundary between different semantic groups is not precisely distinct.

Table 8-1 Brief comparison between probability and fuzzy logic (Continued)

Probability	Fuzzy logic
Differences (actual distinguishing properties) (Continued)	
In the encoding scale: the value of (0) implies that the event can't happen, and the value of (1) indicates that the event is certain to happen.	In the encoding scale: the membership values of (0) or (1) both denote a complete certainty of the occurred event. Precisely, the membership of value (0) indicates that the output is completely not representing the event concept, while the membership of value (1) indicates that the output is totally representative of the event concept. Intermediate values show various degrees of ambiguity of how the outcome should be interpreted.
Based on frequency distribution within a given random population	Based on calculus of compatibility. It describes events which have continuously varying values by assigning partitions of these values with a semantic label.

8.1.3 This Chapter

This chapter explores the utilization of fuzzy logic concepts, techniques, and their exploitation in addressing human reliability issues associated with aviation maintenance errors. The proposed AMMP, as discussed previously, is targeting the assessment of existence of root causes leading to such errors within 'ideal' uncertain and vague environments such as those of the aviation maintenance industry. The usual subjectivity, always present within explorers' and experts' opinions when judging such existence, is yet another vital factor that led, with the first, to the selection of fuzzy analysis modus operandi to be the main practice of the programme ErroDetect New algorithms are introduced within this research to further affectionate the established tactics in this regard, and to significantly reduce the need of complicated and costly systems of experts, thus setting a more industry-oriented product.

It is highly essential to emphasize that the very elongated complex mathematical content of this chapter, although totally applicable to the proposed ErroDetect software, but in fact the targeted user is never expected to go through any of these calculations at any stage of the programme application. The user interface, including their expected assessment input, is targeted to be very focalized and simple, while all the complicated calculations are to occure absolutely at the software background.

8.2 Triangular fuzzy numbers

8.2.1 Definition

According to Zadeh (1965), Kaufmann and Gopta (1986, 1988), and Cox (1999), A Triangular Fuzzy Number (TFN) '*A*' is a special category of fuzzy numbers that is defined by the triplet: *a*, *b*, and *c* where

a : denotes the smallest possible value of *A*

b : denotes the most promising possible value of *A*

c : denotes the largest possible value of *A*

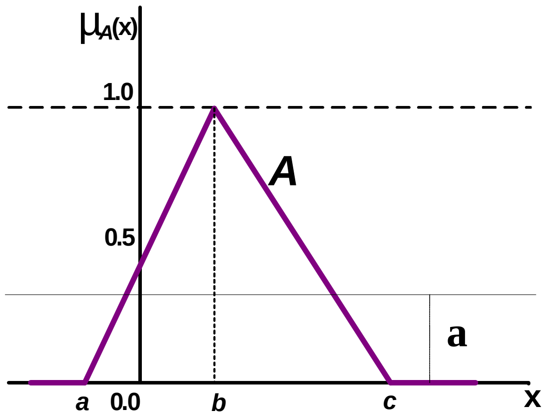


Figure 8-1 A typical triangular fuzzy number

A can be denoted in many ways as follows:

i. First representation:

$$A = (a, b, c) \tag{8-1}$$

ii. Second representation:

$$A = \left(\frac{a}{b}, \frac{b}{c}\right) \tag{8-2}$$

iii. Third representation:

TFN is defined also in terms of membership functions as:

$$\begin{aligned}
\mu_A(x) &= 0 && , x \prec a \\
\mu_A(x) &= \frac{x-a}{b-a} && , a \le x \le b \\
\mu_A(x) &= \frac{c-x}{c-b} && , b \le x \le c \\
\mu_A(x) &= 0 && , x \succ c
\end{aligned} \tag{8-3}$$

iv. Fourth representation:

TFN is given in terms of 'α-cut' level value as:

$$A = (a + (b-a)\alpha, c + (b-c)\alpha) \tag{8-4}$$

8.2.2 Arithmetic Operations of TFN

Since $A = (a,b,c)$ then let A_1 and A_2 be two TFN's given as:

$$A_1 = (a_1, b_1, c_1), \quad A_2 = (a_2, b_2, c_2)$$ and λ : Ordinary number such that $\lambda \in R$

Thus the arithmetic operations joining them are given as follows:

Addition:

$$A_1(+)A_2 = (a_1 + a_2, b_1 + b_2, c_1 + c_2) = \text{ Triangular fuzzy number} \qquad 8\text{-}5$$

Subtraction:

$$A_1(-)A_2 = (a_1 - a_2, b_1 - b_2, c_1 - c_2) = \text{Triangular fuzzy number} \qquad 8\text{-}6$$

Scalar multiplication:

$$\lambda \otimes A = (\lambda \cdot a, \lambda \cdot b, \lambda \cdot c) = \text{Triangular fuzzy number }, \lambda \succ 0 \qquad 8\text{-}7$$

$$\lambda \otimes A = (\lambda \cdot c, \lambda \cdot b, \lambda \cdot a) = \text{Triangular fuzzy number }, \lambda \prec 0 \qquad 8\text{-}8$$

Other operations:

The multiplication, divisions, inverse products of two TFN's can be approximated by a resultant TFN's as in the following lines:

Multiplication:

$$A_1 \otimes A_2 = (a_1 \cdot a_2, b_1 \cdot b_2, c_1 \cdot c_2) \approx \text{ Triangular fuzzy number} \qquad 8\text{-}9$$

Division:

$$A_1(:)A_2 = (\frac{a_1}{c_2}, \frac{b_1}{b_2}, \frac{c_1}{a_2}) \approx \text{ Triangular fuzzy number} \qquad 8\text{-}10$$

Inverse:

$$A^{-1} = \frac{1}{A} = (\frac{1}{c}, \frac{1}{b}, \frac{1}{a}) \approx \text{ Triangular fuzzy number} \qquad 8\text{-}11$$

Minimum and maximum of two TFN's:

Recalling (8.4), A given pair two TFN's can be given as

$$A_1 = (a_1 + (b_1 - a_1)\alpha, c_1 + (b_1 - c_1)\alpha)$$
$$A_2 = (a_2 + (b_2 - a_2)\alpha, c_2 + (b_2 - c_2)\alpha) \qquad 8\text{-}12$$

It can be seen that A_1, A_2 are represented here in (x,y) mode not the triple (x,y,z) mode.

If the values of $(b_1 - a_1), (b_1 - c_1) \ldots$,etc are substituted, then:

$$A_1 = (a_1 + k_1\alpha, c_1 + k_2\alpha)$$
$$A_2 = (a_2 + k_3\alpha, c_1 + k_4\alpha) \quad \text{8-13}$$

$k_1, k_2, k_3, \ldots.$ constants

Thus, the minimum (written as $\min(A_1, A_2)$ or $A_1 \wedge A_2$) and maximum (written as $\max(A_1, A_2)$ or $A_1 \vee A_2$) of the two TFN's can be defined as:

Minimum:

$$A_{1_\alpha} \wedge A_{2_\alpha} = [(a_1 + k_1\alpha) \wedge (a_2 + k_3\alpha), (c_1 + k_2\alpha) \wedge (c_2 + k_4\alpha)] = \text{fuzzy number} \quad \text{8-14}$$

(Not necessarily triangular)

Can be determined according to varying value of α from 0 to 1 as follows:

i. For each value of α compare between ($(a_1 + k_1\alpha)$ and $(a_2 + k_3\alpha)$ and select the least value.

ii. Similarly select the least value between $(c_1 + k_2\alpha)$ and $(c_2 + k_4\alpha)$.

iii. Set the two selected minimal values to compose the (x,y) terms of $A_1 \wedge A_2$.

Maximum:

$$A_{1_\alpha} \vee A_{2_\alpha} = [(a_1 + k_1\alpha) \vee (a_2 + k_3\alpha), (c_1 + k_2\alpha) \vee (c_2 + k_4\alpha)] = \text{fuzzy number} \quad \text{8-15}$$

(Not necessarily triangular)

Similarly this can be determined according to varying value of α from 0 to 1 as:

iv. For each value of α compare between ($(a_1 + k_1\alpha)$ and $(a_2 + k_3\alpha)$ and select the largest value.

v. Also select the largest value between $(c_1 + k_2\alpha)$ and $(c_2 + k_4\alpha)$.

vi. Set the two selected maximal values to compose the (x,y) terms of $A_1 \vee A_2$.

8.3 Constructing the fuzzy mathematical model of AMMP

8.3.1 Essential model build up

Step 1: Construction of the Root Causes Existence Scale (RCES)

The Root Causes Existence Scale (RCES) is a comprehensive sociotechnical fuzzy structure built applying the fuzzy ANP theory. RCES is the major component of the generic (AMMP). ANP structures were already composed as given by Figures 7.7 and 7.8 for both design and workplace continuums respectively. The composed RCES collectively comprises main root causal factors, sub-root causal factors, and 870 associated assessing criteria: 10 for each sub-factor. For simplicity and compactness, only the workplace fold will be discussed in the following mathematical modelling. The same principles are totally applicable for the design section.

Step 2: Determination of the potentiality of existence of each sub-root causal factor by assessing the influence of each of its 10 associated criteria.

This is a newly introduced algorithm. The programme user should have the ability to consider the importance of each of the 10 criteria associated with each sub-causal factor, and to give a single unique judgement whether a given criterion exists when the real conditions of the MRO under investigation are explored. The vital importance of the fuzzy logic here is its inclusive power of accommodating any traces of subjectivity that may encounter the user's thinking. Through evaluating an 'interval of confidence' instead of a single value, the overall assessment is expected to be a subjectivity-free evaluation. Each group of 10 criteria, though different and varying in strength and directness of describing the given sub-factor, works collectively to indicate the presence of that sub-factor and the potentiality of maintenance error that may develop due to its existence within that certain MRO.

A. The only single task that the user has to perform is to judge the influence of each criterion when put in contrast to the actual MRO conditions, the software will automatically execute all the other remaining parts of the procedure. No traditional system of experts is needed. A given criterion should be assigned one of the following options as per Table 8.2 below.

Table 8-2 Options for assessing a given criterion as a potential root causal factor

	Options of a given criterion as a potential error root causal factor	Code
1	Criterion is of no existence/ influence as a potential error root causal factor	n.a.
2	Criterion is of very weak influence as a potential error root causal factor	VWI
3	Criterion is of weak influence as a potential error root causal factor	WI
4	Criterion is of moderate influence as a potential error root causal factor	MI
5	Criterion is of high influence as a potential error root causal factor	HI
6	Criterion is of absolute influence as a potential error root causal factor	AI

B. These qualitative descriptors are changed into a fuzzy linguistic scale which is then represented by a series of intermeshing TFN's (Dagdeviren et al 2008) as indicated by Figure 8.2. Both the linguistic scale and its fuzzy representation are given jointly in Table 8.3. The 'thinking' of the software user can thus be expressed numerically in fuzzy format that can be further processed for the following applications.

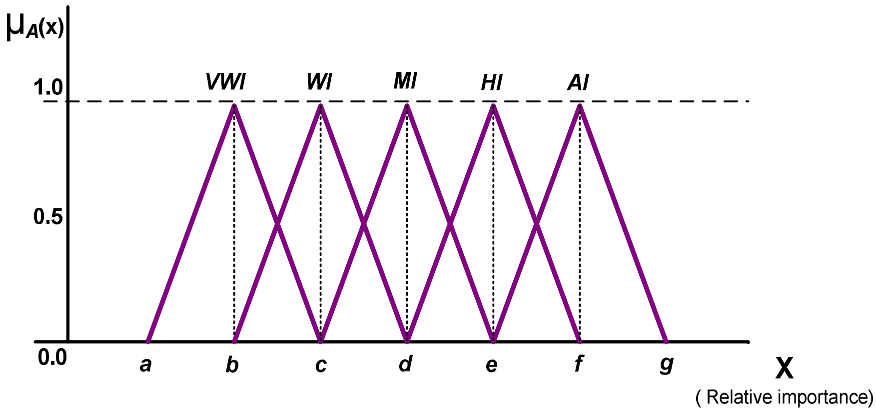


Figure 8-2 Fuzzy linguistic scale for the numerical evaluation of the qualitative judgement of the assessing criteria

Table 8-3 Linguistic scale for the criteria of importance

Code	Linguistic scale for importance	Triangular fuzzy scale	Reciprocal triangular fuzzy scale
n.a.	No influence	*n.a.*	*n.a.*
VWI	Very weak influence	*(a, b, c)*	*(1/c, 1/b, 1/a)*
WI	Weak influence	*(b, c, d)*	*(1/d, 1/c, 1/b)*
MI	Moderate influence	*(c, d, e)*	*(1/e, 1/d, 1/c)*
HI	High influence	*(d, e, f)*	*(1/f, 1/e, 1/d)*
AI	Absolute influence	*(e, f, g)*	*(1/g, 1/f, 1/e)*

C. Each of the 10 criteria is thus expressed numerically in a fuzzy number:

$A_i = (a_i, b_i, c_i)$, $i = 1,2, \ldots, n$.

Where, n is the number of the criteria (out of total 10) that actually have importance varying from very weak to absolute influence.

D. Applying Equations 8.5 through 8.9, an overall potentiality of existence of the sub-factor to which these criteria belong can be obtained through calculating their mean fuzzy number $A_{sub\text{-}f}$ as follows:

$$A_{sub-f} = \left(\sum_{i=1}^{i=n} a_i / n, \sum_{i=1}^{i=n} b_i / n, \sum_{i=1}^{i=n} c_i / n\right) \quad \text{8-16}$$

or

$$A_{sub-f} = (a_{sub-f}, b_{sub-f}, c_{sub-f}) = \text{Triangular fuzzy number} \quad \text{8-17}$$

E. The final potentiality of this sub-factor (P_{sub-f}), as a sub-root cause that may develop maintenance errors within this MRO, can be obtained through *defuzzification* (Cox1999), i.e. reducing the representative fuzzy number, as per Equation 8.17, to only one single numerical value as follows:

$$P_{sub-f} = (a_{sub-f} + b_{sub-f} + c_{sub-f}) / 3 = \text{scalar quantity} \quad \text{8-18}$$

F. The process is repeated for the rest of the 26 sub root causal factors.

Step 3: Determination of potentiality of existence of each main root causal factor referring to existence of its sub-root causal factors

A. The overall potentiality of existence of each of the main root causal factors can then be obtained by calculating the mean fuzzy number $A_{main\text{-}f}$ of the whole set of sub-factors belonging to it as follows:

$$A_{main-f} = (\sum_{j=1}^{j=m} a_{sub-f_j} / m, \sum_{j=1}^{j=m} b_{sub-f_j} / m, \sum_{j=1}^{j=m} c_{sub-f_j} / m) \quad , j = 1, 2, \ldots, m \quad \text{8-19}$$

Where, m is the total number of the sub root causal factors (belonging to this given main root causal factor) that have actually been found to have any potentiality of existence within the given MRO. Equation 8.19 can further be written as:

$$A_{main-f} = (a_{main-f}, b_{main-f}, c_{main-f}) = \text{Triangular fuzzy number} \quad \text{8-20}$$

B. The final potentiality of this main-factor (P_{main-f}), as a main root cause that may develop maintenance errors within this MRO, can similarly be obtained through defuzzification as:

$$P_{main-f} = (a_{main-f} + b_{main-f} + c_{main-f}) / 3 = \text{scalar quantity} \quad \text{8-21}$$

C. The process is repeated for the rest of the 6 main root causal factors.

Step 4: Building 'pair-wise comparison' matrices of existence potentiality of main root causal factors as given by the ANP- workplace structure.

This step accommodates the second major newly introduced algorithm. The pair- wise comparison matrices are effective means to calculate local weights of importance (existence) of the root causal factors. These matrices also show possible inter-relations and mutual impact of the factors on each others. In previous literature, such matrices were constructed manually through direct application of the collective cognitive thinking of a system of experts. This process is now performed by utilising the inputs from previous steps, and a newly introduced algorithm as follows:

A. It is temporarily assumed that there is no mutual dependence among the 6 main factors described as per Step 3. For generalization, the total number of main root causal factors is taken to be ‘k’.

B. A difference matrix for mutual comparison between the k main factors is composed as per Table 8.4:

Table 8-4 Difference matrix for comparison of main root causal factors potentialities

	OP	D	MP	AD	S	R
Organizational Processes (OP)	D_{11}	D_{12}	D_{13}			D_{1k}
Documentation (D)		D_{22}				D_{2k}
Maintainer Preparation (MP)			D_{33}			
Aircraft Design (AD)				D_{44}		
Supervision (S)						
Resources (R)						D_{kk}

C. Numerical differences between existence potentialities of factors are calculated as:

$$D_{ij} = \begin{cases} (P_{main-f_i} - P_{main-f_j}) = 0, & i = 1, 2, \ldots, k \\ & j = i \\ (P_{main-f_i} - P_{main-f_j}) & i = 1, 2, \ldots, k \\ & j = (i+1), (i+2), \ldots, k \end{cases} \qquad 8\text{-}22$$

D. The total range of differences is calculated as :

$$Total\ range = \left| Max\, D_{ij} - Min\, D_{ij} \right| \qquad 8\text{-}23$$

E. This total range of differences is divided into 5 equal bands as per Figure 8.3.

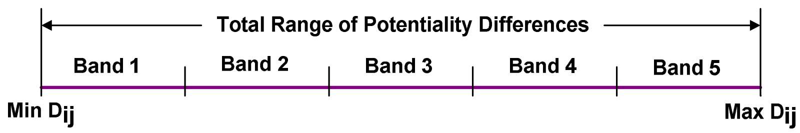


Figure 8-3 Total range of potentiality differences and its inner bands

F. The lower and upper limits for each band are given by:

$$Min\,value\,of\ Band_q = Max\,value\,of\ Band_{q-1} + \delta$$

$$Max\,value\,of\ Band_q = Min\,value\,of\ Band_q + \frac{Total\ range}{5},\ q = 1, 2 \ldots 5 \qquad 8\text{-}24$$

Where, δ is an infinitesimal numerical increment of the order 10^{-6}

G. The importance of any one of the main root causal factor (main-f_1) when mutually compared to another main factor (main-f_2), as indicated by the difference of their potentialities of existence, is obtained by assigning this difference to any of the 5 bands discussed above. This is arranged as follows:

Table 8-5 Mutual comparison bands of differences between main factors

	Code	Interpretation of mutual comparison differences between main factors
1	EI	Factors (main-f_1) and (main-f_2) are of equal importance, (D_{ij} = 0)
2	Band 1	(main-f_1) is of very weak importance over (main-f_2)
3	Band 2	(main-f_1) is of weak importance over (main-f_2)
4	Band 3	(main-f_1) is of moderate importance over (main-f_2)
5	Band 4	(main-f_1) is of high importance over (main-f_2)
6	Band 5	(main-f_1) is of absolute importance over (main-f_2)

H. This variation of importance of main factors as potential root causes of maintenance errors within the given MRO is thus represented by a series of intermeshing TFN's as indicated by Figure 8.4. Both the linguistic scale and its fuzzy representation are given jointly in Table 8.5.

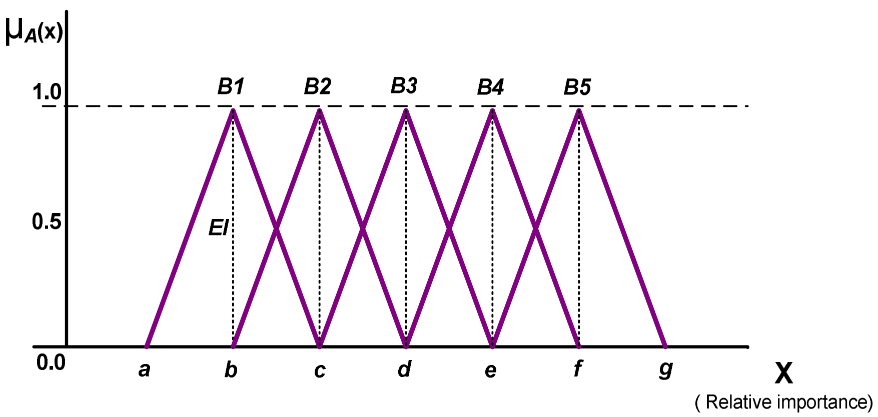


Figure 8-4 Fuzzy linguistic scale for the relative importance of main root causal factors

Table 8-6 Linguistic scale of importance

Code	Linguistic scale for importance	Triangular fuzzy scale	Reciprocal triangular fuzzy scale
JE	Just Equal	*(b, b, b)*	*(1/b, 1/b, 1/b)*
Band 1	Very weakly more important	*(a, b, c)*	*(1/c, 1/b, 1/a)*
Band 2	Weakly more important	*(b, c, d)*	*(1/d, 1/c, 1/b)*
Band 3	Moderately more important	*(c, d, e)*	*(1/e, 1/d, 1/c)*
Band 4	Highly more important	*(d, e, f)*	*(1/f, 1/e, 1/d)*
Band 5	Absolutely more important	*(e, f, g)*	*(1/g, 1/f, 1/e)*

I. Thus fuzzy matrix of pair-wise importance of the main root causal factors can be built using fuzzy numbers A_{ij} and their reciprocals $1/A_{ij}$ calculated in accordance with Equation 8.11. This is illustrated as the following Table 8.7

Table 8-7 Pair-wise comparison of importance of main root causal factors for the given MRO

	OP	D	MP	AD	S	R
Organizational Processes (OP)	(1,1,1)	A_{12}	A_{13}	A_{14}	A_{15}	A_{16}
Documentation (D)	$1/A_{12}$	(1,1,1)	A_{23}	A_{24}	A_{25}	A_{26}
Maintainer Preparation (MP)	$1/A_{13}$	$1/A_{23}$	(1,1,1)	A_{34}	A_{35}	A_{36}
Aircraft Design (AD)	$1/A_{14}$	$1/A_{24}$	$1/A_{34}$	(1,1,1)	A_{45}	A_{46}
Supervision (S)	$1/A_{15}$	$1/A_{25}$	$1/A_{35}$	$1/A_{45}$	(1,1,1)	A_{56}
Resources (R)	$1/A_{16}$	$1/A_{26}$	$1/A_{36}$	$1/A_{46}$	$1/A_{56}$	(1,1,1)

Step 5: Building 'pair-wise comparison' matrices of existing potentiality among each group of sub-root causal factors as given by the ANP- workplace

Similarly to all procedures of step 4, pair-wise comparison matrices can be constructed for each group of sub factors using the potentialities obtained in step 2. These are given in Tables 8.8 to 8.13 as follows:

Table 8-8 Pair-wise comparison of importance for sub-factors associated with the main factor 'organizational processes'

	R	OPR	PT	G	PWS	TD	P
Regulations (R)	(1,1,1)	A_{12}	A_{13}	A_{14}	A_{15}	A_{16}	A_{17}
Oversight Provision (OPR)	$1/A_{12}$	(1,1,1)	A_{23}	A_{24}	A_{25}	A_{26}	A_{27}
Performance Tracking (PT)	$1/A_{13}$	$1/A_{23}$	(1,1,1)	A_{34}	A_{35}	A_{36}	A_{37}
Guidance (G)	$1/A_{14}$	$1/A_{24}$	$1/A_{34}$	(1,1,1)	A_{45}	A_{46}	A_{47}
Planning (PWS)	$1/A_{15}$	$1/A_{25}$	$1/A_{35}$	$1/A_{45}$	(1,1,1)	A_{56}	A_{57}
Task Design (TD)	$1/A_{16}$	$1/A_{26}$	$1/A_{36}$	$1/A_{46}$	$1/A_{56}$	(1,1,1)	A_{67}
Procedures (P)	$1/A_{17}$	$1/A_{27}$	$1/A_{37}$	$1/A_{47}$	$1/A_{57}$	$1/A_{67}$	(1,1,1)

Table 8-9 Pair-wise comparison of importance for the sub-factors associated with the main factor 'Documentation'

	AD	DQ	DU	FM
Documents Availability (AD)	(1,1,1)	A_{12}	A_{13}	A_{14}
Documents Quality (DQ)	1/ A_{12}	(1,1,1)	A_{23}	A_{24}
Documents Updating (DU)	1/ A_{13}	1/ A_{23}	(1,1,1)	A_{34}
Feedback to Manufacturer (FM)	1/ A_{14}	1/ A_{24}	1/ A_{34}	(1,1,1)

Table 8-10 Pair-wise comparison of importance for the sub-factors associated with the main factor 'maintainer preparation'

	QVU	KSD	HFT
Qualification Validity/Update (QVU)	(1,1,1)	A_{12}	A_{13}
Knowledge/ Skill Development (KSD)	1/ A_{12}	(1,1,1)	A_{23}
Human Factors Training (HFT)	1/ A_{13}	1/ A_{23}	(1,1,1)

Table 8-11 Pair--wise comparison of importance for the sub-factors associated with the main factor 'aircraft design'

	ADE	MA	MTC
Aircraft Design Error / Shortage (ADE)	(1,1,1)	A_{12}	A_{13}
Maintenance Accessibility (MA)	1/ A_{12}	(1,1,1)	A_{23}
Maintenance Task Complexity (MTC)	1/ A_{13}	1/ A_{23}	(1,1,1)

Table 8-12 Pair-wise comparison of importance for the sub-factors associated with the main factor 'supervision'

	TDA	IF	UP
Task Delegation / Assignment (TDA)	(1,1,1)	A_{12}	A_{13}
Inspections Failures (IF)	1/ A_{12}	(1,1,1)	A_{23}
Uncorrected Problems (UP)	1/ A_{13}	1/ A_{23}	(1,1,1)

Table 8-13 Pair-wise comparison of importance for the sub-factors associated with the main factor ' resources'

	MNP	MTP	ET	SP	WF	WC
Manning Provision (MNP)	(1,1,1)	A_{12}	A_{13}	A_{14}	A_{15}	A_{16}
Material Provision (MTP)	1/ A_{12}	(1,1,1)	A_{23}	A_{24}	A_{25}	A_{26}
Equipment/ Tools (ET)	1/ A_{13}	1/ A_{23}	(1,1,1)	A_{34}	A_{35}	A_{36}
Spare Parts (SP)	1/ A_{14}	1/ A_{24}	1/ A_{34}	(1,1,1)	A_{45}	A_{46}
Workplace Facilities (WF)	1/ A_{15}	1/ A_{25}	1/ A_{35}	1/ A_{45}	(1,1,1)	A_{56}
Workplace Conditions (WC)	1/ A_{16}	1/A_{26}	1/ A_{36}	1/ A_{46}	1/ A_{56}	(1,1,1)

Step 6: Determination of local weights for main root causal factors using Fuzzy Synthetic Extent Analysis of the fore ANP

Using the fuzzy ANP approach introduced by Chang (1992,1996) and confirmed by Dagdeviren et al (2008), the local weights can be determined through four steps. The following mathematical formulation applies:

A. Evaluating fuzzy synthetic values of pair-wise comparison matrices:

Concept of fuzzy synthetic extent:

Let:

$X = \{x_1, x_2, x_3, ..., x_n\}$ be an object set 8-25

$G = \{g_1, g_2, g_3, ..., g_m\}$ be a goal set 8-26

Objects $x_1, x_2, x_3, ..., x_n$ are subjected individually to an extent analysis for each goal $g_1, g_2, g_3, ..., g_m$, then m-extent analysis values can be obtained for each object in the following order:

$A_{gi}^1, A_{gi}^2, ..., A_{gi}^m$, i = 1,2, 3, …, n

where all the A_{gi}^j , j = 1,2,3,…,m are TFN's.

Value of fuzzy synthetic extent:

Let:

$A_{gi}^1, A_{gi}^2, ..., A_{gi}^m$ be values of extent analysis of *i-th* object for m goals. Using Equations 8.5 through 8.11, the value of fuzzy synthetic extent with respect to *i-th* object is defined as:

$$S_i = \sum_{j=1}^{m} A_{gi}^j \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} A_{gi}^j \right]^{-1} \quad 8\text{-}27$$

Or

$$S_i = (\sum_{j=1}^{m} a_j, \sum_{j=1}^{m} b_j, \sum_{j=1}^{m} c_j) \otimes \left[(\sum_{j=1}^{m} \sum_{i=1}^{n} a_i, \sum_{j=1}^{m} \sum_{i=1}^{n} b_i, \sum_{j=1}^{m} \sum_{i=1}^{n} c_i) \right]^{-1} \quad 8\text{-}28$$

$$S_i = (\sum_{j=1}^{m} a_j, \sum_{j=1}^{m} b_j, \sum_{j=1}^{m} c_j) \otimes (\frac{1}{\sum_{j=1}^{m} \sum_{i=1}^{n} c_i}, \frac{1}{\sum_{j=1}^{m} \sum_{i=1}^{n} b_i}, \frac{1}{\sum_{j=1}^{m} \sum_{i=1}^{n} a_i}) \quad 8\text{-}29$$

Thus a fuzzy synthetic extent system of all factors can be constructed in the following structure:

$$\begin{aligned} S_{OP} &= (a_{synth1}, b_{synth1}, c_{synth1}) \\ S_{D} &= (a_{synth2}, b_{synth2}, c_{synth2}) \\ S_{MP} &= (a_{synth3}, b_{synth3}, c_{synth3}) \\ S_{AD} &= (a_{synth4}, b_{synth4}, c_{synth4}) \\ S_{S} &= (a_{synth5}, b_{synth5}, c_{synth5}) \\ S_{R} &= (a_{synth5}, b_{synth5}, c_{synth5}) \end{aligned} \quad \text{, all triangular fuzzy numbers} \qquad 8\text{-}30$$

B. Evaluating the degree of possibility for a convex fuzzy number to be greater than another fuzzy number:

The ability to compare between values of fuzzy numbers is required so as to calculate local weights of the factors that were previously described by pair-wise comparison matrices, and then have been converted into fuzzy synthetic systems like the one given by Equations 8.30. Formulations to compare two fuzzy numbers are:

If $A_1 = (a_1, b_1, c_1)$ and $A_2 = (a_2, b_2, c_2)$, then the degree of possibility of A_2 to be greater than A_1 is defined by the vectors $V\ (A_2 \geq A_1)\ and\ V\ (A_1 \geq A_2)$ as:

$$V(A_2 \geq A_1) = \begin{cases} 1 & , b_2 \geq b_1 \\ 0 & , a_1 \geq c_2 \\ \dfrac{a_1 - c_2}{(b_2 - c_2) - (b_1 - a_1)} & , otherwise \end{cases} \qquad 8\text{-}31$$

Thus to compare the two fuzzy numbers, both values of $V\ (A_1 \geq A_2)$ and $V\ (A_2 \geq A_1)$ are required.

C. Evaluating the degree of possibility for a convex fuzzy number to be greater than a group of other fuzzy numbers (obtaining vectors of comparison between factors given in synthetic form of S_i):

To get more generalized form of comparison, and using formula 8.31, the degree of possibility of a convex fuzzy number A to be greater than a group of fuzzy numbers A_i, $i = 1, 2, 3, ..., k$ can be defined using vectors as:

$$\begin{aligned} V\ (A \geq A_1, A_2, ..., A_K) &= V\ \left[(A \geq A_1)\, and\ (A \geq A_2)\, and\ ...and\ (A \geq A_k) \right] \\ &= \min V\ (A \geq A_i) \qquad , i = 1, 2, ..., k \end{aligned} \qquad 8\text{-}32$$

D. Evaluating the local weights of factors:

Local weight of various factors can be obtained using Equations 8.30, 8.31, and 8.32. These equations can be joined collectively by assuming:

$$d^{1}(A_i) = \min V(S_i \geq S_k) \quad ,k = 1,2,...,n \quad ,k \neq i \qquad \text{8-33}$$

Then the local weight vector is given by:

$$W^{1} = (d^{1}(A_1), d^{1}(A_2), ..., d^{1}(A_n))^T \qquad \text{8-34}$$

Where $A_i \, (i = 1,2,...,n)$ are n elements.

By normalizing Equation 8.34, the local weight vector of the main factors is given as:

$$W = (d(A_1), d(A_2), ..., d(A_n))^T \quad , W \text{ is a non-fuzzy number} \qquad \text{8-35}$$

The local weights can be calculated for the main root causal factors as given in Tables 8.14. as follows:

Table 8-14 Local weights of main root causal factors for the given MRO

Main Factors	Collective Weight Vector	Local Weights	Normalized Local Weights
Organizational Processes	$W=(d(A_1), d(A_2),..., (A_n))$	$d(A_1)$	$d(A_1)/TW$
Documentation	$W=(d(A_1), d(A_2),..., (A_n))$	$d(A_2)$	$d(A_2)/TW$
Maintainer Preparation	$W=(d(A_1), d(A_2),..., (A_n))$	$d(A_3)$	$d(A_3)/TW$
Aircraft Design	$W=(d(A_1), d(A_2),..., (A_n))$	$d(A_4)$	$d(A_4)/TW$
Supervision	$W=(d(A_1), d(A_2),..., (A_n))$	$d(A_5)$	$d(A_5)/TW$
Resources	$W=(d(A_1), d(A_2),..., (A_n))$	$d(A_6)$	$d(A_6)/TW$
Total Weights		TW	1.0

Step 7: Determination of local weights for sub-root causal factors using Fuzzy Synthetic Extent Analysis of the fore ANP.

Similar to the procedure followed in step 6, local weights can be calculated for each group of sub-factors as given in Tables 8.15 to 8.20.

Table 8-15 Local weights of sub-factors associated with main factor 'organizational processes'

Sub-factors	Collective Weight Vector	Local Weights	Normalized Local Weights
Regulations	$W_{OP}=(d(A_1), d(A_2),..., (A_n))_{OP}$	$d(A_1)_{OP}$	$(d(A_1)/TW)_{OP}$
Oversight Provision	$W_{OP}=(d(A_1), d(A_2),..., (A_n))_{OP}$	$d(A_2)_{OP}$	$(d(A_2)/TW)_{OP}$
Performance Tracking	$W_{OP}=(d(A_1), d(A_2),..., (A_n))_{OP}$	$d(A_3)_{OP}$	$(d(A_3)/TW)_{OP}$
Guidance	$W_{OP}=(d(A_1), d(A_2),..., (A_n))_{OP}$	$d(A_4)_{OP}$	$(d(A_4)/TW)_{OP}$
Planning	$W_{OP}=(d(A_1), d(A_2),..., (A_n))_{OP}$	$d(A_5)_{OP}$	$(d(A_5)/TW)_{OP}$
Task Design	$W_{OP}=(d(A_1), d(A_2),..., (A_n))_{OP}$	$d(A_6)_{OP}$	$(d(A_6)/TW)_{OP}$
Procedures	$W_{OP}=(d(A_1), d(A_2),..., (A_n))_{OP}$	$d(A_7)_{OP}$	$(d(A_7)/TW)_{OP}$
Total Weight		$(TW)_{OP}$	1.0

Table 8-16 Local weights of sub-factors associated with main factor 'Documentation'

Sub-factors	Collective Weight Vector	Local Weights	Normalized Local Weights
Documents Availability	$W_D=(d(A_1), d(A_2),\ldots, (A_n))_D$	$d\ (A_1)_D$	$(d\ (A_1)\ /TW)_D$
Documents Quality	$W_D=(d(A_1), d(A_2),\ldots, (A_n))_D$	$d\ (A_2)_D$	$(d\ (A_2)\ /TW)_D$
Documents Updating	$W_D=(d(A_1), d(A_2),\ldots, (A_n))_D$	$d\ (A_3)_D$	$(d\ (A_3)\ /TW)_D$
Feedback to Manufacturer	$W_D=(d(A_1), d(A_2),\ldots, (A_n))_D$	$d\ (A_4)_D$	$(d\ (A_4)\ /TW)_D$
Total Weight		$(TW)_D$	1.0

Table 8-17 Local weights of sub-factors associated with main factor 'Maintainers preparation'

Sub-factors	Collective Weight Vector	Local Weights	Normalized Local Weights
Qualification Validity	$W_{MP}=(d(A_1), d(A_2),\ldots, (A_n))_{MP}$	$d\ (A_1)_{MP}$	$(d\ (A_1)\ /TW)_{MP}$
Knowledge/ Skill	$W_{MP}=(d(A_1), d(A_2),\ldots, (A_n))_{MP}$	$d\ (A_2)_{MP}$	$(d\ (A_2)\ /TW)_{MP}$
Human F. Training	$W_{MP}=(d(A_1), d(A_2),\ldots, (A_n))_{MP}$	$d\ (A_3)_{MP}$	$(d\ (A_3)\ /TW)_{MP}$
Total Weight		$(TW)_{MP}$	1.0

Table 8-18 Local weights of sub-factors associated with main factor 'Aircraft design'

Sub-factors	Collective Weight Vector	Local Weights	Normalized Local Weights
Aircraft Design Error	$W_{AD}=(d(A_1), d(A_2),\ldots, (A_n))_{AD}$	$d\ (A_1)_{AD}$	$(d\ (A_1)\ /TW)_{AD}$
Maintenance Access	$W_{AD}=(d(A_1), d(A_2),\ldots, (A_n))_{AD}$	$d\ (A_2)_{AD}$	$(d\ (A_2)\ /TW)_{AD}$
Task Complexity	$W_{AD}=(d(A_1), d(A_2),\ldots, (A_n))_{AD}$	$d\ (A_3)_{AD}$	$(d\ (A_3)\ /TW)_{AD}$
Total Weight		$(TW)_{AD}$	1.0

Table 8-19 Local weights of sub-factors associated with main factor 'Supervision'

Sub-factors	Collective Weight Vector	Local Weigh ts	Normalized Local Weights
Task Delegation .	$W_S=(d(A_1), d(A_2),\ldots, (A_n))_S$	$d\ (A_1)_S$	$(d\ (A_1)\ /TW)_S$
Inspections Failures	$W_S=(d(A_1), d(A_2),\ldots, (A_n))_S$	$d\ (A_2)_S$	$(d\ (A_2)\ /TW)_S$
Uncorrected Problems	$W_S=(d(A_1), d(A_2),\ldots, (A_n))_S$	$d\ (A_3)_S$	$(d\ (A_3)\ /TW)_S$
Total Weight		$(TW)_S$	1.0

Table 8-20 Local weights of sub-factors associated with main factor 'Resources'

Sub-factors	Collective Weight Vector	Local Weights	Normalized Local Weights
Manning Provision	$W_R=(d(A_1), d(A_2),\ldots, (A_n))_R$	$d\ (A_1)_R$	$(d\ (A_1)\ /TW)_R$
Material Provision	$W_R=(d(A_1), d(A_2),\ldots, (A_n))_R$	$d\ (A_2)_R$	$(d\ (A_2)\ /TW)_R$
Equipment/ Tools	$W_R=(d(A_1), d(A_2),\ldots, (A_n))_R$	$d\ (A_3)_R$	$(d\ (A_3)\ /TW)_R$
Spare Parts	$W_R=(d(A_1), d(A_2),\ldots, (A_n))_R$	$d\ (A_4)_R$	$(d\ (A_4)\ /TW)_R$
Workplace Facilities	$W_R=(d(A_1), d(A_2),\ldots, (A_n))_R$	$d\ (A_6)_R$	$(d\ (A_5)\ /TW)_R$
Workplace Conditions	$W_R=(d(A_1), d(A_2),\ldots, (A_n))_R$	$d\ (A_6)_R$	$(d\ (A_6)\ /TW)_R$
Total Weight		$(TW)_R$	1.0

Step 8: Evaluation of dependencies among the causal factors and determination of their interdependent weights.

This is the third newly introduced algorithm within this mathematical model to fulfil the partial target of automating the decision making processes that is associated with the inter-factors comparisons. Through this algorithm the dependence among main factors (represented in Figures 7.7 and 7.8 by vertical errors between factors) is determined by evaluating impact of each factor on every other factor through pair-wise comparison as well. In this stage a more sophisticated set of enquiries will be used for the pair-wise comparison such as: ‘‘What is the relative importance of ‘documentation’ when compared with ‘maintainer preparation’ on controlling (affecting) ‘organizational processes’ in the given MRO?’’. By answering such questions, a complete set of inner dependence matrices describing the mutual influences between main factors can be built, thus representing the actual real-world conditions of factors interdependency.

A. Introducing the Index of Factors Mutual Influence (IFMI)

Let A be one factor of weight of importance W_A among a set of K factors with total combined weight of importance W_T.

Let B_i , $i = 1, 2, \ldots, K$ be another factor of weight of importance W_{B_i} within the same set, then the index of influence of A on B_i, written as I_{A/B_i}, can be indicated by comparing the proportions of W_{B_i} to W_T in the two cases of W_T including and excluding W_A . Mathematically:

$$I_{A/B_i} = \left| \frac{W_{B_i}}{W_T - W_A} - \frac{W_{B_i}}{W_T} \right|, \ i = 1, 2, \ldots, K \qquad 8\text{-}36$$

This IFMI is perfectly constructive in directly comparing between main factors using their weights, as potential root causes, obtained as per Table 8.14. By mathematically evaluating the index of influence that each factor exerts on the others, a complete true mapping of real dynamics of the mutual interaction of factors can be achieved. The full scope of the IFMI's can be illustrated as per matrix of Table 8.21.

Table 8-21 IFMI matrix of main root error causal factors

	OP	D	MP	AD	S	R
Organizational Processes	*n.a.*	$I_{OP/D}$	$I_{OP/MP}$	$I_{OP/AD}$	$I_{OP/S}$	$I_{OP/R}$
Documentation	$I_{D/OP}$	*n.a.*	$I_{D/MP}$	$I_{D/AD}$	$I_{D/S}$	$I_{D/R}$
Maintainer Preparation	$I_{MP/OP}$	$I_{MP/D}$	*n.a.*	$I_{MP/AD}$	$I_{MP/S}$	$I_{MP/R}$
Aircraft Design	$I_{AD/OP}$	$I_{AD/D}$	$I_{AD/MP}$	*n.a.*	$I_{AD/S}$	$I_{AD/R}$
Supervision	$I_{S/OP}$	$I_{S/D}$	$I_{S/MP}$	$I_{S/AD}$	*n.a.*	$I_{S/R}$
Resources	$I_{R/OP}$	$I_{R/D}$	$I_{R/MP}$	$I_{R/AD}$	$I_{R/S}$	*n.a.*

B. Building inner dependence pair-wise comparison matrices

Mutual inner dependence comparison matrices were then constructed to explore the influence of main factors on each others using the IFMI matrix of Table 8.21. The importance of 'documentation' when compared to 'maintainer preparation' in influencing the 'organizational processes' is the net difference between the two indices $I_{D/OP}$ and $I_{MP/OP}$. These differences, when assigned to various bands like the ones given in step 4, can allow for the use of a similar fuzzy linguistic scale to generate the relative weights of the factors when their mutual inner dependence is considered, thus more accurately representing the real world situations within MRO's. This third batch of fuzzy matrices of pair-wise, mutually-dependent, importance of the main root causal factors are built using fuzzy numbers Z_{ij} and their reciprocals $1/ Z_{ij}$ calculated in accordance with sequence described in step 4.

Table 8-22 Inner dependence matrix of importance of main root factors as they mutually influence the factor: 'Organizational Processes'

	D	MP	AD	S	R
Documentation (D)	*(1,1,1)*	Z_{23}	Z_{24}	Z_{25}	Z_{26}
Maintainer Preparation (MP)	$1/ Z_{23}$	*(1,1,1)*	Z_{34}	Z_{35}	Z_{36}
Aircraft Design (AD)	$1/ Z_{24}$	$1/ Z_{34}$	*(1,1,1)*	Z_{45}	Z_{46}
Supervision (S)	$1/ Z_{25}$	$1/ Z_{35}$	$1/ Z_{45}$	*(1,1,1)*	Z_{56}
Resources (R)	$1/Z_{26}$	$1/ Z_{36}$	$1/ Z_{46}$	$1/ Z_{56}$	*(1,1,1)*

Table 8-23 Inner dependence matrix of importance of main root factors as they mutually influence the factor: 'Documentation'

	OP	MP	AD	S	R
Organizational Processes (OP)	(1,1,1)	Z_{13}	Z_{14}	Z_{15}	Z_{16}
Maintainer Preparation (MP)	1/ Z_{13}	(1,1,1)	Z_{34}	Z_{35}	Z_{36}
Aircraft Design (AD)	1/ Z_{14}	1/ Z_{34}	(1,1,1)	Z_{45}	Z_{46}
Supervision (S)	1/ Z_{15}	1/ Z_{35}	1/ Z_{45}	(1,1,1)	Z_{56}
Resources (R)	1/ Z_{16}	1/ Z_{36}	1/ Z_{46}	1/ Z_{56}	(1,1,1)

Table 8-24 Inner dependence matrix of importance of main root factors as they mutually influence the factor: 'Maintainer Preparation'

	OP	D	AD	S	R
Organizational Processes (OP)	(1,1,1)	Z_{12}	Z_{14}	Z_{15}	Z_{16}
Documentation (D)	1/ Z_{12}	(1,1,1)	Z_{24}	Z_{25}	Z_{26}
Aircraft Design (AD)	1/ Z_{14}	1/ Z_{24}	(1,1,1)	Z_{45}	Z_{46}
Supervision (S)	1/ Z_{15}	1/ Z_{25}	1/ Z_{45}	(1,1,1)	Z_{56}
Resources (R)	1/ Z_{16}	1/Z_{26}	1/ Z_{46}	1/ Z_{56}	(1,1,1)

Table 8-25 Inner dependence matrix of importance of main root factors as they mutually influence the factor: 'Aircraft Design'

	OP	D	MP	S	R
Organizational Processes (OP)	(1,1,1)	Z_{12}	Z_{13}	Z_{15}	Z_{16}
Documentation (D)	1/ Z_{12}	(1,1,1)	Z_{23}	Z_{25}	Z_{26}
Maintainer Preparation (MP)	1/ Z_{13}	1/ Z_{23}	(1,1,1)	Z_{35}	Z_{36}
Supervision (S)	1/ Z_{15}	1/ Z_{25}	1/ Z_{35}	(1,1,1)	Z_{56}
Resources (R)	1/ Z_{16}	1/Z_{26}	1/ Z_{36}	1/ Z_{56}	(1,1,1)

Table 8-26 Inner dependence matrix of importance of main root factors as they mutually influence the factor: 'Supervision'

	OP	D	MP	AD	R
Organizational Processes (OP)	(1,1,1)	Z_{12}	Z_{13}	Z_{14}	Z_{16}
Documentation (D)	1/ Z_{12}	(1,1,1)	Z_{23}	Z_{24}	Z_{26}
Maintainer Preparation (MP)	1/ Z_{13}	1/ Z_{23}	(1,1,1)	Z_{34}	Z_{36}
Aircraft Design (AD)	1/ Z_{14}	1/ Z_{24}	1/ Z_{34}	(1,1,1)	Z_{46}
Resources (R)	1/ Z_{16}	1/Z_{26}	1/ Z_{36}	1/ Z_{46}	(1,1,1)

Table 8-27 Inner dependence matrix of importance of main root factors as they mutually influence the factor: 'Resources'

	OP	D	MP	AD	S
Organizational Processes (OP)	(1,1,1)	Z_{12}	Z_{13}	Z_{14}	Z_{15}
Documentation (D)	1/ Z_{12}	(1,1,1)	Z_{23}	Z_{24}	Z_{25}
Maintainer Preparation (MP)	1/ Z_{13}	1/ Z_{23}	(1,1,1)	Z_{34}	Z_{35}
Aircraft Design (AD)	1/ Z_{14}	1/ Z_{24}	1/ Z_{34}	(1,1,1)	Z_{45}
Supervision (S)	1/ Z_{15}	1/ Z_{25}	1/ Z_{35}	1/ Z_{45}	(1,1,1)

C. Calculation of relative importance weights of causal factors

Applying the full mathematical sequence discussed previously in step 6, the *relative importance weights* of the main causal factors, that map their inner dependence, can be listed as well.

D. Construction of master matrix for main root causal factor interdependent weights

The above calculated relative importance weights for the main causal factors are used to construct a master Relative Importance Matrix W_{RI} in the following shape:

$$W_{RI} = \begin{pmatrix} w_{11} & \cdots & w_{1n} \\ \vdots & \ddots & \vdots \\ w_{n1} & \cdots & w_{nn} \end{pmatrix}, \text{(n = 6 for the current analysis)} \qquad 8\text{-}37$$

E. Calculation of interdependent weights of the main causal factors

The final interdependent weights of the n causal factors can then be calculated through multiplying the relative importance weights matrix W_{RI} above by the local weights of the n factors obtained before as in Table 8.13. This can be indicated as follows:

$$W_{\text{relative importance}} \ \text{X} \ W_{\text{local}} = W_{\text{interdependent}}$$

$$\begin{pmatrix} w_{11} & w_{12} & w_{13} & w_{14} & w_{15} & w_{16} \\ w_{21} & w_{22} & & w_{23} & & \\ w_{31} & w_{32} & & w_{33} & & \\ w_{41} & & & & & \\ w_{51} & & & & & \\ w_{61} & & & & & w_{66} \end{pmatrix} \times \begin{pmatrix} w_{L_{OP}} \\ w_{L_D} \\ w_{L_{MP}} \\ w_{L_{AD}} \\ w_{L_S} \\ w_{L_R} \end{pmatrix} = \begin{pmatrix} w_{I_{OP}} \\ w_{I_D} \\ w_{I_{MP}} \\ w_{I_{AD}} \\ w_{I_S} \\ w_{I_R} \end{pmatrix} \qquad 8\text{-}38$$

Step 9: Determination of Global Weights for causal sub-factors and

Global weights of the sub-factors are obtained by multiplying local weights of these sub-factors (Tables 8.15 to 8.20) with the interdependent weight of the main factor to which they belong (as obtained by Equation 8.38). This can be illustrated by system of Equations 8.39.

$$
\begin{Bmatrix}
W_{\text{Local RE}} \times W_{\text{Interdependent OP}} = W_{\text{Global RE}} \\
W_{\text{Local OPR}} \times W_{\text{Interdependent OP}} = W_{\text{Global OPR}} \\
W_{\text{Local PT}} \times W_{\text{Interdependent OP}} = W_{\text{Global PT}} \\
W_{\text{Local G}} \times W_{\text{Interdependent OP}} = W_{\text{Global G}} \\
W_{\text{Local PWS}} \times W_{\text{Interdependent OP}} = W_{\text{Global PWS}} \\
W_{\text{Local TD}} \times W_{\text{Interdependent OP}} = W_{\text{Global TD}} \\
W_{\text{Local R}} \times W_{\text{Interdependent OP}} = W_{\text{Global R}} \\
W_{\text{Local DA}} \times W_{\text{Interdependent D}} = W_{\text{Global DA}} \\
W_{\text{Local DQ}} \times W_{\text{Interdependent D}} = W_{\text{Global DQ}} \\
W_{\text{Local DU}} \times W_{\text{Interdependent D}} = W_{\text{Global DU}} \\
W_{\text{Local FM}} \times W_{\text{Interdependent D}} = W_{\text{Global FM}} \\
W_{\text{Local QVU}} \times W_{\text{Interdependent MP}} = W_{\text{Global QVU}} \\
W_{\text{Local KSD}} \times W_{\text{Interdependent MP}} = W_{\text{Global KSD}} \\
W_{\text{Local HFT}} \times W_{\text{Interdependent MP}} = W_{\text{Global HFT}} \\
W_{\text{Local ADE}} \times W_{\text{Interdependent AD}} = W_{\text{Global ADE}} \\
W_{\text{Local MA}} \times W_{\text{Interdependent AD}} = W_{\text{Global MA}} \\
W_{\text{Local MTC}} \times W_{\text{Interdependent AD}} = W_{\text{Global MTC}} \\
W_{\text{Local TDA}} \times W_{\text{Interdependent S}} = W_{\text{Global TDA}} \\
W_{\text{Local IF}} \times W_{\text{Interdependent S}} = W_{\text{Global IF}} \\
W_{\text{Local UP}} \times W_{\text{Interdependent S}} = W_{\text{Global UP}} \\
W_{\text{Local MNP}} \times W_{\text{Interdependent R}} = W_{\text{Global MNP}} \\
W_{\text{Local MTP}} \times W_{\text{Interdependent R}} = W_{\text{Global MTP}} \\
W_{\text{Local ET}} \times W_{\text{Interdependent R}} = W_{\text{Global ET}} \\
W_{\text{Local SP}} \times W_{\text{Interdependent R}} = W_{\text{Global SP}} \\
W_{\text{Local WF}} \times W_{\text{Interdependent R}} = W_{\text{Global WF}} \\
W_{\text{Local WC}} \times W_{\text{Interdependent R}} = W_{\text{Global WC}}
\end{Bmatrix}
\qquad \text{8-39}
$$

8.3.2 Automating the expert's role

The above described procedure is built taking into account many vital considerations that crucially influenced the model structure. Some of these are:

1. Human factors research has always been described as being of limited direct practical benefits to industry due to significant variations between the agendas of both researchers and industry professionals. This is thoroughly discussed in

previous chapters of this thesis. Research works and theories tend to rely heavily on selective 'laboratory-conditioned' situations of which the utilization of complicated and costly systems of experts is a major feature. Industry seems to be keener to have specific focused solutions that can be used within the real hangar atmosphere. This research, in bridging the gap between these two worlds, paid sincere attention to eliminate, as far as possible, the direct need for experts systems. Instead, the role that such systems usually do is transferred to the pre-built algorithms within the AMMP mathematical model.

2. The fuzzy logic concepts, being totally dedicated to accommodate subjectivity and uncertainty, are found through this research to be of high capability and flexibility to handle the 'automation' of the roles of experts groups. Using the RCES criteria and introducing new fuzzy algorithms within the model, it is only required now to have the initial assessing inputs of the user. No further judgements or evaluations are required. The model can sequentially provide for such judgements and evaluations.
3. The adopted methodology, in its prospective part, calls for the creativity of the researcher in order to transfer the learned backward-oriented knowledge, including limitations of previous solutions, into inventive future plans. Eliminating the need for traditional experts systems is a satisfier to such call.
4. By building such a practical tool as ErroDetect, this researcher is demonstrating a trial to master both the fluency in the relatively-new fuzzy logic applications as well as the ability of building lengthy sophisticated software codes.

8.4 Chapter summary

In this chapter the main mathematical model of the AMMP process is thoroughly discussed. The model, comprising excessive sequential formulations and tabulations, is built to receive a sole input by the process applicant. This input is a direct assessment of the overall evaluation of the given aircraft design, or an accurate mapping of a given MRO and its position within the safety space. The core of the input process uses the pre-discussed 870 RCES criteria. The expected product is an overall evaluation of the content of root causes, promoting aviation maintenance errors, that may be embodied within design or hidden within a MRO environment.

9 Building and Verification of AMMP Software and Process

The longer mathematics lives the more abstract - and therefore, possibly also the more practical - it becomes.
E.T. Bell (1883 – 1960)

9.1 Introduction

This chapter describes the activities carried out, as part of this research, to structure, build, test through simulation, and verify within-industry the ErroDetect software, which is the core element of the AMMP concept and practice.

9.2 Construction of AMMP software (ErroDetect)

9.2.1 Overall layout of ErroDetect package

As part of the prospective pillar of the applied research methodology, the ErroDetect software is built referring to the following featuring guidelines:

1. The package is composed of two similar, yet independent software codes serving the design and workplace folds of the AMMP concept. The layout of each code is structured following the relative fuzzy ANP diagram as per Figures 7.7 and 7.8.
2. The package is built using the well-spread Microsoft Office Excel Spreadsheets. This is to give more flexibility during software design, and to provide users with software that is built in an environment which they thoroughly know. 12 different spreadsheets are used for the Design code, while 9 different spreadsheets are used for the workplace one.
3. The fuzzy logic calculations are performed through sequential layers of complex inter-referred equations, matrices, and tabulations. The calculations are automatically propagated starting with the user unique input (using the previously discussed 870 assessment criteria of the RCES), and ending with numerical and graphical representation of the weights of each potential error root cause that may be embodied within design or hidden within the MRO's atmosphere.
4. Although the package is structured mainly for the purposes of this research at the current time, but it is designed to be at the maximum flexibility and 'user-friendly' features that the available research time allowed to incorporate. The software is always available for further promotions if it is to be fully industrialized later.

9.2.2 *Detailed structure of ErroDetect package*

The two parts of the ErroDetect package are similar in general layout, thus only the workplace code will be described here in details for simplicity and compactness of the thesis. The workplace code is composed of 4 basic sections:

1. Logo and introduction page.
2. User input pages
3. Calculations page.
4. Final numerical and graphical report

The Logo and introduction page, partially shown in Figure 9.1, gives brief instructions for users, and describes the methodology in which the software performs.

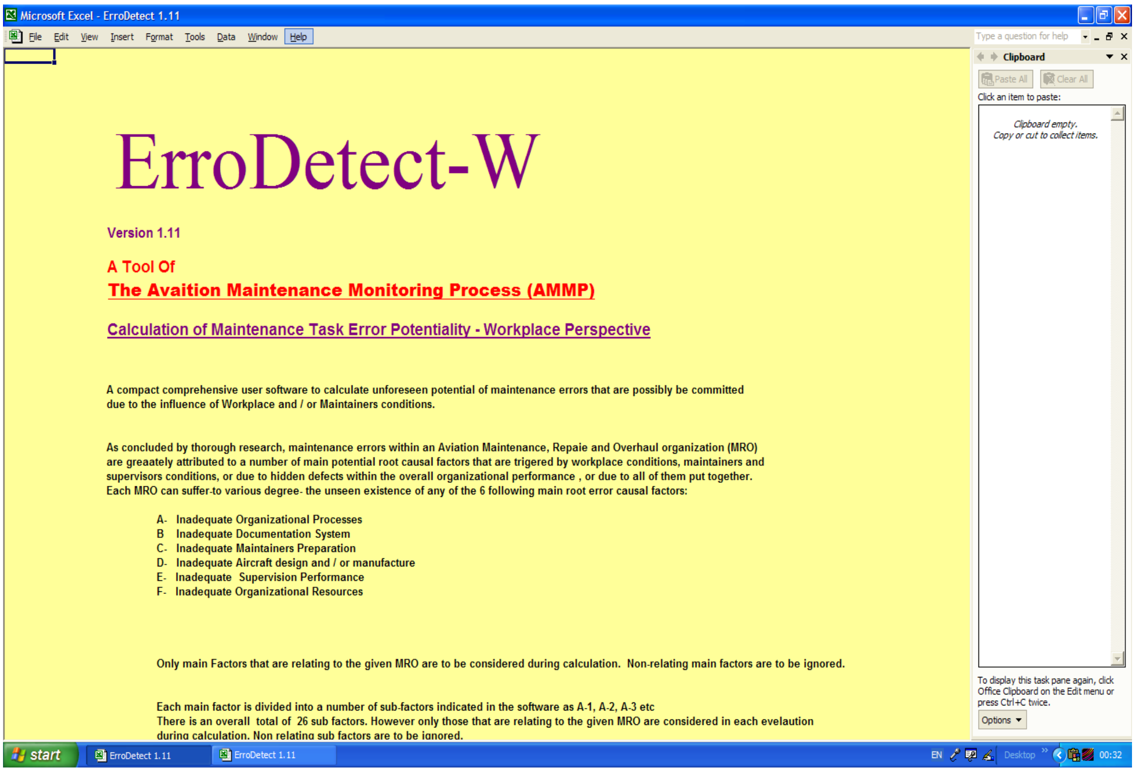


Figure 9-1 ErroDetect-Workplace Version 1.11 software home page

The user is tasked then to use the following 6 input pages (individual yet interlinked spreadsheets) to inter his/ her unique single input task. Each page is devoted to one of the 6 main root causes of the ANP given in Figure 7.8. Initial assessment weights of individual sub-causal factors are obtained as a result of the evaluation of the 10 criteria associated with each sub-factor, thus concluding the initial assessment of the specific main root cause by the end of its devoted page.

The calculations are simultaneously performed as the input process progresses. The calculation page uses inputs from the 6 previous spreadsheets and performs all the successive operations discussed in chapter 8 leading to an accurate map of root causes presence within the MRO under investigation. The overall weights of importance of these root causal factors (mapping their existence) are given numerically and graphically in the final report page. A typical ErroDetect description of the safety behaviour of certain MRO is given as seen in Figure 9.2.

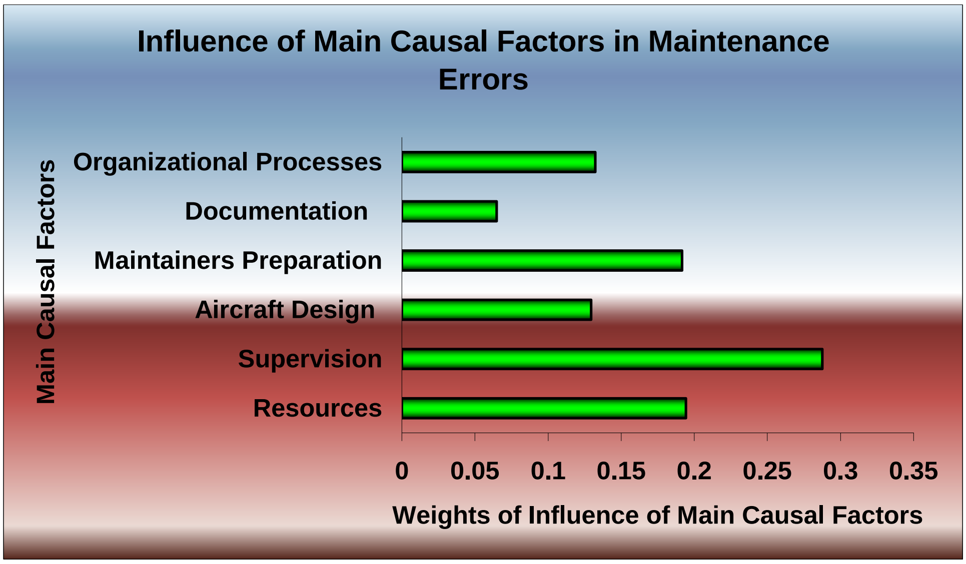


Figure 9-2 Typical existence of main error root causes detected within a given MRO using ErroDetect-Workplace Version 1.11 software

9.3 ErroDetect simulation

In order to further exhibit the AMMP concept and to demonstrate the sensitivity of its ErroDetect tool, two isolated groups of serious helicopter incidents are utilized as a base for a reverse-directed error causal factor prediction process using the software. The two simulation case studies illustrate ErroDetect implementation for both design and workplace folds respectively.

9.3.1 Case Study 1: ErroDetect simulation within design and manufacturing organizations

Three helicopters of identical type in UK and Spain (AAIB 2001a, b, FSF 2001) suffered a loss of control that led each of them to crash as a result of fracturing of their attachment bolts of swash plates scissors links. In all cases, a very short time before each accident occurred, the swash plate scissors link had been incorrectly assembled and installed. The accidents involved fatality and extensive aircrafts destruction. Consequently, an investigative survey of the fleet within UK showed that several other helicopters of the same type have their scissors links incorrectly assembled and installed as well, both during maintenance or even from the very initial assembly at the manufacturer facilities. Detailed examination of the main rotor heads of the three crashed helicopters revealed that the rotating scissors linkage of each aircraft had become detached as a result of a failure in the bolt that attached the lower link to the rotating swash plate. This resulted in sudden loss of control accompanied by abrupt drop of lift that led to high rates of falling descend. In all the mentioned three cases, the lower scissor links have been installed back to front in the incorrect orientation. Schematic configuration of the assembly is given by Figure 9.3.

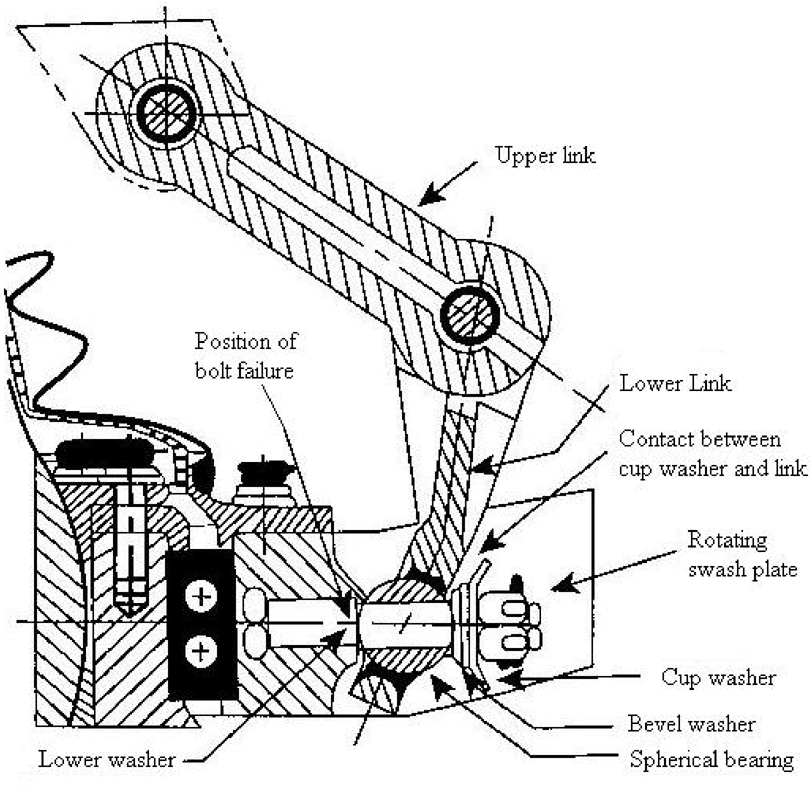


Figure 9-3 Schematic diagram of swash plate assembly for case study 1 (AAIB, in FSF 2001)

Further factual information regarding the three accidents and the relative maintenance that preceded them are given in Table 9.1. Thorough investigations concerning these maintenance activities revealed significant shortages in regard to this type design as well as its relative technical maintenance manuals. This is deeply discussed in Table 9.2.

Table 9-1 General factual information of accidents analysed in case study 1

Aircrafts	EC-Gxx	G- Jxxx	G- Txxx
Manufacture date	1998	1998	1999
Accident date	July 1999	January 2000	June 2000
Total flying hrs	300	--------	271
Cause of last maintenance	--------	Combined annual /100 hrs inspection	An 'A' check due to excessive play in swash plate scissors linkage bearings
Flying hrs after last maintenance	2 hrs 0 min	0 hrs 45 min	3 hrs 10 min
Severity	Fatal	Substantial damage to fuselage and rotors	Extensive damage to aircraft

There is physical evidence shown by the technical investigations that even if the lower link is correctly installed, some undesired contact can take place between the cup washer and the link especially at high pitch settings. Although this has no direct influence on maintenance sub-tasks effectiveness, but the case definitely involves an incorrect design feature with potential damage to aircraft parts during operation.

The next step was to upload trends of causal factors listed in the last column of Table 9.2 as input descriptors of the manufacturer's malfunctioning in regard to design, manufacturing processes, and associated aircraft maintenance documentation into the ErroDetect software. Exact numerical input to the software is given in Table 9.3. A comprehensive detailed analysis showing impact of the aircraft's design on maintenance is thus obtained as per Figure 9.4. This figure represents direct mapping of the hidden potentialities of maintenance human errors that can uncontrollably results of the various above named triggers. If this software is fed, at an early stage during prototype finalization, with the direct descriptors of the design features and any complementary documentation that are to be used by the aircraft operators in regard to each aircraft part and associated expected maintenance, then a thorough prophetic prediction of the kind given in Figure 9.4 can be obtained, in advance, that early highlights the areas prone to give problems during related foreseen maintenance activities.

Table 9-2 Error prone features of design that triggered maintenance human errors in case study 1

Maintenance-Related Activities or Facts Directly Before The Accidents	Influence on maintenance sub-tasks	Associated inherent shortage areas (maintenance error causal factors initiators)
1. Lower link was reportedly difficult to remove from the swash plate bolt Reason may be corrosion of the bolt. This resulted in damage to spherical bearing during lower link removal.	Removal: a. Difficult removal. b. Associated parts damage	Design : a. Material selection (Manufacturer). b. Accessibility (Manufacturer). c. Anti-corrosion Techniques (Manufacturer).
2. Lower scissors link had been installed back to front such that the spherical bearing at the base of the link, through which passed the attachment bolt, was restricted in its range of movement. The result of this incorrect installation will be: a. contact between the cub washer and outer face of the lower link b. the spherical bearing will run out of travel. c. Ultimately the main bolt fractures at the point where it emerges from the swash plate	Installation: a. incorrect installation	Design: a. Part can easily be incorrectly installed (Manufacturer)
3. Relevant diagram in Maintenance Manual doesn't show sufficient details of the lower link that could assist an engineer in identifying the correct orientation during installation. The manual contains no other written guidance as to the correct installation	Installation: a. Incorrect installation.	Documentation: a. Insufficient details in maintenance manuals drawings (Manufacturer). b. No written guidance (caution) on the correct installation (Manufacturer).

Relevant diagram in Maintenance Manual doesn't show sufficient details of the lower link that could assist an engineer in identifying the correct orientation during installation. The manual contains no other written guidance as to the correct installation (continued)	Installation: a. Incorrect installation (continued)	c. No relative information in the working task sheets (MRO).
4. The only clue given in the Manual that might help indicating incorrect installation is to compare such installation on aircraft with the shown diagram in the manual. However, this clue would not preclude correct installation of the hinge bolt even if the link itself is in an opposite orientation.	Inspection: a. Incorrect / ineffective inspection (self certification or by supervisor)	Design: a. No physical clue built within assembly that can indicate incorrect installation (Manufacturer).
5. There is an error in the instructions where the beveled washer (included in the attachment of the link to the swash plate bolt) is called item no 29 when it appears as item 25 in the diagram.	Removal / Installation: a. Incorrect removal and / or installation	Documentation: a. Wrong (conflicting) information within manual (Manufacturer).
6. The design of the scissors linkage is unique to this type. The lower link on earlier versions is asymmetric in planform and thus can't be installed incorrectly.	Installation: a. Incorrect installation	Design: a. Non-symmetric design of the lower link. Thus orientation is critical (Manufacturer).
7. The Part and Batch numbers are embossed on the inboard side of the link for the previous versions, whereas the equivalent numbers appears on the outboard face of the link for this type (This would result in confusion for mechanics accustomed to link numbers being always to the inboard face during installation). The manufacturer confirmed the correct installation orientation only after reference to production drawings.	Installation: a. Incorrect installation	Design: a. Non-familiar design of the lower link compared to similar previous versions (Manufacturer). b. No physical clue to correct orientation of parts assembly (Manufacturer).

8. The close metallurgical and physical examination of the broken bolts indicated that for all the given cases: a. The bevel washer had been installed incorrectly at the inboard part of the bolt instead of being at the outer part as indicated in the figure. This is probably the case since the aircrafts was built. b. The thin washer was incorrectly installed during the last maintenance in the outer side of the bolt instead of being in the inner part as indicated in the figure. c. Due to the beveled washer (with 4 mm thickness) being installed incorrectly in the inner side of the bolt, thus the lower link was incorrectly displaced outwards with this distance. This induced an un-noticed bending load to the bolt. d. The misplacement of the beveled washer resulted also in the main bolt retaining nut being thread-bound, consequently part of the specified assembly torque in the Manual was expended in tightening the nut to the end of the bolt's threaded portion. This left the stack-up assembly loose. This, in turn, induced relative fretting between the assembly components.	Installation: a. incorrect initial assembly at the factory. b. Incorrect assembly during the maintenance c. Loose assembly (Bolt's nut is thread –bound).	Documentation: a. Insufficient information on the correct assembly layout (Manufacturer). Manufacturing processes: a. Poor quality control and quality assurance of the manufacturing processes (Manufacturer). Design: a. Insufficient length of the bolt thread allowance (Manufacturer).
9. Further enquiries showed that other three additional cases within the UK-based fleet (total of 8 at the time of enquiry) have their swash plates joints incorrectly installed. In all the total 5 cases, the bevelled washer has been incorrectly placed at the inner part of the assembly. Evidence concluded that these aircrafts apparently left the factory in this incorrect configuration.	Installation: a. Incorrect initial assembly at the factory.	Documentation: a. Insufficient information on the correct assembly layout (Manufacturer). Manufacturing processes: a. Poor quality control and quality assurance of the manufacturing processes (Manufacturer).

Table 9-3 Numerical input to ErroDetect v.1.12 – Design software in regard to design shortages of case study 1

Main maintenance tasks	Sub-maintenance tasks	Numerical value (1 to 5) entered for each assessing criterion (C1 to C10) as per RCES - Design									
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
Preparation for maintenance	Task assignment / Responsibility allocation	1	0	0	0	0	0	0	3	0	0
	Aircraft documents / Task job cards	0	5	4	0	4	0	0	0	0	0
	A/c location, orientation, levelling	0	0	0	0	0	0	0	0	0	0
	Required standard tools / Special tools	0	0	0	0	0	0	0	0	0	0
	Required equipments, devices, testers	0	0	0	0	0	0	0	0	0	0
	Workshops shelves, part stands, hoists	0	0	0	0	0	0	0	0	0	0
Maintenance preliminary steps	Identification of a/c targeted systems / parts	0	0	0	0	2	0	0	0	0	0
	A/c jacking, hoisting, supporting	0	0	0	0	0	0	0	0	0	0
	Required hydraulic/ pneumatic supplies	0	0	0	0	0	0	0	0	0	0
	Electric / electronic facilities	0	0	0	0	0	0	0	0	0	0
	Fuels, lubricants, gases	0	0	0	0	0	0	0	0	0	0
	Maintainer positioning, using walkways, etc.	1	0	0	0	0	0	0	1	0	1
	Accessing, cowlings, covers, etc	0	0	0	0	0	0	0	0	0	0
	Initial checks, observations, etc.	0	0	0	0	0	0	0	0	0	3
Parts removal / Paints and sealants stripping	Discharge liquids, gases/ Power off	0	0	0	0	0	0	0	0	0	0
	Removing access-blocking items	0	0	0	0	0	0	0	0	0	0
	Removing job-targeted items	0	0	0	0	0	3	0	0	0	4
	Stripping paints, sealants	0	0	0	0	0	0	0	0	0	0
	Applying covers, seals, fixtures, orientation indicators,etc	0	1	0	0	0	0	4	0	0	0
	Apply removed parts indicators, warning signs,	0	0	0	0	0	0	0	0	0	0
	Apply shelf control/ bags, labels, tags, etc	0	0	0	0	0	0	0	0	0	0
	Recording removed, loosened parts	0	0	0	0	0	0	0	0	0	0
Parts cleaning	Clean removed parts	0	0	0	0	0	0	0	0	0	0
	Clean associated parts on the a/c	0	0	0	0	0	0	0	0	0	0
	Overall a/c cleaning	0	0	0	0	0	0	0	0	0	0

Table 9-3 Numerical input to ErroDetect v.1.12 – Design software in regard to design shortages of case study 1 (Continued)

Table Main maintenance tasks	Sub-maintenance tasks	Numerical value (1 to 5) entered for each assessing criterion (C1 to C10) as per RCES - Design									
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
Detailed checks, readings, measurements	Check safety locks, guiding marks, etc	0	0	0	0	0	0	0	0	0	0
	Read gauges, indicators, displays, etc	0	0	0	0	0	0	0	0	0	0
	Check parts play, fitness, wear, dents, etc	0	0	0	0	0	0	0	0	0	0
	Measure dimensions, weights, movements, etc	0	0	0	0	0	0	0	0	0	0
	Measure cable tension , rods alignments, etc	0	0	0	0	0	0	0	0	0	0
	Inspect structures, surfaces, joints, etc	0	0	0	0	0	0	0	0	0	0
	Check wiring, sockets, connections, etc	0	0	0	0	0	0	0	0	0	0
	Measure currents, voltages, impedances	0	0	0	0	0	0	0	0	0	0
	Check signal distortion, interference, etc	0	0	0	0	0	0	0	0	0	0
	Check fluids viscosities, purity, colours, etc	0	0	0	0	0	0	0	0	0	0
	Perform diagnostic functional tests	0	0	0	0	0	0	0	0	0	0
	Apply NDI, NDT, etc	0	0	0	0	0	0	0	0	0	0
Troubleshooting / Analysis / Decision making	Applying trouble shooting procedures	0	0	0	0	0	0	0	0	0	0
	Revising, setting, observing criteria for decision making	0	0	0	0	0	0	0	0	0	0
	Decide: Accept, repair or correct, replace	0	0	0	0	0	0	0	0	0	0
Topping / Charging / Installation / Fixing / Sealing / Adjustment	Fluid topping / flow pressure, temperature adjusting	0	0	0	0	0	0	0	0	0	0
	Cable / pulley configuration, tension, etc	0	0	0	0	0	0	0	0	0	0
	Adjust currents, voltages, signals, etc	0	0	0	0	0	0	0	0	0	0
	Fix pipe-works / Seal leakages, etc	0	0	0	0	0	0	0	0	0	0
	Repair / replace electric, electronic parts	0	0	0	0	0	0	0	0	0	0
	Repair / replace structural parts, surfaces	0	0	0	0	0	0	0	0	0	0
	Repair / replace fits, joints, bearings, etc	5	0	3	0	0	5	0	0	5	0
	Repair / replace power plants	0	0	0	0	0	0	0	0	0	0
	Repair / replace a/c systems components	0	0	0	0	0	0	0	0	0	0
	Repair / replace rotary system parts	0	5	0	0	5	0	0	5	0	0
	Re-fix removed access-blocking parts	0	0	0	0	0	0	0	0	0	0

Table 9-3 Numerical input to ErroDetect v.1.12 – Design software in regard to design shortages of case study 1 (Continued)

Main maintenance tasks	Sub-maintenance tasks	Numerical value (1 to 5) entered for each assessing criterion (C1 to C10) as per RCES - Design									
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
Inspections / Functional tests / Air tests	Apply visual inspection, observation	5	0	0	0	0	0	0	3	5	5
	Apply checks by hand-feel, hearing, smelling. etc	4	0	0	0	1	0	0	3	0	0
	Apply functional tests	3	0	0	0	2	0	0	1	0	2
	Apply ground run / air test	2	0	0	0	1	0	1	0	0	1
Final steps	Apply final cleaning on a/c	0	0	0	0	0	0	0	0	0	0
	Remove warning tags , indicators, etc,	0	0	0	0	0	0	0	0	0	0
	Re-fit accessories, covers, cowlings, etc	0	0	0	0	0	0	0	0	0	0
	Apply tool and material control	0	0	0	0	0	0	0	0	0	0
	Remove stands, walkways, dummy equipment	0	0	0	0	0	0	0	0	0	0
	Update aircraft logs and documentations	0	0	0	0	0	0	0	0	0	0

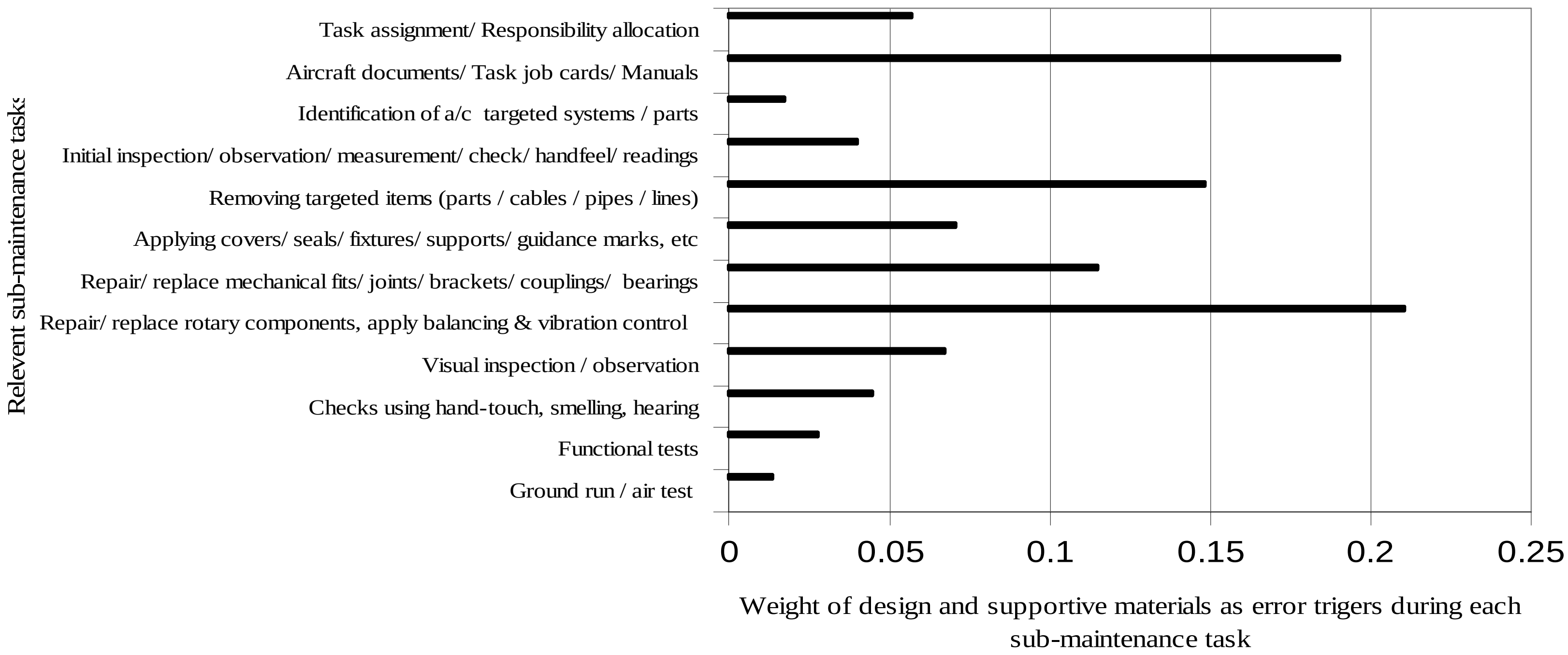


Figure 9-4 Detailed description of the design influence on each maintenance subtask as obtained by ErroDetect-Design for case study 1

Figure 9.4 tells that this current design and the corresponding related maintenance documentation are of potential, according to the configuration in which the aircraft is released to service, to trigger human maintenance errors regardless of the situation within the MRO's or the competences and skills of the maintainers. It can thus be concluded from this case study that if this software had properly been applied during design for maintainability or prototype production phases, then the designers would have received a warning that this swash plate lower link will trigger maintenance errors during removal and installation as long as the corresponding manuals are as given before this series of accidents took place. This is clearly conveyed through Figure 9.4 above.

9.3.2 Case Study 2: ErroDetect simulation within aviation MRO's

The incident involved a helicopter transporter flying over the North Sea with 17 passengers and crew when there was a sudden onset of severe airframe vibration that put the flight at risk. Subsequent examination of the helicopter revealed that a tail rotor blade flapping hinge retainer had fractured on one side. The formal investigation (AAIB 1995) identified the following main causal factors:

"1. Maintenance inspections conducted over a period prior to the incident flight did not detect a developing surface crack in the Blue tail rotor blade flapping hinge retainer, despite additional work on the associated tail rotor drive shaft assembly to rectify a tail rotor vibration problem, which was detectable as a trend recording within the Health and Usage Monitoring System some 50 flying hours previously and was the subject of an associated alert 5 hours before the incident.

2. The inspection provisions within the aircraft Maintenance Manual and associated Maintenance Requirements did not specify periodic visual inspections of such retainers, since they had been designed and certificated on a 'safe life' basis".

Further human factors-oriented analysis as per the pre-mentioned retrospective studies is conducted on this incident. Findings revealed a number of 'specific failures' that led, collectively, to the incident. An overview of the 'context' of these failures which were dominating within the MRO before the incident is given in Table 9.4 which also shows main parties involved in the associated errors initialization as the MRO management (organization), supervisors , designers , and maintainers. Numerical input to the software is provided in a similar manner to that of case study 1.

Table 9-4 Specific Failures which were dominant within the MRO before the incident of case study 2

Dominant specific failures before incident	HFACS-ME 3rd order categories	Main parties involved in maintenance error initialization
Fail to provide oversight	Inadequate processes	Organization management
Fail to track performance	Inadequate processes	Organization management
procedures incomplete	Inadequate processes	Organization management
Non existing procedures	Inadequate processes	Organization management
No/ poor documentation	Inadequate documents	Organization management
Conflicting information	Inadequate documents	Organization management
.Information not available	Inadequate documents	Organization management
Delayed informing response	Inadequate documents	Organization management
Lack of parts/ equipment	Inadequate resources	Organization management
Inadequate facilities	Inadequate resources	Organization management
Failure to inspect	Inadequate supervision	Supervisors
No corrective actions	Uncorrected problems	Supervisors
Corrective action delayed	Uncorrected problems	Supervisors
Ignoring risks	Supervisory misconduct	Supervisors
Workspace illumination	Lighting	Organization management
Constrained position	Confining work area	Designers
Not directly visible	Obstructed working area	Designers
Inadequate support equipment	Inaccessible work area	Designers
Loss of situational awareness	Attention / memory	Maintainers
fail to recognize condition	Attention / memory	Maintainers
procedural mistakes	Attention / memory	Maintainers
omitted procedural step	Attention / memory	Maintainers
maintainer poor decision	Decision making	Maintainers
misdiagnosed situation	Judgment	Maintainers
improper procedures	Decision making	Maintainers
improper cross check	Skill / techniques	Maintainers
falsifying inspections	exceptional violation	Maintainers

Transferring these circumstances which were either in-built within the aircraft design or cast dominant within the MRO for long time before the incident into input codes for the ErroDetect software, a comprehensive detailed description of the MRO management and workplace conditions is obtained as given in Figure 9.5.

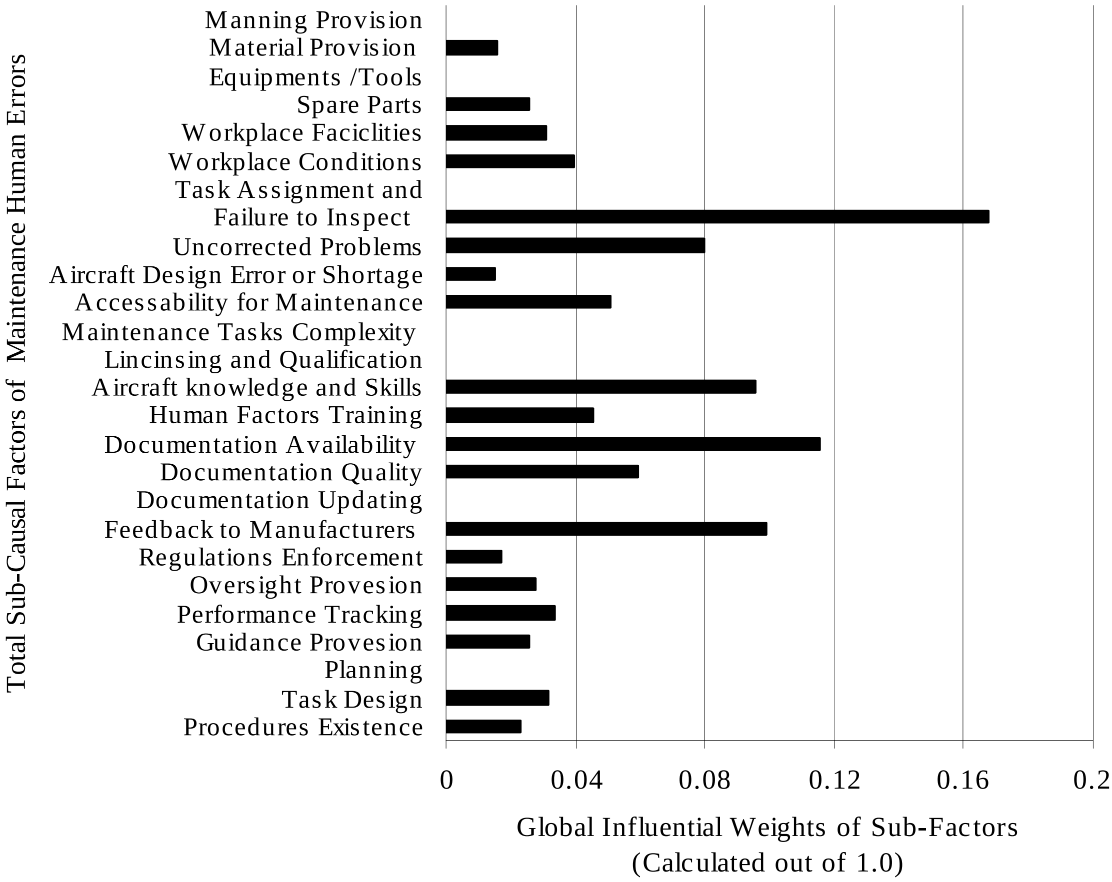


Figure 9-5 Detailed description of the MRO conditions before the incident as obtained by ErroDetect -workplace for case study 2

This figure illustrates direct mapping of the situation before the incident occurred. This early prognostic alert would have been obtained in advance if the AMMP tools were efficiently applied then. The result shows clearly that there was malfunctioning within the involved MRO regarding the provision for adequate inspection practices, furnishing of proper documentations, and maintaining effective links with manufacturer, all of which played vital roles that led to the incident. If such a predictive tool can be applied regularly in MRO's, and simultaneously added to the design for maintainability assessing tools during aircrafts design, then a complete cycle of human error-triggers sensors can be secured. This will resemble a dynamic proactive monitoring process that works to detect existence of any maintenance human error initiators.

9.4 ErroDetect verification

9.4.1 Objectives behind ErroDetect within-industry verification

By the end of its simulation approval phase, the AMMP as a concept with its ErroDetect tool were further pushed for verification under real-world professional environment conditions. The verification process aimed at the following objectives:

- Backing-up the sensitivity results obtained during the simulation stage, and indicating whether the concept and its tools have any usefulness, relevance, and applicability within industry.
- Exploring operational features of the software such as clarity of layout, clarity of contents (especially the core 870 assessing criteria), flexibility of usage, time required for completion, etc.
- Discovering any inbuilt or foreseen weaknesses within theory and practicalities relating to the AMMP and its software.
- Exploring scope for future applications of the process and whether the industry is keen to invest in such type of thinking.
- Further emphasizing the application of adopted research methodology which calls for the integration of theoretical modelling into practical living solutions.
- Achieving some major objectives of this research such as research mastering satisfaction and enhancing aviation safety by introducing practical tools.

9.4.2 Initial assessment and feedback from industry

The completed versions of ErroDetect as well as the overall AMMP model were presented for initial assessment and evaluation by a number of active industry stakeholders. The main AMMP model structure, the theory on which it is built, its targeted objectives, and its practical aspects, nevertheless its core software, all were thoroughly described, explained, and practically demonstrated to subject matter experts from academia and research centres, aviation safety consultants, MRO's as well as aircraft manufacturers. Initial assessment and industry-reflective feedback were received from: AAIB-UK, EU Joined Research Centre- Ispra- Italy, Baines Simmons Aviation Safety Consultants Ltd-UK, Human Factors Group of The Royal Aeronautical

Society -UK, Human Factors Team of Boeing Commercial Airplanes Company – USA, Eurocopter-UK, European Safety and Reliability Conference ESREL09, Czech Rep. An overall collective account of these feedbacks indicated that both the theoretical model and its practical applications were satisfactorily understood, appreciated, accepted, and encouraged by the industry to help fill the current aviation maintenance safety gaps.

In the above sequence, the design package of ErroDetect software was compared, by Boeing experts, to another Excel-based software application that is being currently used by the human factors team, as part of design for maintainability, within Boeing company-USA. Having acknowledged that ErroDetect provides deeper insight analysis when it comes to considering the human factors surrounding each maintenance task and sub-task separately, these experts indicated their satisfaction that the proposed AMMP and its ErroDetect tool are promising steps in the direction of proactively identifying and eliminating design-induced maintenance error causal factors.

9.4.3 Practical application within helicopter MRO

After the initial positive feedback from the industry, the model and its software, in the workplace and maintainer preparation version, were both put to practical verification within real working context. This is discussed through the following sections

9.4.3.1 Selected Organization

The selected organization is a UK-based MRO's facility of a major helicopter manufacturer. Being a part of a bigger manufacturing organization, the selected facility performs, in addition to the normal line maintenance functions of usual MRO's, some major design and modification activities on various types of helicopters. It is thus clearly observed that the facility plays a double-role operations with both maintenance and design orientations being in place. Thus, the quality department responsible for safety of operations within this facility performs a more sophisticated role covering both customs. The quality department is composed of a number of employees with various integrated rich skills in line operation safety, airworthiness and certification requirements, staff training and development, safety-related occurrences investigation, for-management consultation, quality control and assurance, and other aspects as well. The selected organization enjoyed excellent relations with Cranfield, and consequently both parties, in addition to the current researcher, arranged for the ErroDetect practical application and evaluation at the facility under a mutually agreed confidentiality policy.

9.4.3.2 Methodology

The verification process was performed in the following sequence:

1. Thorough explanation of the AMMP as a theory and strategic model was provided for the quality department employees of the facility. This is followed by a practical demonstration and detailed hands-on training on the ErroDetect such that all members of the team were made fully aware of the process and software. This first interaction of the employees with the software resulted in useful remarks and additional requirements raised by them to be further embodied in the software.
2. Necessary time was taken to ensure that all the new requirements were carried out on the software to make it more profession-friendly, and to cover additional areas called upon by the industry practitioners.
3. The software was then put for practical application at the facility. Two different options of application were given for the quality department team:
    - Team members should apply the software independently as individual users, then results can be discussed collectively and points of variation in results can be subjected to further group evaluation till final out put is concluded
    - Team members can apply the software collectively by discussing each point thoroughly, reaching a conclusive shared opinion about it, and then providing a single final input regarding that point. Thus a collective single final output will be obtained.
4. The quality department team decided to take the second method of application due to the fact that they will need more joined efforts to grasp a proper handling of the RCES criteria being only newly introduced within the industry. However, they emphasized the opinion that the first option of application will be the logical solution once practitioners are more accustomed with the software.
5. There was no interference from the researcher or any other group on the software application process in order to keep highest levels of accuracy and transparency of the evaluation process. The facility took the necessary time to independently run the application process and provide its results.
6. The application process involved mainly the ErroDetect-Workplace version at this stage of the research. The design-oriented version is left to be later applied at the design bureau of the parent manufacturer organization. However, the design-

focussed interests within the selected facility were totally present during the software application process.

9.4.4 Results of the selected MRO assessment using ErroDetect

The 'Final Report' page of the applied ErroDetect record for this MRO/design facility shows the overall mapping of the maintenance error root causes existing within the organisation as indicated by Figure 9.2 before. More detailed graphical results were obtained as follows in Figure 9.6 to 9.12. The first page of the completed software applied at the selected MRO organization is partially given in Appendix L.

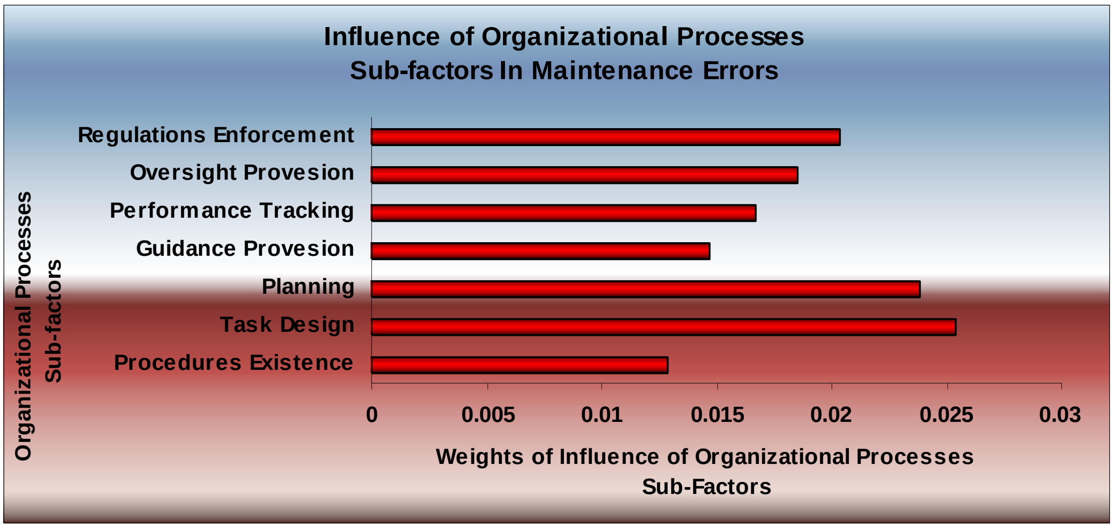


Figure 9-6 Existence of organizational root sub- causal factors within the selected facility

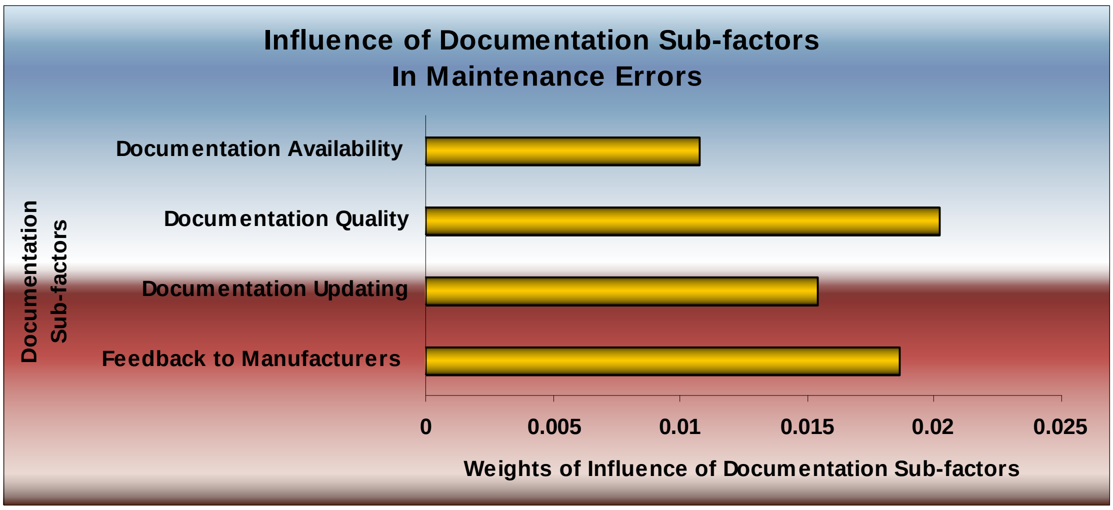


Figure 9-7 Existence of documentation root sub-causal factors within the selected facility

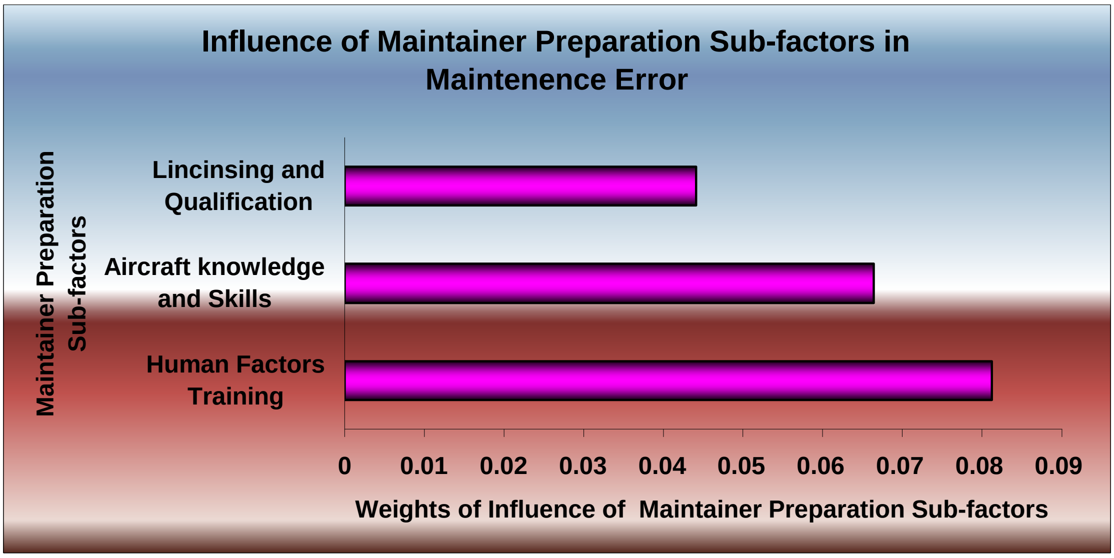


Figure 9-8 Existence of maintainer preparation root sub-causal factors within the selected facility

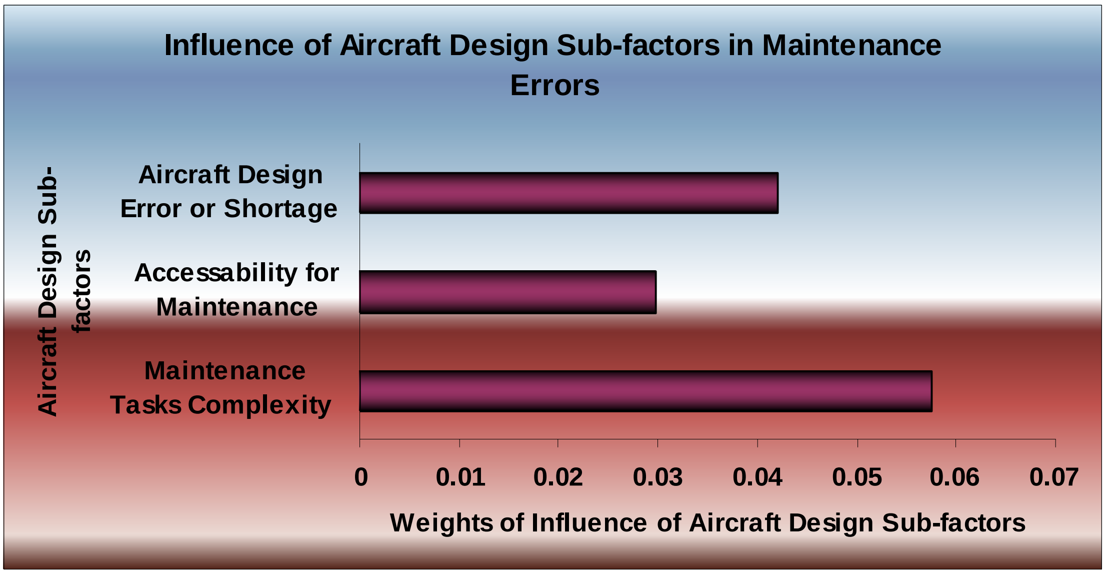


Figure 9-9 Existence of aircraft design root sub-causal factors within the selected facility

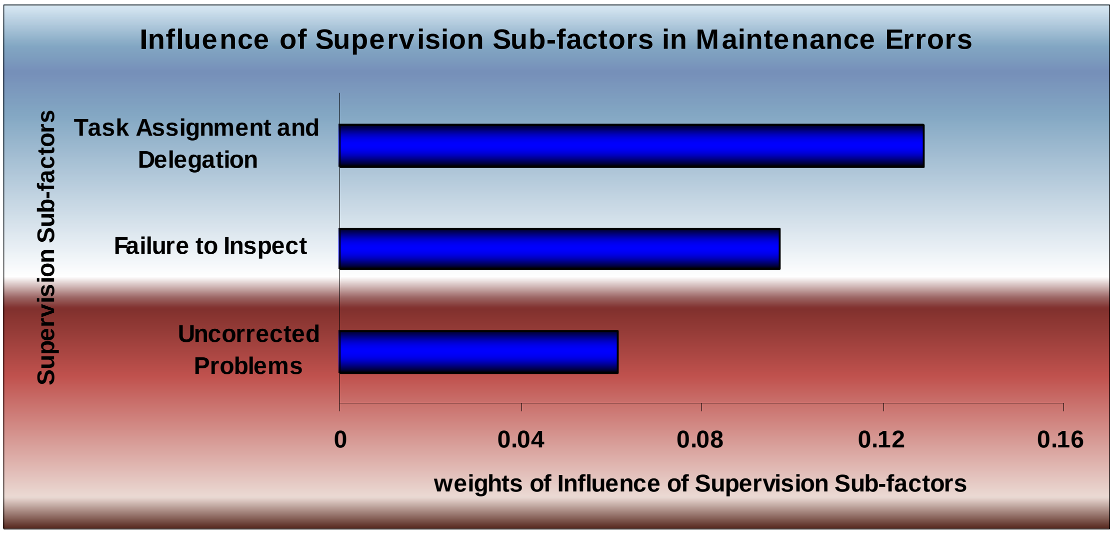


Figure 9-10 Existence of supervision root sub-causal factors within the selected facility

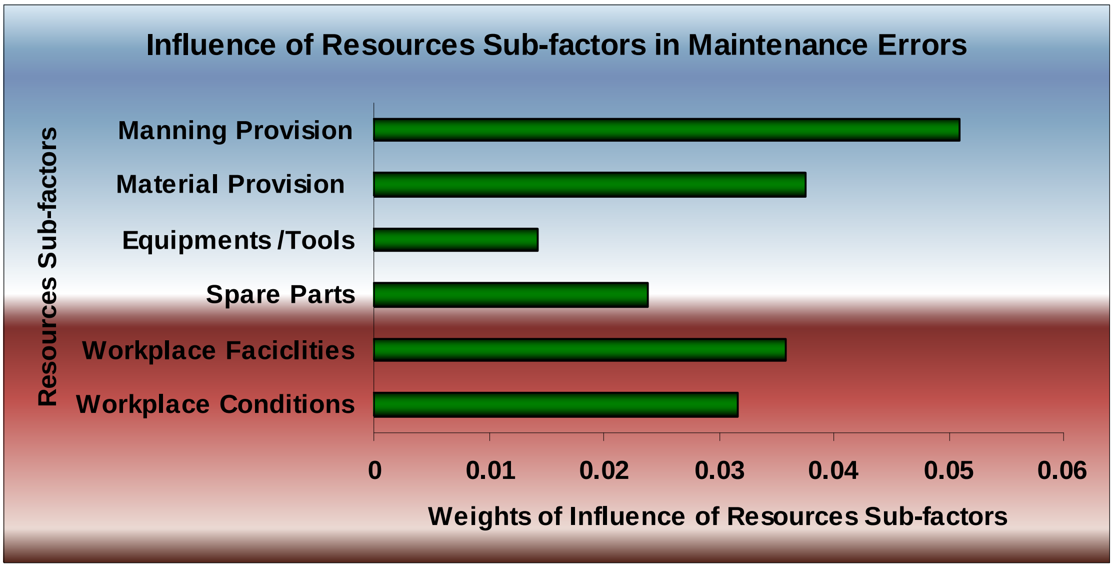


Figure 9-11 Existence of resources root sub-causal factors within the selected facility

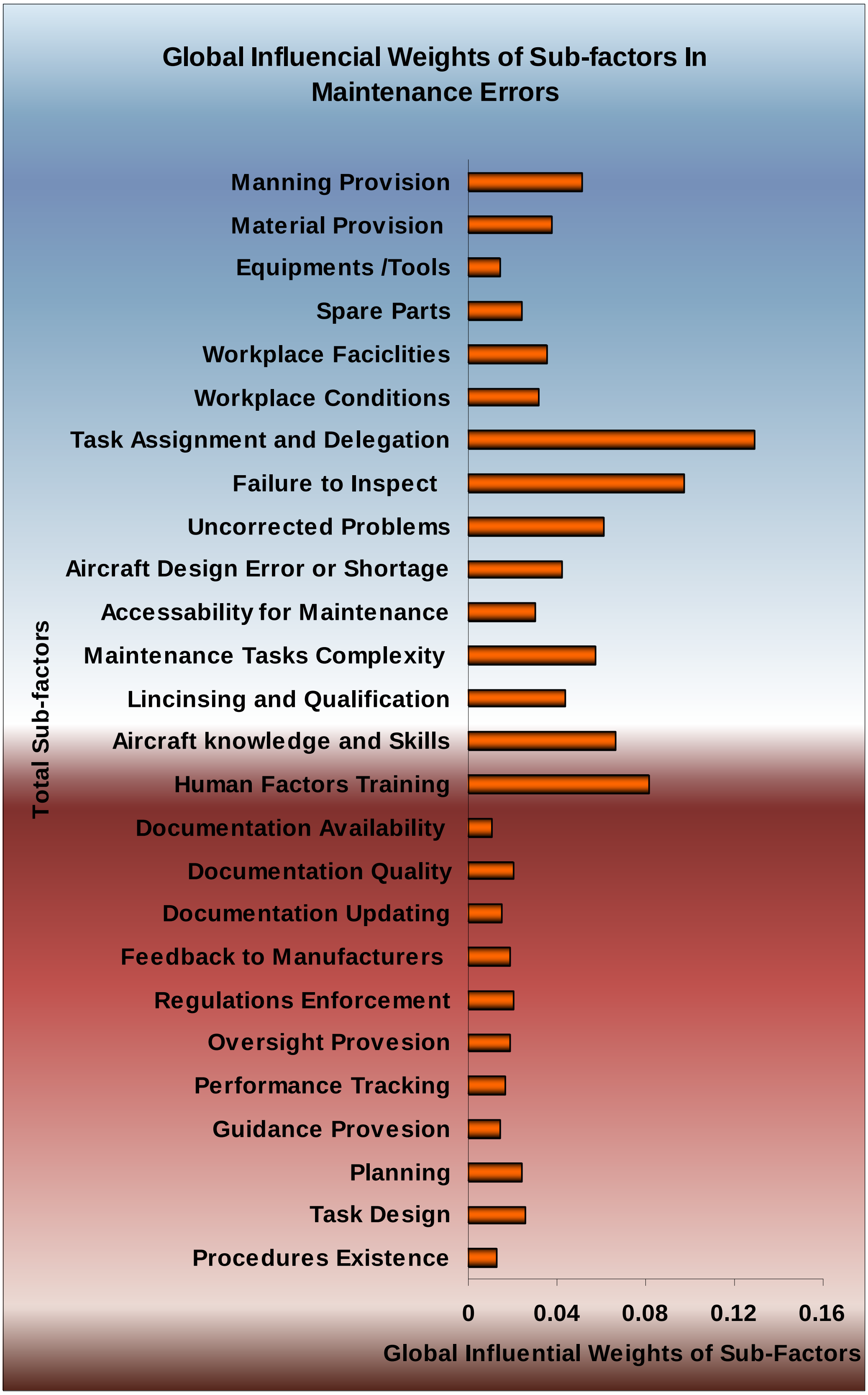


Figure 9-12 Global existence weights of root sub-causal factors within the selected facility as obtained by ErroDetect-Workplace version 1.12

9.4.5 Verification Analysis and Conclusions

9.4.5.1 Verification results analysis

The graphical results obtained through this verification process at the selected highly-profiled aviation maintenance facility, as shown in previous sections, give exact mapping of the level of safety performance that the organization enjoys. These graphical results can be interpreted, as a typical case of aviation MRO, in the following sequence:

Recalling the first general description of the organization's situation as indicated by Figure 9.2, it can obviously be seen that this organization faces critical shortcomings within the functioning of the mid-level employees playing the supervision roles. These supervisory malfunctioning represents 29% of the overall gaps of safety performance within the organization at the time of evaluation. This, in turn, is clearly to have its impact as well on the continuous preparation and development of maintainers as well as the accurate decent provision and application of sound overall organizational processes.

In fact, it is an interesting feature of this software to clearly emphasize the critical, yet unseen, inter-relations between various interactive factors within the organization under focus. This current inter-relation between supervision and the two other factors is quite logical when emphasizing that supervisors are the dynamic core of work that bridges the higher strategic policies to the base-level of work execution. Any drop in the level of supervision function within a MRO will automatically adversely influence the upper and lower ends of the organization functionality. A deficiency in the required organizational resources may also be seen to have participated by almost 19% of the overall drawbacks that this figure shows. One direct feedback from the quality department in this selected facility is their plans to use this mapping to convince their higher management on the next probable areas of investment in order to reduce the proactively foreseen gaps within safety performance.

The Figures 9.6 to 9.11 further illustrate details of drawbacks and gaps within each of the 6 overall safety-mapping areas given in Figure 9.2. The weights of factors given within these 6 figures are global weights comparing collectively the overall listing of the 26 root sub-factors of the workplace ANP model. It is seen from Figure 9.6 that the organization have some deficiency in the technical aspects of maintenance tasks designing as well as administrative difficulties in the overall work planning capacity.

Lagging in planning and work design will undoubtedly impose a collective impact on regulation enforcement, oversight, and overall performance tracking. Thus again, clear mutual interaction between various safety-influencing factors can repeatedly be observed.

In another orientation, although problems expected from technical documentations and documentary system in general are relatively low as indicated by the overall mapping, but details of Figure 9.7 indicate a low quality of the available documentation provisions. This will again recall the fact of the limited available resources as previously discussed. An interesting feature, that this figure shows as well, is the low performance of information transfer between this specific facility and its main parent manufacturer organization in regard to safety-related issues. In fact, this specific facility, being of double-role nature, performs internally most of the major or frequent technical assistance calls or manufacturer-oriented consultations and feedbacks. Thus they have lesser external flow of safety-related information with the main parent manufacturer bureaus if compared to a normal MRO that functions as a maintenance facility only. This is another indication of the sensitivity of the software to exactly describe actual features of a given organization.

Figure 9.8 indicates a deficiency in human factors-oriented training provided for maintainers and supervisors within this facility. It is also seen that both qualification and aircraft knowledge features of the maintenance staff are of lesser importance as potential sources of maintenance errors. This is again of reasonable logic since this facility, being a part of a major manufacturer organization, is in fact bound to invest in a higher calibre of workers if compared to normal MRO's. Another interesting feedback from the quality team at the facility was that they rarely recognized the lack of human factors training provision for the maintenance staff to be of such potentiality to cause future problems. This totally back-up the previous findings of the ethnographic study part of this research which indicated a lack of human factors-oriented scientific considerations and applications within the facilities of aviation manufacturers, and their dependence merely on previous experiences when deciding for human factors-related issues such as duplicate inspection items.

Figure 9.9 highlights maintenance task complexity as a major adverse impact of aircrafts' design features on maintenance safety. Aircrafts design errors or shortages come in the second rating. In fact, the output information displayed by this figure represents a typical core subject matter of information exchange between MRO's and aircrafts manufacturers in regard to maintenance errors triggers. It was of special interest for this particular facility, being involved in aircraft design activities as well, to observe the influences of task complexity and design shortages on maintenance safety. The presumed ability of handling such design-related issues internally within the facility significantly reduced the volume of the out-going information to the major manufacturer, this comes in total harmony with the fact indicated by Figure 9.7 that the exchange of safety-related information with manufacturers is weak.

Figure 9.10 approves the factor of task assignment and duty delegation to maintainers as a major deficiency of the supervisory system within the organization. This has already been conveyed before by the main comprehensive mapping of Figure 9.2. In fact a deeper focus of analysis can further explore this phenomenon within this specific facility as a natural upshot of its double-role functionality. Being a part of a major manufacturing company dictated, from one side, highest levels of performance from higher management of the facility in a major strategic scale to handle sophisticated duties such as aircraft designing, redesigning, and certification processes, and in the other side gave clear approval and reasonable capacity for hiring maintainers of higher technical qualifications to reflect the standard of technical work a manufacturer usually targets. This only left the mid-section of the hierarchy, which is mainly the supervisory layer, without much elevated performance capabilities. The quality department team were really interested in having the ErroDetect software as a tool that helped to uncover this unthought-of weak point within the overall organizational layout.

Figure 9.11 shows a significant deficiency in manning provision within the maintainers workforce. This is quite coinciding with the limitation in resources that was discussed before, and with the fact that only maintainers with higher qualifications, and thus of higher wages, are expected to join the organization. Material provision and workplace facilities come in the next levels of importance as potential root causes of maintenance errors. However, this facility, still being a part of a major manufacturing company, can never consider resources to be its major cause of potential safety difficulties, as will be clearly observed when all factors are put in mutual contrast as shown in Figure 9.12.

Figure 9.12 joins the global weights of importance that the communal 26 root causal factors encompass within the facility under evaluation. True proportion of importance of each factor as a potential root cause can be clearly distinguished when factors are put to the same scale. Supervisory roles of maintenance task assignment and maintenance work inspection are the most critical safety gaps within this facility with respective 13% and 10% shares of the total spectrum of potential problems. Human factor training is the next deficiency comprising 8% of the total weight. Aircraft knowledge, supervisors not correcting safety-critical problems, and manning provision come next in importance. It is clear that this facility is having lesser problems when the factors further involve higher management roles such as procedures incorporation, guidance, oversight, regulation enforcement, etc. It was consequently planned by the quality department to start enhancing safety within the facility by addressing the first three weak points, then moving to the next most critical factors in the list.

9.4.5.2 Overall conclusive results of the application process

The second, yet crucially important, part of ErroDetect verification process within the industry is the overall feedback, on the AMMP concept and its facilitating software, that was collected before and after its application. This feedback is obtained during the interviews and open discussions held with the quality department team at the selected facility. An overall collective account of this feedback can be summarized as follows:

1. The industry is really looking for proactive safety tools to help ensure safe performance. All the current methodologies that they espouse now for safety enhancement are reactive. The AMMP is a promising concept in this direction. It is of real relevance to current aviation industry safety enhancement needs.
2. The AMMP strategy can easily be integrated within the existing network of information transfer channels between manufacturers, MRO’s, and regulators.
3. The software is totally satisfactory in regard to clarity, content, easiness and flexibility of use, and required time of application.
4. The output of the software application really highlights areas of shortages that can develop maintenance errors.

5. The graphical mapping of the organization safety performance obtained by the software can help management informed-decision making in regard to future investments in safety enhancement.
6. The software helped uncover hidden latent conditions of potentiality to develop maintenance errors which were never thought to be existent.
7. The software is very efficient regarding application costs. It is almost of no additional expenses to have the program running since it utilizes the usual Excel environment, and only simple limited training is needed to describe the whole concept and set users ready for the application.
8. The AMMP concept and the ErroDetect software are both recommended for further development to be practically applied by the aviation maintenance industry.

9.5 Chapter summary

The up-to-date results of AMMP simulation through actual accidents and incidents case studies are highly promising. The system, with 870 different error causal factor assessing criteria, works as a sensor station to proactively detect high risk situations involving aircrafts, maintenance workplace, or humans working there-in, thus, gradually eliminating such situations. The whole process is then put to practical application to be further verified within aircraft design and maintenance organizations. An aviation MRO facility of a certain major helicopter manufacturer was selected to evaluate the full scope of the AMMP and to run its ErroDetect software in real world live conditions. Verification results were obtained and thoroughly analysed and discussed. The AMMP and its software were found to be of direct relevance, ans promising abilities to address current gaps in the aviation maintenance error management.

PART FOUR

RESEARCH DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

10 Research Discussion, Conclusions, and Recommendations

If I have seen farther than other men,
it is because I stood on the shoulders of giants.
Sir Isaac Newton

10.1 Introduction

10.1.1 The final act: putting it together

This chapter sums up the full account of this research. Having the notion of aviation safety as a focus, this research challenged the problematical human factors intrusions that colour aviation maintenance, being a dynamic and demanding industry as it is. The influence of human factors in aviation safety in general, and in its maintenance strand in particular, is immense. Humans are the foremost line of defence against errors and their deadly consequences, alas, they are also the source of these errors themselves, a prisoner's dilemma that this study tried to handle and to contribute to its solution. According to Mitchell and Carroll (2008), such a targeted solution "is often demonstrated through theory development, presenting new perspectives upon accepted theories, and developing new knowledge".

This research comprised many folds of activities packed into two main streams of study: backward-oriented investigations of previous maintenance–induced safety occurrences and future-aimed introduction of new tools that can help eliminate such occurrences. The previous chapters of this thesis described in details all ingredients that shape various behaviours, being faulty or successful, of aviation maintainers, their supervisors, and their higher managements within work environment. This chapter is devoted to finalize this research by putting all data, information, theory, modelling, and practical interventions covered during this research into one mould that can best cast these ingredients in an irrefutable conclusive harmony. A main aim of this chapter is to further demonstrate a required level of scholarship which can always be expected of a research targeting both academic satisfactions forcefully coupled to industrial functionality.

10.1.2 The HERMES influence

Paltridge (2002) identified four categories of writing styles universally used for degree theses, including those of doctoral research: Simple traditional, complex traditional, topic-based, and research article compilation thesis configurations. Each category has its own features, applications, and validating circumstances. These styles differ significantly in their overall layouts and internal building structures, regardless of the degree sought or discipline of knowledge encountered. The criteria for selecting a writing category principally depend on the nature of the research itself, background theory, materials and methods, and number of topics involved. This current research, when weighed in contrast to these exact specific criteria, is never found to fit reasonably into any of the pre-mentioned categories. A fifth category is thus needs to be additionally suggested to accommodate the structure and appearance that this thesis is presented in. This thesis can best be an actual evident manifestation of the various activities conducted within the current research, only if it is designed in synchronization with the size, sequence, and inter-linkage of these activities. It is thus quite logical for this thesis to follow the events flow governed by the HERMES methodology, the core terms-of-conduct adopted by this study. This is again noticeable in the setting of this last conclusive chapter where two main streams of overall strategic analysis are present to represent the retrospective and prospective parts of the methodology. An all- contained conclusion then follows. The methodology influence on the writing style is thus undoubtedly significant. The call for adopting a new thesis layout strategy, that is a methodology-based, is thus sensibly backed-up.

10.1.3 This chapter

As above signified, this chapter encompasses a comprehensive discussion of this research as seen from the two main perspectives of the applied methodology. This discussion is intended to accomplish a deep secondary mining of findings, where tactical analysis and local discussions scattered through out the previous chapters are to be collectively re-visited in a more strategic vista. An inclusive conclusive account then follows to finally state what this research contributed to aviation safety in particular and to knowledge in general.

10.2 Research Discussion

10.2.1 Strategic discussion of the retrospective studies

A series of backward investigative studies on the causation and mechanisms of human errors within aviation maintenance settings formed the first part of this research. An overall analysis regarding the theories, methodologies, conduction, and results of these studies can be presented as follows:

1. The sociotechnical context of aviation maintenance was understood as the entire mutual influence of, and between, humans and technology put together within a dynamic working environment. The interaction between maintainers and aircrafts forms a unique predicament, a special throng of behaviours, when contrasted to other sets of sociotechnical systems. Human malfunctioning within this setting can be detected and addressed as swiftly and assuredly as changing the face of a washer to the correct orientation in the last second as it is being inserted over a bolt. Alas, such malfunctioning, in the same moment, can easily pass-by undetected if that same washer goes over that bolt in the wrong orientation, thus producing an erroneous assembly which can cause a fatal accident. Huge involvements of human health and cognition, human behaviour, human capabilities, aircraft design, work pressures, organizational management and resources, governmental regulations, and so many others ingredients could have caused that washer to go, within that assembly, in the right or wrong orientations, with potential respective safe or fatal flights down stream. Causation and propagation scenarios of aviation maintenance errors are thus found to be very diverse and complex both to understand and to intervene.
2. The work within aviation maintenance industry is heavily regulated through aircraft airworthiness technical requirements, and authenticated personnel qualifications and certification processes. Both of these streams mainly targeted assurance of standard procedures and practices within the maintenance work context such that safety - as a whole - is granted. Any deviations from the nominated standards form a potential procreation yard for maintenance error producing conditions and factors. The social component, the human capital members within MRO’s, are the most vulnerable fibre within this network. Their qualifications, professional characteristics and competences, health and physical capabilities, emotions, work habits, norms, living pressures, inter-personal relations including vertical and horizontal organizational

relations, etc. all form either concrete pillars of quality and safety or exasperating deficiencies of inferiority and injury. Appreciating the impact of the ‘cultural pyramid’, enveloping maintainers, their supervisors, and higher management within each specific MRO, on their behaviours can help, among other attributes, putting the human performance at the required level of excellence, thus help achieving error-free aviation maintenance.

3. MRO’s are located within Reason’s safety space (Reason 1997) in accordance to the overall resultant of their safety-related performance. Potential root causal factors of maintenance errors are the major safety-threatening hazards for a MRO. Accordingly, a MRO applying necessary measures to early detect and eliminate such hazards of these potential root causal factors is located to the ‘safe’ side of the safety space, while those organizations vulnerable to these root causal factors are undoubtedly operating in the ‘unsafe’ zone of the space.
4. Performance within a MRO’s, although being a self-contained context, but it is highly influenced by external organizations such as parent companies, MRO’s clients, aircraft manufacturers, suppliers, and regulators. The impact of such organizations, positive or negative, and the role played internally by the specific MRO’s management either prevent or lead collectively to what is known as the ‘organizational accidents’: aviation safety-related occurrences that have their root causes deeply inherent within one, a combination, or all of these organizations. The maintainer who directly triggers an erroneous maintenance activity is the last and least to be blamed – if ever – in such circumstances.
5. Extended ethnographic study of aviation maintenance within this research showed direct influence of a set of factors and ingredients on the overall adequacy of maintenance activities and their conformity with standards. Such factors include full complexity of human cognition, physiology, and behaviour, organizational management, aircraft design concepts and manufacturing features, aircraft operation conditions, and the dominant surrounding economic and political environments. Each of these factors can generate limitless numbers of conditions and actions that can cause maintenance errors.
6. Aviation maintenance tasks have immense influence on the maintenance error causation scenarios as well. Maintenance tasks conceptualization, design, delegation

and execution are four tight sequential inter-linked cycles that either help securing safe performance or set the scene for errors to be committed. A well philosophised and designed maintenance task can never guarantee or enhance safety if it is assigned to the wrong worker. Similar results are expected if a qualified maintainer is tasked to implement a poorly designed job. Fighting and preventing maintenance errors must always be approached in a strategic view and a whole collective understanding of these maintenance tasks cycles.

7. Helicopters have their specific characteristics when contrasted to fixed-winged aircrafts. This variation involves aircrafts designing, manufacturing, operating, and consequently, maintaining. The criticality of rotorcrafts safety issues can be obviously established when recalling the high percentage of fatal accidents that involved 57% of the total maintenance-induced safety occurrences covered by this study. The importance of determining types of maintenance errors that are usually committed transpires from the fact that they, being the answer to the question 'what had happened', represent at the same time clear indications for the answer to the 'why it happened' question. In other words: listing these 'errors types' is a strong tool to help identify their causes. Further, an interesting relation can be identified between aircraft systems, components, or parts and types of maintenance-error usually committed on them. It is found that smaller frequently-removed and installed parts are always affected by mal-application of maintenance procedures or by improper installation errors, while the rarely removed large airframe components are mostly exposed to improper inspection types of maintenance errors. Such approaches for errors types identification and their assignment to various parts and systems of aircrafts are crucial foundations for any strategic vision targeting future interventions.

8. Human factors-based analysis of helicopter safety occurrences helped valuing the influence of human factors on maintenance safety as well as identifying individuals' and organizations' shares of maintenance error causation, thus furnishing the base to identify associated root causes and propagation scenarios of maintenance errors. It is found that 44% of the total root causal factors involved in the studied occurrences have their roots originated within management sectors compared to 41% attributed to maintainers' acts. Some of these maintainers' acts, all the same, can be linked to

some managerial malfunctioning as well, thus further enlarging the managements' share in error causation. It is thus arguable that if MRO's managements are to further elevate their performance to higher levels of perfection, then huge proportions of maintenance errors may be brought under control.

9. An absolute human reliability within complex sociotechnical systems such as aviation maintenance has always been questionable. Aviation maintenance is a dynamic critical environment for human / machine interaction (HMI). Consequently, any solutions that target maintenance error elimination must address both the human-associated elements, the maintainer and all the conditions that influences his/her activities and behaviour, and the machine-associated element, the aircraft design and its resultant hard and software.

10. Accidents fault trees were built within this research to provide deeper understanding of maintenance errors propagation scenarios. Due to the highly sophisticated nature of maintenance activities, significant amounts of precautions and regulations were introduced within the daily maintenance procedures, as in-built defence lines, in order to ensure adequateness of work during sequential progressing of these activities. Unfortunately, such local defence lines may be breached when an error is committed, thus it can continue on without being detected. Fault trees were constructed to show various possibilities of error initiation and propagation. It is found that each single error face multiple chances in which it can be detected and corrected. Figure 6.4 was composed to illustrate an overall strategic outcome of these fault trees. Having a maintenance error continuing to exist up to the time the aircraft is released to service indicates multiple collapses of the quality assurance systems both those in-built within direct maintenance procedures or others external to them.

11. The newly introduced concept of the 'specific failures' preceding each of the committed maintenance errors provided higher resolution of their root causal factors. These specific failures, the main of these given by Table 6.1, can be taken as deeper manifestation of the performance influencing factors within aviation maintenance.. Future intervention theory and practices suggested by this research are totally built on these findings. A complete reactive /proactive organizational learning process can thus be claimed.

10.2.2 Strategic discussion of prospective studies

Findings from the first investigative part of this research formed a foundation for the next innovative part of it. A series of newly introduced hypothesis', models, and tools constitute this second part's prospective studies. An overall strategic analysis of this fold of the research can be presented as follows:

1. It is high time to think proactively both as individuals and organizations. Aviation maintenance industry, like other complex sociotechnical contexts, is eagerly looking forward for proactive solutions that can enhance safety without paying huge social and economical penalties usually associated with reactive learning. Practically applicable tools that can help proactively prevent maintenance errors or detect them in advance are rare if not totally inexistent. Such forward-oriented solutions require taking a more inclusive hold of the human factors impacting the HMI operations and utilizing such knowledge in developing theories and applications leading to performance efficiency and safety enhancements.
2. To conceptualize the contrast between current actual level of safety within every day's performance and the future targeted error-free maintenance practice, the SWAMP Model of maintenance error propagation is introduced. The margin between current reality and future aim is formed and framed by the Swamp: a combination pool of all possible root causal factors that can promote maintenance errors. Drying up this pool, by proactively eliminating root causes, will vanish that margin 'and the organizations would perform (at least theoretically) at the level of absolute safe environment'.
3. Root causal factors of maintenance errors are to be early detected and eliminated through the proposed Aviation Maintenance Monitoring Process (AMMP): An interactive coordination between various industry stakeholders, the major of these being manufactures and MRO's. The concept is to continuously monitor existence of human error root causes that may be triggered during initial design or later modification process, as well as during actual maintenance practices at the MRO lines. Having error root causes identified in advance, they can then be eliminated methodically, thus forcing the aforementioned 'Swamp' to shrink down throughout the various sectors of the industry. Both elevated spirits and volumes of information and knowledge exchange between these sectors are required. The AMMP is really

waited to gallop from the academic research envelop it is designed within, to the open industry application world of aviation maintenance. This is a sound approval of the general conceptualization governing the 'industry – research' relation within a holistic organizational learning as that illustrated by Figure 7.1.

4. Selecting fuzzy logic to handle the core mathematical formulation of the AMMP model can be justified referring to the ability of this freshly introduced mathematical concept to eliminate-out shares of uncertainty and subjectivity that used to accompany human cognitive processes when deciding within 'fuzzy' environments, thus providing for superior more accurate decisions. Maintenance errors are utterly unpredictable, thus a total context of uncertainty will always envelop any trial to evaluate possibilities of a maintenance error to be committed within a given MRO setting. In addition, an observer to such a setting can hardly control the subjectivity that may attend his decisive evaluations. It was thus perfectly natural for this research to pick-up the fuzzy logic when building the AMMP model, thus ensuring production of results that are free of uncertainty or subjectivity traces when users are set to evaluate the presence of error root causes within a given design or at a certain MRO maintenance line.

5. Building the Root Causes Existence Scale (RCES), the core of the AMMP software, facilitated monitoring existence of root causes. As can partially be seen in Appendices J and K, the 870 assessment criteria inbuilt within the RCES covered all potentialities that can initiate maintenance errors. These potentialities are direct mapping and response to the previous retrospective findings. Existence of any root cause can be determined within a specific maintenance line or as a feature of a given design by contrasting these to the associated group of criteria from among the 870 available. This process, conducted in terms of fuzzy logic milieu, ensures early detection of root causes and other error promoting situations. The proactive sense of treatment can thus be guaranteed. These criteria are dynamic. As application of the whole AMMP concept within industry progresses, new listings of emerging conditions may be added to the current cycles of root error promoters. Also, some current root causes may be permanently eliminated, industry-wise, in the future due to newly invented technologies or additionally adjusted regulations or enhanced procedures. Both cases dictate a continuous reviewing of the RCES content of

assessment criteria as the overall industry learning develop and get more mature in understanding and fluent in implementation of the whole process..

6. AMMP concept is verified through simulation of its core user programme; ErroDetect, and by fully applying this software to the real live conditions within industry. A first case study involved testing the design version of the software by conducting an examining evaluation of the swash plate design of a given rotorcraft type. The sensitivity of the software in detecting inbuilt root error promoter features within design is backed-up. This software is premeditated to be utilized by designers as part of the 'design for maintainability' process where doubtful features are pointed out in advance. In this occasion the programme was successful in pointing to a mere potentiality of wrong-oriented installation of a specific part. A similar application of the workplace version of the programme gave accurate description of the error-promoting conditions inherent within a specific MRO line. In both cases the software showed high flexibility to absorb all the different indicators that it received as inputs, and high precision in determining the folds and features of potential error-generating tendencies.
7. ErroDetect was then set to be tested in real MRO conditions. A rotorcraft manufacturer and maintenance provider was carefully selected to implement the practical evaluation of the whole concept with particular focus on the software itself. Results of the verification process were satisfying and promising. Tactics and details of this evaluation process and various abilities of the software have already been discussed within section 9.4 of this thesis. However, this verification process proved the strategic importance of such proactive thinking that can generate future-oriented tools such as the proposed AMMP. The AMMP is found to be promising in filling the gap, and in satisfying the industry needs, some of these being:
    - The need for strategic proactive thinking, as well as collective industry-wise cooperation in regard to maintenance error elimination. This involve far more effective and efficient channels of information exchange than the currently available ones.
    - The need for practical solutions than can easily be integrated within the existing safety management systems. The industry currently is not keen, and can not go, for any additional costs to enhance safety. The return on the very

limited investment that the industry needs to pay to master a solution like the proposed AMMP will be very high.

- The need for a solution that can easily be standardized and adopted, in total flexibility, by the industry as a whole. The proposed concept already joins efforts from manufacturers, maintenance organizations, and regulators in order to mutually control maintenance error root causes initiation.

10.3 Research conclusions

10.3.1 Achieving research objectives

This research claims to have satisfied its written objectives as follows:

1. Human factors theories and models, error management systems, error classification schemes, and other related aspects are methodically studied in the general settings of aviation, aviation maintenance, and in particular deeper focus on helicopter maintenance. A comprehensive grasp of the ins and outs of aviation maintenance error causes and effects is obtained.
2. The concept of maintenance error root causes is further studied. Complicated theories and complex methods are consulted and applied such that mechanisms of error initialization and propagation are totally understood. On top, new models are introduced within the research to set the scene for further achievements in this field.
3. An industry-oriented Aviation Maintenance Monitoring Process (AMMP) is introduced as a strategic concept comprising practical tools to proactively eliminate root causes of maintenance errors. This process, with its dedicated software coded ErroDetect, can be used to:
   - Monitor and early detect the existence of maintenance error root causes in both individual and organizational levels within MRO's.
   - Readily help practitioners in scientifically identifying the items suggestible for the 'Duplicate Inspection' lists for each aircraft type.
   - Early detect existence of maintenance error root causes that may be inbuilt within design features of aircrafts. The AMMP process can thus be adopted as genuine part of the 'design for maintainability' practices.
4. The AMMP process is completely simulated and practically applied within industry for verification. Obtained results are satisfactory.

10.3.2 Answering research hypotheses

The current research introduced the following hypotheses for verification:

Hypothesis 1: '*Human factors errors within aviation maintenance industry can be more effectively managed by applying proactive monitoring and early error detecting techniques at both organizational and individual levels.*'

Hypothesis 2: *'An aviation maintenance task can be executed at a significantly higher level of safe performance such that human-induced undesired outcomes would almost be nil if possibilities of human error that can be initiated due to any design features associated with that task are eliminated'.*

Hypothesis 3: *'An aviation MRO can operate at a significantly higher level of safe performance such that human-induced undesired outcomes would almost be nil if the existing unseen accumulation of mutually- interrelated root causes that lead to maintenance human errors are eliminated'.*

These hypotheses attempted the conceptualization of possible treatment of human factors-induced errors during aviation maintenance via proactive means. The hypotheses further suggested an approach for proactive monitoring of error root causes existence, when being embodied within aircraft design features, or inherent within maintenance workplace facilities.

Recalling the comprehensive studies conducted throughout this research, and building on the collective output of the theorization and practical applications of the Swamp and AMMP models, it can be concluded that all the three above mentioned hypotheses are verified to be correct.

10.3.3 Research originality and relevance features

The current research enjoys several elements of originality as well as multiple series of new introductions. A brief listing of these can be presented as follows:

1. Originality of this work is fundamentally ensured by the fact that aviation maintenance industry is facing a serious gap in proactive strategies and tools that can treat maintenance errors. The proposed AMMP is the first in its both concept and applications in this regard.
2. The already-fresh HERMES methodology is applied within the context of aviation maintenance safety enhancement in the first occasion through this research.
3. No previous thorough investigations in maintenance error causation and treatment within rotorcraft maintenance organizations could be detected prior to this work.
4. Other major newly introduced concepts and tools within this research are:
    - The Research Front End Design (RFED): Generic systemic procedural methodology for early planning of research works within industry or for academic purposes.

- The 'Specific Failures', a newly introduced error causal factors classification scheme of 197 categories that resemble a new fourth order added to the well established HFAC-ME taxonomy of maintenance error classification.
- The Maintenance Error History model (MEH) of maintenance error causation, occurrence, and propagation scenarios.
- The Swamp Model of maintenance error initiation and propagation.
- The Root Causes Existence Scale (RCES): An extended listing of 870 different criteria for assessing potentiality of existence of maintenance error root causes.
- Various newly introduced algorithms within the fuzzy mathematical formulation of the Errodetect software targeting the significant automation of the normal experts' systems role that recurrently dominated previous fuzzy ANP applications.

10.3.4 Contribution to knowledge

The current research work claims to have added the following contributions to the pool of human knowledge:

1. Setting bases of new knowledge of maintenance error causation, initiation and propagation that comprised the introduction of the generic MEH and Swamp models.
2. Introducing the AMMP strategic concept for proactive treatment of aviation maintenance errors, thus significantly improving aviation safety.
3. Introducing ErroDetect user software for early detection of aviation maintenance errors root causes that can initiate within aircrafts and associated equipment design, or due to workplace conditions within MRO's.
4. Introducing new algorithms within fuzzy logic arithmetic to resemble the role of expert's systems, thus significantly elevating practicality and flexibility of such fuzzy ANP applications.

10.3.5 Managing research challenges

The application of HERMES in this research was faced by many challenges, the earliest of these was the need to modify the original methodology layout in order to accommodate the present research requirements. This was first suggested by the researcher and then approved by Cacciabue, the original methodology initiator, and his team at the European Union's Joined Research Centre-Italy. This modification consequently gave rise to a new challenge to the adapted methodology being the first to be thus implemented. Another difficulty was in-built within the methodology itself, in fact, HERMES is a multi-teamwork-oriented protocol due to its well branched and diverse activities that need to be simultaneously addressed, thus it proved out to be very challenging for a single researcher to cope.

The most critical conundrum that faced the application of this methodology broke out at the phase of data collection. It was very difficult to get formal helicopter accidents reports that are written with satisfactorily reflection to human factors issues, consequently only 58 reports could be used for data analysis out of a total number of 804 thoroughly reviewed reports. The wide spectrum and diversity of HERMES sub-components necessitated serious upgrading and enrichments to the researcher's abilities and know-how such that such these sub-components may be satisfactorily handled, for instance, a formal accident investigation qualification was obtained first in order to better understand accidents occurrence mechanisms and accident reports writing and analysis. A tactical problem faced the execution of the inter-rater reliability for the analysed reports. It was critically suppressing to allocate experienced co-workers with approved qualification in the yet new HFACS-ME taxonomy and associated report coding and analysis.

A major practical challenge as well was to initiate and develop necessary links with industry, throughout the research stages, in order for the required exchange of information to take place. The summit of this mutual cooperation with industry was reached as the selected aviation maintenance organizations managed to allocate the necessary provisions within their daily activities and staff workforce to practically apply the designed AMMP in the course of its verification.

Each of the afore-discussed challenges and the ways they were tackled represents an indispensable learning opportunity, the flexibility of HMI models selection and application, the non-availability of co-workers, the desperate data hunt, the required analysis reliability affordability, and the innovative introduction of additional analytical tools.

10.4 Research Recommendations for future work

This research work, although having achieved all its objectives, but the question it tried to answer calls for even more efforts to be further realized in order for a true aviation maintenance safety enhancement to be secured. This writer considers the following areas as being eligible for further focussing:

1. A holistic front of proactive thinking regarding treatment of maintenance errors must be further crystallized and disseminated within various industry sectors involved, thus furnishing more absorbent environments for practical proactive tools such as those created by this research.
2. The AMMP strategy and its ErroDetect tool are to be changed into some industry standardized practices that can ensure early detection of maintenance errors root causes. This can be achieved by any sector of the industry: Regulators, manufacturers, MRO’s, or even private providers.
3. Accumulative reliability databases are to be established throughout the industry as indicated by AMMP strategy. Such reliability databases are the collective memory of the industry in respect to most safe level of performance achieved industry-wise at any given time. The momentary level of safe performance can be considered as the foundation for further safety enhancements that must be targeted for next future practices, consequently, a continuous progression for safer aviation maintenance can be sustained.

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APPENDICES

Appendix A: Interviewing main aviation active informants

Appendix B: Aviation maintenance sociotechnical relations chart

Appendix C: Typical task analysis diagram of aviation maintenance (partial)

Appendix D: 58 analyzed maintenance- related helicopter safety occurrences

Appendix E: Factual analysis of 58 analyzed maintenance- related helicopter safety occurrences

Appendix F: Specific Failures analysis of 58 maintenance- related helicopter safety occurrences

Appendix G: HFACE-ME 3rd Order analysis of 58 maintenance- related helicopter safety occurrences

Appendix H: Fault Tree Diagram of Puma G-PUMH Helicopter Accident Over The North Sea

Appendix I: Specific Failures for the analysed 58 helicopter safety occurrences

Appendix J: Maintenance Error Root Causes Existence Scale (RCES) of 870 Assessment Criteria – Design Practice. (Excerpts)

Appendix K: The basics of Fuzzy Sets theory

Appendix L: First page of ErroDetect V.1.12 – Workplace software as being applied within industry at the selected MRO organization

Appendix A
Interviewing Main Active Informants from the Aviation Industry

A-1 Interviewing aviation accidents investigators

The basic set of launching questions to aviation accidents investigators were as follows:

1. Does an accident site usually tell directly whether maintenance errors were involved? Are there any specific symptoms proposing a probable maintenance malfunctioning?
2. Do maintenance errors have fixed specified routs of propagation and consequences?
3. What are the most frequent types of maintenance errors that found to be involved in aviation incidents and accidents?
4. What are the most frequent causes that led to maintenance errors that promoted such accidents and incidents?
5. Can maintenance errors be monitored or detected in advance? And how?
6. How do investigators acknowledge the concept of maintenance error causal factor? From what level in the organizational structure do these causal factors firstly emerge?
7. What types of taxonomies or other tools that accident investigators use to up-track maintenance errors causal factors? Can a comparison be held between these taxonomies and tools in regard to their effectiveness and relevance?
8. What controls the degree of human factors depth of analysis within aviation accidents and incidents investigation reports? What are the investigators' perceptions of the role that human factors play in maintenance errors initiation?
9. What are the normal procedures that is usually followed by the investigating authority when a definite individual, or a group of individuals, are found to be responsible for a certain maintenance error that promoted incident or accident?
10. What is the investigators' evaluation of the approach of learning from previous mistakes and experiences, in a reactive orientation, to prevent incidents and accidents re-occurrences? What other approaches can they think of?

A-2 Interviewing aviation MRO's safety managers

The basic set of launching questions to aviation MRO's safety managers were as follows:

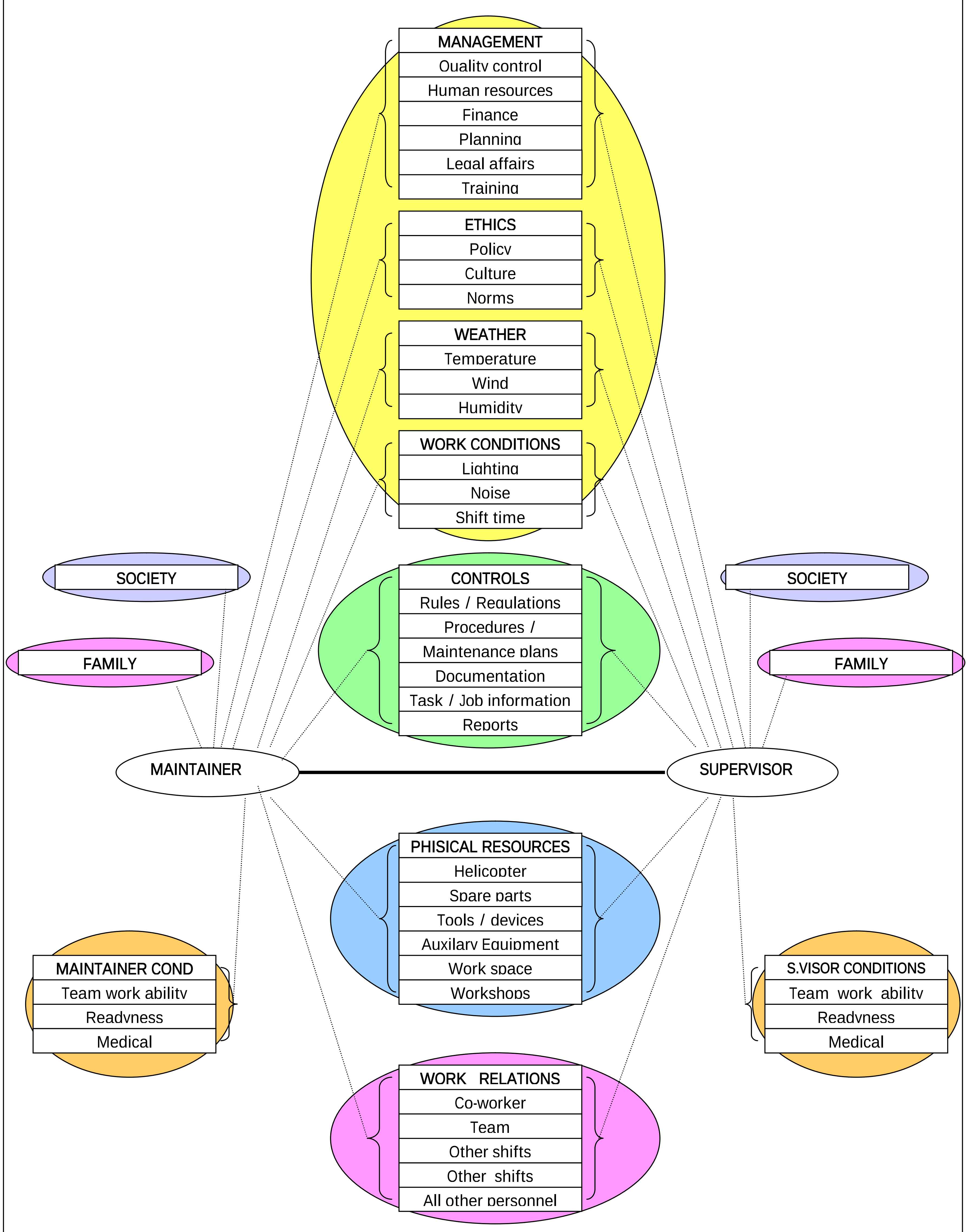
1. What are the general maintenance safety and maintenance error prevention measures currently in action within the general organizational SMS's or in parallel to them?
2. What is the specific nature of these measures? Are they reactive, proactive, hybrid, or of other nature?
3. What are the shortage areas within these measures currently in place that occasionally cause safety concerns or at least need to be re-addressed for further enhancement?
4. What are the most frequent types of maintenance errors that these organizations witness? What are the main causes behind these errors as seen from the internal perspective of the own organisations' safety- responsible personnel?
5. How do these MRO's handle specific maintenance safety-critical issues in regard to various aircrafts types such as the management and control of Flight Safety Sensitive Maintenance Tasks (FSSMT) and the consequential determination of the duplicate inspection items and vital points lists?
6. What new tools, procedures, measures that, if introduced, may further help reducing maintenance errors rates and risks? What are the characteristics of such tools, and what, in general, is expected out of their proposed introduction into the active safety systems throughout the industry?
7. How can such proposed safety advancements be integrated within the current active safety systems without the need for major changes in the organizational layout, in the workplace infrastructures, or without imposing additional time or financial costs?
8. How far developed and effective are the links between these MRO's and their aircrafts' manufacturers? What types of difficulties do these links face? What developments are required for their improvements?
9. What are the internal activities that address human factors impact on maintenance safety? How far are such activities developed and effectuated? What is the degree of human factors understanding and appreciation in the daily life within workplace?
10. Where do these safety officers place their organizations within the safety space? What type of organizational culture do they think that their organizations enjoy? What further efforts that they intend to exert in order to further enhance maintenance safety within their organizations?

A-3 Interviewing main helicopter manufacturers

The basic set of launching questions to main helicopter manufacturers were as follows:

2. What are the procedures that the given manufacturer applies when determining the independent inspection items (III) and the vital points lists within maintenance tasks of a type?
3. What provisions / options are given to the operators to apply the manufacturer's III lists or to add other items to them? What measures should the operators apply in such cases?
4. What are the procedures / measures that the manufacturer applies to eliminate any maintenance error-prone features at the design phase or afterwards?
5. What are the procedures for preparing a maintenance manual, job cards, logbooks, and log cards? What is the current policy for manuals amendments and if there is a fixed frequency periods for such amendments.
6. What are the maintenance issues that Westland requires or expects the operators to give feedback on?
7. What channels are there for feedback from operators regarding technical and other issues of aircraft maintenance?
8. How far is Westland satisfied by the current mutual interaction with the operators (maintenance organizations) (regarding information flow and feedback as well as correct application of Westland's requirements and recommendations as a manufacturer)? What are the future targets for such issues?
9. Are there any maintenance proactive monitoring activities that Westland requires, recommends, or expects? What are the general ideas / structures of such activities?
10. What Safety measures does Westland highlight during providing the 'type maintenance' training to maintenance crews? Any specific activities / rules that are given during such training to prevent maintenance errors?

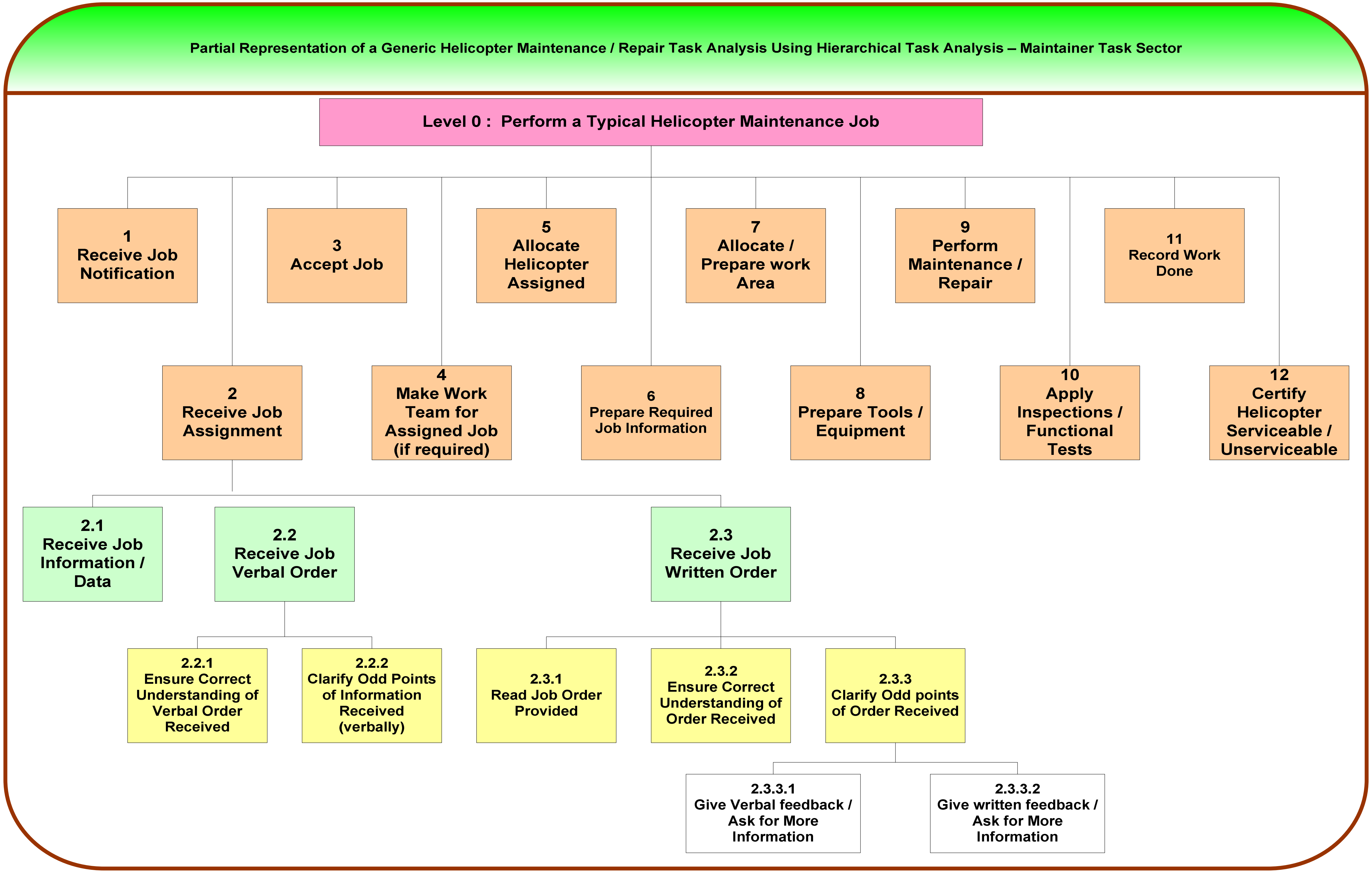
Appendix B
Aviation Maintenance Sociotechnical Relations Chart



AVIATION MAINTENANCE SOCIO-TECHNICAL RELATIONS CHART

(SHELL Model Components General Breakdown)

Appendix C
Partial Representation of Maintainer Task Analysis using HTA Method



Appendix D
58 analyzed maintenance- related helicopter safety occurrences

S No	A/C Registration	Country	Occurrence Date	Report Reference
1	G - PUMH	UK	27-Sep-95	EW/C95/9/4
2	C-GFHO	Australia	13-Dec-95	Bell 205,30257
3	N196CH	USA	10-Apr-96	SEA97FA001
4	N9579F	USA	23-Apr-96	LAX96FA177
5	N598F	USA	28-Jun-96	MIA96FA168
6	C-GTWH	Canada	16-Oct-96	A96
7	N465JR	USA	5-Nov-96	SEA97LA025
8	G - PUMA	UK	6-Mar-97	EW/C1997/03/02
9	N909CP	USA	15-Apr-97	NYC97FA076
10	N5105N	USA	10-May-97	LAX97LA176
11	N30005J	USA	21-May-97	SEA97LA117
12	N4250N	USA	20-Jun-97	LAX97LA218
13	N482SA	USA	27-Aug-97	FTW97FA330
14	N896W	USA	27-Aug-97	SEA97FA196
15	G – BCLC	UK	19-Nov-97	EW/C1997/11/04
16	G - PUMK	UK	9-Mar-98	EW/C1998/03/06
17	N90230	USA	23-Mar-98	LAX98GA127
18	N95MS	USA	16-Jun-98	LAX98LA200
19	C-GHJL	Canada	17-Jun-98	A98P0156
20	N64KL	USA	18-Jul-98	LAX98FA236
21	G - PUMB	UK	20-Jul-98	EW/C1998/07/05
22	N8171U	USA	14-Aug-98	CH98FA313
23	N30SV	USA	20-Aug-98	CH98FA323
24	G – ATBG	UK	26-Aug-98	EW/C1998/08/10
25	G – USTA	UK	27-Mar-99	EW/C1999/03/02
26	C-GTUI	Canada	28-Apr-99	A99W0061
27	N100PL	USA	25-Sep-99	LAX99FA317
28	N904PD	USA	25-Oct-99	LAX00GA025
29	N8144M	USA	27-Nov-99	MIA00FA030
30	G - ZAPS	UK	8-Mar-00	EW/C2000/3/3
31	G - SAEW	UK	21-Apr-00	EW/C2000/04/05
32	G - JRSL	UK	14-Jan-00	EW/C2000/01/01
33	G - TVAA	UK	17-Jun-00	EW/C2000/06/06
34	N355DU	USA	16-Oct-00	MIA01FA006
35	ZK - HVY	New Zealand	15-Jan-01	CAA-ZK 01/44
36	C-FHFS	Canada	15-Jan-01	A01P0003
37	C-FRHO	Canada	15-Mar-01	A01P0047
38	C-GXYM	Canada	8-Nov-01	A01P282
39	G - BJVX	UK	16-Jul-02	EW/C2002/07/04
40	C-GGHG	Canada	15-Aug-02	AO2P0179
41	G - ODNH	UK	7-May-03	EW/C2003/05/02
42	C-GPOS	Canada	6-Jun-03	A03P0136
43	VH-OHA	Australia	20-Jun-03	200302820
44	G - BXXW	UK	6-Aug-03	EW/C2003/08/03
45	C-GEAP	Canada	17-Aug-03	A03P0247
46	VH-BHY	Australia	29-Aug-03	200303804
47	VH-UXF	Australia	28-Sep-03	2003304074
48	VH-EWH	Australia	1-Oct-03	200304105
49	N286M	USA	20-Nov-03	SEA04LA019
50	C-FZQF	Canada	8-Mar-04	A04Q0026
51	G - TASS	UK	10-May-04	EW/C2004/05/02
52	N115ES	USA	14-May-04	ATL04TA116
53	VH-PHF	Australia	14-Jun-04	200402194
54	VH-MPI	Australia	21-Jun-04	200402243
55	N2566W	USA	2-Aug-04	MIA04FA115
56	G - DERB	UK	15-Nov-04	EW/C2004/11/03
57	N4029Q	USA	27-Nov-04	SEA05FA019
58	N331TA	USA	11-May-05	DFW06LA027

Appendix E
Factual analysis of 58 analyzed maintenance- related helicopter safety occurrences

Cases	Registration	Type	Engines	Acc/Inc Date	Country	Total On Board	Severity
Case 1	G - PUMH	Aerospecial AS332L Super Puma	Two	27-Sep-95	UK	17	No injury
Case 2	C-GFHO	Bell 205	One	13-Dec-95	Australia(Ca-reg)	1	Fatal
Case 3	N196CH	Boeing Vertol BV-107 II	Two	10-Apr-96	USA	3	Fatal
Case 4	N9579F	Hughes 269 C	One	23-Apr-96	USA	2	Fatal
Case 5	N598F	Hiller FH-1100	One	28-Jun-96	USA	2	Fatal
Case 6	C-GTWH	Bell 214B-1	Two	16-Oct-96	Canada	2	Serious injury
Case 7	N465JR	Garlick TH-1L	One	5-Nov-96	USA	1	Fatal
Case 8	G - PUMA	Aerospecial AS332L Super Puma	Two	6-Mar-97	UK	18	No injury
Case 9	N909CP	MBB-BK117- B2	Two	15-Apr-97	USA	4	Fatal
Case 10	N5105N	Hughes 369D	One	10-May-97	USA	4	Fatal
Case 11	N30005J	Hiller UH-12E	One	21-May-97	USA	1	Fatal
Case 12	N4250N	HUghes 369 SH	One	20-Jun-97	USA	2	Fatal
Case 13	N482SA	Southwest Florida Aviation SW204	One	27-Aug-97	USA	1	Fatal
Case 14	N896W	Southern Aero UH-1B	One	27-Aug-97	USA	1	Fatal
Case 15	G - BCLC	Sikorisky S - 61 N	Two	19-Nov-97	UK	14	Fatal
Case 16	G - PUMK	Aerospecial AS332L Super Puma	Two	9-Mar-98	UK	17	No injury
Case 17	N90230	Bell 205A-1	One	23-Mar-98	USA	6	Fatal
Case 18	N95MS	Hughes 369 HS	One	16-Jun-98	USA	1	Fatal
Case 19	C-GHJL	Sikorsky S- 76A	Two	17-Jun-98	Canada	10	No injury
Case 20	N64KL	Sikorsky CH-54A	Two	18-Jul-98	USA	3	Fatal
Case 21	G - PUMB	Aerospecial AS332L Super Puma	Two	20-Jul-98	UK	2	No injury
Case 22	N8171U	Hiller FH-1100	One	14-Aug-98	USA	1	Fatal
Case 23	N30SV	Bell 222	Two	20-Aug-98	USA	3	Fatal
Case 24	G - ATBG	Sikorisky S - 61 N	Two	26-Aug-98	UK	10	No injury
Case 25	G - USTA	Agusta A109 A	Two	27-Mar-99	UK	2	No injury
Case 26	C-GTUI	Aerospatial AS355 F1 Twinstar	Two	28-Apr-99	Canada	2	No injury
Case 27	N100PL	Karman HH-43F	One	25-Sep-99	USA	2	Fatal
Case 28	N904PD	Macdonnell Douglas 500N	One	25-Oct-99	USA	2	Fatal
Case 29	N8144M	Bell 212	One	27-Nov-99	USA	2	Fatal
Case 30	G - ZAPS	Hughes 269C	One	8-Mar-00	UK	3	Fatal
Case 31	G - SAEW	Aerospecial AS355 F2	Two	21-Apr-00	UK	3	No injury
Case 32	G - JRSL	Agusta A109 E	Two	14-Jan-00	UK	3	Minor injury
Case 33	G - TVAA	Agusta A109 E	Two	17-Jun-00	UK	3	Minor injury
Case 34	N355DU	Aerospecial AS355 F2	Two	16-Oct-00	USA	1	Fatal
Case 35	ZK - HVY	Bell 204 UH - 1F	One	15-Jan-01	New Zealand	1	Fatal
Case 36	C-FHFS	Sikorsky S - 61N	Two	15-Jan-01	Canada	2	Serious injury
Case 37	C-FRHO	Schweizer 269B	One	15-Mar-01	Canada	1	No injury
Case 38	C-GXYM	Aerocopter SA 315B LAMA	One	8-Nov-01	Canada	1	Fatal
Case 39	G - BJVX	Sikorsky S - 76A+	Two	16-Jul-02	UK	11	Fatal
Case 40	C-GGHG	Aerocopter SA 315 LAMA	One	15-Aug-02	Canada	3	Minor injury
Case 41	G - ODNH	Schweizer 269C	One	7-May-03	UK	2	No injury
Case 42	C-GPOS	Bell 206B	One	6-Jun-03	Canada	3	Serious injury
Case 43	VH-OHA	Robinson R22 Mariner	One	20-Jun-03	Australia	2	Fatal
Case 44	G - BXXW	Enstrom F28A	One	6-Aug-03	UK	3	No injury
Case 45	C-GEAP	Bell 204B	One	17-Aug-03	Canada	1	Fatal
Case 46	VH-BHY	Aerospecial AS332L Super Puma	Two	29-Aug-03	Australia	8	No injury
Case 47	VH-UXF	Robinson R22	One	28-Sep-03	Australia	2	Fatal
Case 48	VH-EWH	Bell 206B	One	1-Oct-03	Australia	1	No injury
Case 49	N286M	Karman K-600	One	20-Nov-03	USA	1	Fatal
Case 50	C-FZQF	Schweizer 269C-1	One	8-Mar-04	Canada	2	No injury
Case 51	G - TASS	Schweizer 269C	One	10-May-04	UK	2	Serious injury
Case 52	N115ES	Hughes 269 A	One	14-May-04	USA	2	Fatal
Case 53	VH-PHF	Bell 206B (II) Jetranger	One	14-Jun-04	Australia	5	No injury
Case 54	VH-MPI	MD helecopters MD 520N	One	21-Jun-04	Australia	2	No injury
Case 55	N2566W	Robinson R22 Beta	One	2-Aug-04	USA	2	Fatal
Case 56	G - DERB	Robinson R22 Beta	One	15-Nov-04	UK	2	No injury
Case 57	N4029Q	Robinson R22 Beta	One	27-Nov-04	USA	2	Fatal
Case 58	N331TA	Arrow F OH - 58A	One	11-May-05	USA	1	Fatal

Appendix E
Factual analysis database of 58 maintenance- related helicopter safety occurrences (Continued)

Cases	Occurrence Summary	Defected Systems	Defected components	Error Key word
Case 1	Flapping hing retainer of one tail rotor blade fractured	Tail rotor	Hing retainer	Detection
Case 2	Engine accessory drive gearbox failure	Engine	Gears	Installation
Case 3	Flight control jammed due to un-installed cotter pin	Flight control	Cotter pin	Omission
Case 4	Partial Engine power loss	Engine	Exhaust valves	Procedure
Case 5	Failure of tension-torsion bar of tail rotor blade	Tail rotor	TT bar	Procedure
Case 6	Tail rotor drive shaft broke after maingearbox transmission spindle failure	Transmission system	Spindle	Procedure
Case 7	Vertical stabilizer failure and loss	Air frame	Spar cap	Diagnosis, Inspection
Case 8	Bolts of Tail rotor drive shaft cover falled off	Air frame	Bolts	Defected parts
Case 9	Vertical fin failure	Air frame	Rivets	Unauthorised parts
Case 10	Engine power loss - Component failure	Engine	Compressor stator vane	Inspection
Case 11	One main rotor blade separation during flight	Main rotor	Main blade spar	Procedure, Inspection
Case 12	Flight control cyclic trim failure	Flight control	Trim electrical switch	Modification, Unauthorised parts,Procedure
Case 13	Main rotor system separation due to main blade fatique failure	Main rotor	Main blade spar	Repair,Inspection
Case 14	Fatique fracture of the main roter mast	Main rotor	Main rotor mast	Standards
Case 15	Winch cable jammed.	Air frame	Cutter chisel blade	Installation
Case 16	Heli-raft covers separated in flight.	Air frame	Screws	Fitting
Case 17	Tail rotor separation due to tail roror blade fatique fracture	Tail rotor	Tail blade	Inspection
Case 18	Tail rotor drive shaft broke due to improper shimmying	Transmission system	Shimms	Fitting
Case 19	Tail rotor pitch change unit failure	Tail rotor	Pitch change rod	Inspection,Omission
Case 20	Main rotor blade spar separation	Main rotor	Main blade spar	Repair
Case 21	Engine oversped, power turbine output shaft destroyed.	Engine	Bolts	Omission
Case 22	Tail rotor failure due to tail blade debonding	Tail rotor	Tail blade	Inspection
Case 23	Main rotor swash plate outer pin failure	Main rotor	Pin	Fitting
Case 24	Tail rotor control cable fractured.	Tail rotor	Control cable	Installation
Case 25	Tail rotor gearbox torn out.	Tail rotor	Tail blade	Detection
Case 26	In-flight fire	Air frame	Battery cables	Omission, Detection
Case 27	Horizontal stabilizer failure	Air frame	Stabilizer attach fitting	Detection, Unauthorised parts
Case 28	Separation of forward thruster control cable fitting	Flight control	Control cable	Inspection
Case 29	Main rotor blade pitch change horn and grip attachment failure	Main rotor	Main blade horn	Detection
Case 30	Central frame rear cluster fitting fractured in flight	Air frame	Cluster fitting	Repair, Procedure
Case 31	Tail rotor pitch change unit out of function	Tail rotor	Pitch change rod	Omission
Case 32	Bolts of swash plate scissors link attachment fractured	Main rotor	Bolts	Installation
Case 33	Bolts of swash plate scissors link attachment fractured	Main rotor	Bolts	Installation
Case 34	Failed main rotor gearbox oil pump	Main rotor	Gearbox oil pump	Procedure, Release
Case 35	Hydraulic system failure due to pressure line crack	Hydraulic system	Pressure tube	Fitting
Case 36	Main rotor transmission failure	Main rotor	Shimms	Installation
Case 37	Tail rotor drive decoupling	Transmission system	Shaft splined drive coupling	Omission,Procedure,Detection
Case 38	Input freewheel unit and drive shaft assemply (transmission) failure	Main rotor	Input freewheel unit	Procedure
Case 39	Main rotor blade failure and main rotor assembly separation	Main rotor	Main blade spar	Unauthorised materials
Case 40	Engine power loss - Component failure	Engine	Engine coupling sleeve& shaft	Installation
Case 41	Tail rotor teeter pivot bolt broken	Tail rotor	Tail fork bolt and nut	Installation, Procedure
Case 42	Engine power loss - Component failure	Engine	Gas turbine blade	Inspection
Case 43	Main rotor blade separation	Main rotor	Blade root fitting	Diagnosis
Case 44	Main gearbox fracture due to mal lubrication	Main rotor	Chip detector wiring	Unauthorised parts, Oil level
Case 45	Loss of engine power	Engine	Compressor rotor	Procedure, Adjustment
Case 46	Tail rotor pitch change rod assembly failure	Tail rotor	Pitch change rod bearing	Defected parts
Case 47	Engine/main gear box clutch shaft inflight fractured	Transmission system	A166 clutch shaft	Unauthorised materials,Procedure
Case 48	Engine flame out	Engine	Fuel tank quantity transmiter	Installation
Case 49	Right main rotor shaft failure	Main rotor	Main rotor mast	Standards
Case 50	Transmission gearbox failure and main rotor separation during ground run	Transmission system	Input quill bearing housing	Installation, Inspection
Case 51	Engine stopped, fuel flow cut off.	Engine	Fuel control cable attachment	Installation
Case 52	Fatique fracture of the tailboom saddle fitting	Air frame	Tail boom saddle support fitting	Procedure
Case 53	Engine/main gear box clutch shaft inflight fractured	Transmission system	Kaflex drive shaft	Procedure, Detection
Case 54	Right landing gear struts fractured during landing	Air frame	Landing strut	Repair, Unauthorised parts
Case 55	Fixed swach plate assembly left lug loosening	Main rotor	Push/pull tube of swach plate	Omission
Case 56	Main rotor blade cracked due to stiff bearings.	Main rotor	Main blade teeter hing	Omission
Case 57	Main rotor diverted from normal plane of rotation	Main rotor	Door pins	Omission
Case 58	Loss of engine power due to disconnected pneumatic line	Engine	pneumatic line tube	Fitting

Appendix E
Factual analysis database of 58 maintenance- related helicopter safety occurrences
(Continued)

Cases	Detailed Organizational / Maintainer Errors
Case 1	1)Undetected fatique crack despite additional maintenance work in this area
Case 2	1)Incorrect installation of gears during overhaul
Case 3	1)Missing cotter pin in a clevis bolt in the flight control system
Case 4	1)Recommended engine maintenance procedure skiped
Case 5	1)Non-compliance with an Advisory Directory (AD) and a Service Buletine(SB)
Case 6	1)Omission of magnetic particle inspection of the transmission spindle during last overhaul
Case 7	1)Inadequate trouble-shooting of the tail cone when the sheet metal skin cracks were stop-drilled, 2)and inadequate inspection after that
Case 8	1)Old securing self-locking nuts of the tail shaft fairing had not been replaced after they had lost their locking property for long time
Case 9	1)Solid rivetsof the vertical fin SAS mount support were replaced by unauthorized blind rivets
Case 10	1)Inadequate maintenance inspection of the second stage stator vanes of the engine compressor
Case 11	1)Inadequate application of an airworthiness directive, 2) and inadequate inspection of the main rotor blades
Case 12	1)Unapproved field modification of the cyclic trim switch, 2)use of non-standard parts, 3)and non-compliance with a service bulletine
Case 13	1)Unapproved repair of the main rotor blade, 2) and failure to locate this repair twice: during later blade modification and during applying a related AD
Case 14	1)Insufficient FAA airworthness standards and requirements regarding this aircraft main rotor mast
Case 15	1)Winch cable cutting mechanism was assembled in a wrong way,
Case 16	1)Incomplete securing of the heli-raft pod covers, only three screws were hand tightened insteade of complete eight fully tightened screws as required
Case 17	1)Inadequate inspection for the tail rotor yoke's straightness
Case 18	1)Improper shimmying of the tail rotor drive shaft
Case 19	1)Failure to inspect the tail rotor pitch control rod ends for cracks after a SB had been complied with, 2)corrosion prevention material not applied
Case 20	1)Improper repair to the main rotor blade
Case 21	1)Six bolts securing the splined sleeve to the power turbine output shaft of the engine had not been fitted
Case 22	1)Inadequate maintenance inspection of the tail rotor blades, 2)Improper other maintenance procedure of the maintenance personnel
Case 23	1)Below standard (loose) fit of the white swashplate outer ring pin
Case 24	1)Incorrect installation of tail roter cables over a guard pin (misrouted)
Case 25	1)Failure to detect a tail rotor blade fatique crack during dye penetrant inspection
Case 26	1)Auxiliary-main battery paralleling cable was not attached to the positive post of the main battery, 2) and failure to detect the loose cable during BFS
Case 27	1)Inadequate maintenance inspection for cracks in the horizontal stabilizer left attach point, 2) and use of unapproved parts
Case 28	1)Failure to remove an access panel to fully and completely examine the thruster control cable to diagnose the yaw anomaly reported previously
Case 29	1)Failure to detect the signs of fretting and loosiness in the red main rotor blade pitch change horn to main rotor blade grip attachment
Case 30	1)Critical unauthorised welding repair of the tail boom clevis lugs, 2) and ommiting of refering to the manual standards regarding this repair
Case 31	1)Both anti -corrosion and anti-fretting compounds were not applied during the last modification applied to tail rotor spider assembly
Case 32	1)Swash plate scissors link had been incorrectly installed
Case 33	1)Swash plate scissors link had been incorrectly installed
Case 34	1)Non-compliance with manufacturer's instructions regarding illuminated MGB oil pressure warning light, 2) setting aircraft to fly with major defect
Case 35	1)Overtightening of main hydraulic system flareless fitting to stop a leak
Case 36	1)Spiral bevel pinion and the main bevel gears were misaligned during overhaul
Case 37	1)Bumper plug missed during installation of aft end of drive shaft, 2) Maintainer didn't refere to manual, 3)Defect was not detected during inspections
Case 38	1)Operator didn't perform the 800 hrs inspection of the input free wheel unit required by maintenance manual
Case 39	1)Use of an unauthorised opaque protective patch on the erosion cover's scraf joint hid external symptoms of a developing blade spar crack
Case 40	1)improper axial placement of the stub shaft into the coupling sleeve of the ngine drivetrain
Case 41	1)Incorrect seating of the bolt within the threaded insert of tail rotor fork assembly, 2)25hrs required torque inspection of the assembly not performed
Case 42	1)No periodic power checks or inspections for corrosive sulfidation were performed on engine components
Case 43	1)Icorrect diagnosis of the reported main rotor vibration
Case 44	1)Maingear box chip detector wired with unauthorised cables, 2) Main gear box oil level not properly checked
Case 45	1)Inaacurate engine overhaul procedures as reqired by the overhaul manual, 2)Inacurate N1 field adjustment of fuel control unit
Case 46	1)The tail rotor pitch change rod bearing left to continue in service after it has been discovered to be defected
Case 47	1)Non-approved joining compound was used to join a166 shaft to its yoke, 2) paint was not removed before joining as required
Case 48	1) Lower fuel tank quantity indicator unit has been incorrectly installed in the tank
Case 49	1) No action was taken to treat the reported corrosion of the right main rotor shaft (no action is highlighted by the manufacturer)
Case 50	1) Input quill bearing housing was not positioned correctly, 2)Independent inspection didn't detect this incorrect installation
Case 51	1)Incorrect attachment of the fuel control injection servo to the engine- too short control cable was used
Case 52	1)Non complience with an airworthness directive requiring inspection of the tailboom saddle fitting
Case 53	1)STC inspection was overlooked by maintenance personnel, 2)Shaft flex frame joints were loosen for long time without being detected.
Case 54	1) Rough machining of the inner surface of the rear strut drag brace lower connection hole, 2)Use of non standard bushing component.
Case 55	1)Push/pull tube of the left lug of the non-rotatingportion of the swashplate assembly was not secured in place following maintenance
Case 56	1) Main rotor blade teeter hinge was assembled without the necessary shims
Case 57	1)Helicopter door pins were not installed (doors separated in flight and affected the main rotor normal rotation)
Case 58	1)Insufficient torque was applied to the "B-NUT" joining a pneumatic line to the fuel control unit, 2)Tube was deformed & improperly fitted

Appendix F
Specific Failures analysis of 58 maintenance- related helicopter safety occurrences

HFACS-ME FIRST ORDER FACTOES MANAGEMENT CONDITIONS																																				
	SECOND ORDER ORGANIZATIONAL CONDITIONS																																			
	Inadequate Processes									Inadequate Documents												Inadqt. Design									Indqt. Resources					
	SPECIFIC FAILURES (1 TO 31)																																			Orgniz.
	1	2	3	4	5	6	7	8	Sum	9	10	11	12	13	14	15	16	17	18	19	Sum	20	21	22	23	24	25	26	27	Sum	28	29	30	31	Sum	Sum
Case 1	0	2	2	0	0	0	1	1	6	2	0	0	0	1	0	0	0	1	0	1	5	0	0	0	0	0	0	0	0	0	0	0	1	1	2	13
Case 2	1								1		1										1						1			1					0	3
Case 3									0												0									0					0	0
Case 4	1				1				2												0									0					0	2
Case 5			1						1									1			1									0					0	2
Case 6					1	1		1	3	1								2			3									0					0	6
Case 7									0												0									0					0	0
Case 8									0								2				2		1		2	1				4					0	6
Case 9									0	1							1	2			4									0					0	4
Case 10									0		1										1									0					0	1
Case 11			1						1												0					1				1					0	2
Case 12	1								1												0									0					0	1
Case 13									0												0									0					0	0
Case 14			1					1	2												0		1							1					0	3
Case 15									0	1				1		1	1	2			6						2		1	3					0	9
Case 16									0												0									0	1				1	1
Case 17	1	1	1			1			4		2			2							4			1						1					0	9
Case 18							1		1												0									0			1		1	2
Case 19							1	1	2								1	2			3									0					0	5
Case 20								1	1		1										1									0			1		1	3
Case 21								1	1												0									0	1				1	2
Case 22									0												0									0					0	0
Case 23									0												0	1								1					0	1
Case 24								1	1										1		1								1	1					0	3
Case 25									0	1							1				2									0					0	2
Case 26	1	1	1	1	2				6		2										2						1			1					0	9
Case 27		1							1												0									0					0	1
Case 28									0												0					1				1					0	1
Case 29									0												0									0					0	0
Case 30	1	4	2	2			2	1	12	6	7			1			1	2			17					1	1			2			1		1	32
Case 31						1		1	2					1		1		1			3									0				1	1	6
Case 32									0												0								1	1					0	1
Case 33									0					1	1			1			3						1		1	2					0	5
Case 34	3		1	1					5												0									0					0	5
Case 35									0									2			2						1			1					0	3
Case 36		1						1	2		1							1			2									0					0	4
Case 37	1				1				2	2				1				1			4									0					0	6
Case 38	1			1	1				3												0									0					0	3
Case 39							2	2	4	1											1		2			1				3				1	1	9
Case 40									0												0									0					0	0
Case 41		1			1				2					1			1	1			3						1			1					0	6
Case 42								2	2												0						1			1					0	3
Case 43					1			1	2		1	1						2			4									0					0	6
Case 44									0								1				1									0					0	1
Case 45						1			1												0						1			1					0	2
Case 46								1	1												0					1				1					0	2
Case 47		1							1												0									0					0	1
Case 48									0	1								1			2								1	1					0	3
Case 49									0	1								1			2									0					0	2
Case 50									0												0								1	1					0	1
Case 51			1						1	1											1									0					0	2
Case 52	1								1												0									0					0	1
Case 53		2	2	1	1			2	8	1	1		1					1			4									0					0	12
Case 54								1	1		1										1									0					0	2
Case 55		2	1			1			4								1	1			2									0					0	6
Case 56									0												0									0			1		1	1
Case 57									0												0									0					0	0
Case 58									0												0									0					0	0
	12	16	14	6	9	5	7	19		19	18	1	1	9	1	2	10	25	1	1		1	4	1	2	6	10	0	6		2	0	5	3		
	All Indqut Prcess events =								88	All Indqut Dcmnts events=											88	All Inadqt.Dsgn events=								30	All.Rsrces events=				10	
	TOTAL ORGANIZATIONAL EVENTS FOR ALL CASES =																																			216

Appendix F
Specific Failure analysis of 58 maintenance- related helicopter safety occurrences (Continued)

HFACS-ME FIRST ORDER FACTORS MANAGEMENT CONDITIONS (Continued)																																		
	SECOND ORDER SUPERVISORY CONDITIONS																																Each	Each
	Inappropriate Operations								Inadequate Supervision										Uncorrected Problem							Suprvr. Misconduct							Case	Case
	SPECIFIC FALURES (32 TO 59)																																Spr V.	Mngmt
	32	33	34	35	36	37	38	Sum	39	40	41	42	43	44	45	46	47	Sum	48	49	50	51	52	53	Sum	54	55	56	57	58	59	Sum	Sum	Sum
Case 1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	0	0	0	1	2	2	0	0	0	0	0	2	5	18
Case 2								0										0							0							0	0	3
Case 3								0										0							0							0	0	0
Case 4								0										0							0							0	0	2
Case 5								0										0							0							0	0	2
Case 6								0				1			1			2							0							0	2	8
Case 7								0						1				1							0							0	1	1
Case 8								0										0							0							0	0	6
Case 9							1	1				1						1							0							0	2	6
Case 10								0										0							0							0	0	1
Case 11								0										0							0							0	0	2
Case 12								0										0							0							0	0	1
Case 13								0						1				1							0							0	1	1
Case 14								0										0							0							0	0	3
Case 15								0										0							0							0	0	9
Case 16			1					1										0							0							0	1	2
Case 17								0										0							0							0	0	9
Case 18								0										0							0							0	0	2
Case 19								0										0							0							0	0	5
Case 20								0										0							0							0	0	3
Case 21								0										0							0					1		1	1	3
Case 22								0						1				1							0							0	1	1
Case 23								0										0							0							0	0	1
Case 24								0						1				1							0							0	1	4
Case 25								0										0							0							0	0	2
Case 26							1	1										0	1						1							0	2	11
Case 27								0						1				1							0							0	1	2
Case 28								0										0							0							0	0	1
Case 29								0						1				1							0							0	1	1
Case 30								0										0					1		1	1						1	2	34
Case 31								0										0							0							0	0	6
Case 32								0										0							0							0	0	1
Case 33								0										0							0							0	0	5
Case 34								0										0							0							0	0	5
Case 35								0										0	1						1							0	1	4
Case 36								0										0							0							0	0	4
Case 37								0						1	1	1		3							0							0	3	9
Case 38								0										0							0							0	0	3
Case 39								0										0					1		1							0	1	10
Case 40								0										0							0							0	0	0
Case 41								0										0							0							0	0	6
Case 42								0										0							0							0	0	3
Case 43								0										0							0							0	0	6
Case 44								0										0							0							0	0	1
Case 45								0										0							0							0	0	2
Case 46								0										0							0							0	0	2
Case 47								0						1				1							0							0	1	2
Case 48								0						1				1							0							0	1	4
Case 49								0										0							0							0	0	2
Case 50								0						1				1							0							0	1	2
Case 51								0										0	1		1				2							0	2	4
Case 52								0										0							0							0	0	1
Case 53								0						1				1							0							0	1	13
Case 54								0										0							0							0	0	2
Case 55								0										0							0							0	0	6
Case 56								0						1				1							0						1	1	2	3
Case 57								0										0							0							0	0	0
Case 58								0										0							0							0	0	0
	0	0	1	0	0	0	2		0	0	0	2	0	13	2	1	0		4	0	1	0	2	1		3	0	0	0	1	1			
	All Indqut Operations events=							3	All Indqute Supervision events=									18	All Uncrctd Prblm events=						8	All Sup. Mscndct evnts=						5		
	TOTAL SUPERVISORY EVENTS FOR ALL CASES =																																34	
	TOTAL MANAGEMENT CONDITION EVENTS FOR ALL CASES =																																	250

Appendix F
Specific Failure analysis of 58 maintenance- related helicopter safety occurrences (Continued)

	HFACS-ME			FIRST ORDER FACTORS							MAINTAINER CONDITIONS											
	SECOND ORDER								MEDICAL CONDITIONS													Each
	Mental State									Physical State					Limitations							Case
	SPECIFIC FAILURES (60 TO 77)																					Med. Cond.
	60	61	62	63	64	65	66	67	Sum	68	69	70	71	Sum	72	73	74	75	75	77	Sum	Sum
Case 1									0					0							0	0
Case 2									0					0							0	0
Case 3									0					0							0	0
Case 4									0					0							0	0
Case 5									0					0							0	0
Case 6									0					0							0	0
Case 7									0					0							0	0
Case 8									0					0							0	0
Case 9									0					0							0	0
Case 10									0					0							0	0
Case 11									0					0							0	0
Case 12									0					0							0	0
Case 13									0					0							0	0
Case 14									0					0							0	0
Case 15									0					0							0	0
Case 16						1			1					0							0	1
Case 17									0					0							0	0
Case 18									0					0							0	0
Case 19									0					0							0	0
Case 20									0					0							0	0
Case 21									0					0							0	0
Case 22									0					0							0	0
Case 23									0					0							0	0
Case 24									0					0							0	0
Case 25									0					0							0	0
Case 26		1		1					2					0							0	2
Case 27									0					0							0	0
Case 28									0					0							0	0
Case 29									0					0							0	0
Case 30									0					0							0	0
Case 31									0					0							0	0
Case 32									0					0							0	0
Case 33									0					0							0	0
Case 34									0					0							0	0
Case 35									0					0							0	0
Case 36									0					0							0	0
Case 37									0					0							0	0
Case 38									0					0							0	0
Case 39									0					0							0	0
Case 40									0					0							0	0
Case 41									0					0							0	0
Case 42									0					0							0	0
Case 43									0					0							0	0
Case 44									0					0							0	0
Case 45									0					0							0	0
Case 46									0					0							0	0
Case 47									0					0							0	0
Case 48									0					0							0	0
Case 49									0					0							0	0
Case 50									0					0							0	0
Case 51									0					0							0	0
Case 52									0					0							0	0
Case 53									0					0							0	0
Case 54									0					0							0	0
Case 55		1		1					2					0							0	2
Case 56									0					0							0	0
Case 57									0					0							0	0
Case 58									0					0							0	0
	0	2	0	2	0	1	0	0		0	0	0	0		0	0	0	0	0	0		
	All Mental events =								5	All Physcl events=				0	All Lmtatns events=						0	
				TOTAL MEDICAL CONDITIONS EVENTS FOR ALL CASES =																		5

Appendix F
Specific Failure analysis of 58 maintenance- related helicopter safety occurrences (Continued)

HFACS-ME FIRST ORDER FACTORS MAINTAINER CONDITIONS (Continued)																									
	SECOND ORDER CREW COORDINATION																								Each
	Communication									Assertiveness								Adapt/Flexibility							Case
	SPECIFIC FAILURES (78 TO 98)																								Crew Cond.
	78	79	80	81	82	83	84	85	Sum	86	87	88	89	90	91	92	Sum	93	94	95	96	97	98	Sum	Sum
Case 1									0								0							0	0
Case 2									0								0							0	0
Case 3									0								0							0	0
Case 4									0								0							0	0
Case 5									0								0							0	0
Case 6									0								0							0	0
Case 7									0								0							0	0
Case 8									0								0							0	0
Case 9									0								0							0	0
Case 10									0								0							0	0
Case 11									0								0							0	0
Case 12									0								0							0	0
Case 13									0								0							0	0
Case 14									0								0							0	0
Case 15									0								0							0	0
Case 16							1		1								0							0	1
Case 17									0								0							0	0
Case 18									0								0							0	0
Case 19									0								0							0	0
Case 20									0								0							0	0
Case 21							1	2	3								0			1				1	4
Case 22									0								0							0	0
Case 23									0								0							0	0
Case 24									0								0							0	0
Case 25									0								0							0	0
Case 26									0								0							0	0
Case 27									0								0							0	0
Case 28									0								0							0	0
Case 29									0								0							0	0
Case 30							1		1								0							0	1
Case 31									0								0							0	0
Case 32									0								0							0	0
Case 33									0								0							0	0
Case 34									0								0							0	0
Case 35									0								0							0	0
Case 36									0								0							0	0
Case 37									0								0							0	0
Case 38									0								0							0	0
Case 39									0								0							0	0
Case 40									0								0							0	0
Case 41									0								0							0	0
Case 42									0								0							0	0
Case 43									0								0							0	0
Case 44									0								0							0	0
Case 45									0								0							0	0
Case 46									0								0							0	0
Case 47									0								0							0	0
Case 48									0								0							0	0
Case 49									0								0							0	0
Case 50									0								0							0	0
Case 51									0								0							0	0
Case 52									0								0							0	0
Case 53									0								0							0	0
Case 54									0								0							0	0
Case 55									0								0							0	0
Case 56									0								0							0	0
Case 57									0								0							0	0
Case 58									0								0							0	0
	0	0	0	0	0	0	3	2		0	0	0	0	0	0	0		0	0	1	0	0	0		
	All Commnctn events=								5	All Assrtvnss events=							0	All Adpt/Flxblt events=						1	
						TOTAL CREW COORDINATION EVENTS FOR ALL CASES =																			6

Appendix F
Specific Failure analysis of 58 maintenance- related helicopter safety occurrences (Continued)

HFACE-ME FIRST ORDER MAINTAINER CONDITIONS (Continued)																				
	SECOND ORDER READYNESS																		Each	Each
	Train/Preparation							Certf. /Qualification					Infringement						Case	Case
	SPECIFIC FAILURES (99 TO 113)																		Readinss	Maintainer
	99	100	101	102	103	104	Sum	105	106	107	108	Sum	109	110	111	112	113	Sum	Sum	Cond. Sum
Case 1							0					0						0	0	0
Case 2							0					0						0	0	0
Case 3							0					0						0	0	0
Case 4							0					0						0	0	0
Case 5							0					0						0	0	0
Case 6							0					0						0	0	0
Case 7							0					0						0	0	0
Case 8							0					0					1	1	1	1
Case 9							0					0						0	0	0
Case 10							0					0						0	0	0
Case 11							0					0						0	0	0
Case 12							0					0						0	0	0
Case 13							0					0						0	0	0
Case 14							0					0						0	0	0
Case 15							0					0						0	0	0
Case 16							0					0			1			1	1	3
Case 17							0					0						0	0	0
Case 18							0					0						0	0	0
Case 19							0					0						0	0	0
Case 20							0					0						0	0	0
Case 21							0		1			1			1			1	2	6
Case 22							0					0						0	0	0
Case 23							0					0						0	0	0
Case 24							0					0						0	0	0
Case 25							0					0						0	0	0
Case 26							0					0						0	0	2
Case 27							0					0						0	0	0
Case 28							0					0						0	0	0
Case 29							0					0						0	0	0
Case 30	1						1					0						0	1	2
Case 31						1	1					0						0	1	1
Case 32							0					0						0	0	0
Case 33							0					0						0	0	0
Case 34							0					0					1	1	1	1
Case 35							0					0						0	0	0
Case 36							0					0						0	0	0
Case 37						1	1					0						0	1	1
Case 38							0					0						0	0	0
Case 39							0					0						0	0	0
Case 40							0					0						0	0	0
Case 41							0					0						0	0	0
Case 42							0					0						0	0	0
Case 43							0					0						0	0	0
Case 44							0					0						0	0	0
Case 45							0					0						0	0	0
Case 46							0					0						0	0	0
Case 47							0					0						0	0	0
Case 48							0					0						0	0	0
Case 49							0					0						0	0	0
Case 50							0					0						0	0	0
Case 51							0					0						0	0	0
Case 52							0					0						0	0	0
Case 53							0					0						0	0	0
Case 54							0					0						0	0	0
Case 55							0					0						0	0	2
Case 56				1	1		2				1	1						0	3	3
Case 57	1						1	1				1						0	2	2
Case 58							0					0						0	0	0
	2	0	0	1	1	2		1	1	0	1		0	0	2	0	2			
	All Trn/Prprtn events=						6	All Qulfctn events=				3	All Infrgmnt events=					4		
				TOTAL READYNESS EVENTS FOR ALL CASES =															13	
					TOTAL MAINTAINER CONDITIONS FOR ALL CASES =															24

Appendix F
Specific Failure analysis of 58 maintenance- related helicopter safety occurrences (Continued)

	HFACS-ME FIRST ORDER FACTORS WORKING CONDITIONS																	
	SECOND ORDER ENVIRONMENT																	Each
	Lighting					Weather/Exposure							Envrn Hazards					Case
	SPECIFIC FAILURES (114 TO 127)																	Environment.
	114	115	116	117	Sum	118	119	120	121	122	123	Sum	124	125	126	127	Sum	Sum
Case 1		1			1							0					0	1
Case 2					0							0					0	0
Case 3					0							0					0	0
Case 4					0							0					0	0
Case 5					0							0					0	0
Case 6					0							0					0	0
Case 7					0							0					0	0
Case 8					0							0					0	0
Case 9					0							0					0	0
Case 10					0							0					0	0
Case 11					0							0					0	0
Case 12					0							0					0	0
Case 13					0							0					0	0
Case 14					0							0					0	0
Case 15					0							0					0	0
Case 16				1	1	1						1					0	2
Case 17					0							0					0	0
Case 18					0							0					0	0
Case 19					0							0					0	0
Case 20					0							0					0	0
Case 21					0							0					0	0
Case 22					0							0					0	0
Case 23					0							0					0	0
Case 24		1			1							0					0	1
Case 25					0							0					0	0
Case 26					0							0					0	0
Case 27					0							0					0	0
Case 28					0							0					0	0
Case 29					0							0					0	0
Case 30					0							0					0	0
Case 31					0							0					0	0
Case 32					0							0					0	0
Case 33					0							0					0	0
Case 34					0							0					0	0
Case 35					0							0					0	0
Case 36					0							0					0	0
Case 37					0							0					0	0
Case 38					0							0					0	0
Case 39					0						1	1					0	1
Case 40					0							0					0	0
Case 41					0							0					0	0
Case 42					0							0					0	0
Case 43					0							0					0	0
Case 44					0							0					0	0
Case 45					0							0					0	0
Case 46					0							0					0	0
Case 47					0							0					0	0
Case 48					0							0					0	0
Case 49					0							0					0	0
Case 50					0							0					0	0
Case 51					0							0					0	0
Case 52					0							0					0	0
Case 53					0							0					0	0
Case 54					0							0					0	0
Case 55					0							0					0	0
Case 56					0							0					0	0
Case 57					0							0					0	0
Case 58					0							0					0	0
	0	2	0	1		1	0	0	0	0	1		0	0	0	0		
	All Lighting events=				3	All Wthr / Expsor events=						2	All Envrnmt evnts=				0	
			TOTAL ENVIRONMENTAL EVENTS FOR ALL CASES =															5

Appendix F
Specific Failure analysis of 58 maintenance- related helicopter safety occurrences (Continued)

	HFACS-ME FIRST ORDER FACTORS WORKING CONDITIONS (Continued)																
	SECOND ORDER EQUIPMENT																Each
	Damaged/ Unserviceable							Unavail / Inapproprte					Uncertified				Case
	SPECIFIC FAILURES (128 TO 140)																Equipment.
	128	129	130	131	132	133	Sum	134	135	136	137	Sum	138	139	140	Sum	Sum
Case 1							0					0				0	0
Case 2					1		1					0				0	1
Case 3							0					0				0	0
Case 4							0					0				0	0
Case 5							0					0				0	0
Case 6							0					0				0	0
Case 7							0					0				0	0
Case 8							0					0				0	0
Case 9							0					0				0	0
Case 10							0					0				0	0
Case 11							0					0				0	0
Case 12							0					0				0	0
Case 13							0					0				0	0
Case 14							0					0				0	0
Case 15							0					0				0	0
Case 16							0					0				0	0
Case 17							0					0				0	0
Case 18							0					0				0	0
Case 19							0					0				0	0
Case 20							0					0				0	0
Case 21				1			1			1		1				0	2
Case 22							0					0				0	0
Case 23							0					0				0	0
Case 24							0					0				0	0
Case 25							0					0				0	0
Case 26							0					0				0	0
Case 27							0					0				0	0
Case 28							0					0				0	0
Case 29							0					0				0	0
Case 30							0					0				0	0
Case 31							0					0				0	0
Case 32							0					0				0	0
Case 33							0					0				0	0
Case 34							0					0				0	0
Case 35							0					0				0	0
Case 36							0					0				0	0
Case 37							0					0				0	0
Case 38							0					0				0	0
Case 39							0					0				0	0
Case 40							0					0				0	0
Case 41							0					0				0	0
Case 42							0					0				0	0
Case 43							0					0				0	0
Case 44							0					0				0	0
Case 45							0					0				0	0
Case 46							0					0				0	0
Case 47							0					0				0	0
Case 48							0					0				0	0
Case 49							0					0				0	0
Case 50							0					0				0	0
Case 51							0					0				0	0
Case 52							0					0				0	0
Case 53							0					0				0	0
Case 54							0					0				0	0
Case 55							0					0				0	0
Case 56							0					0				0	0
Case 57							0					0				0	0
Case 58							0					0				0	0
	0	0	0	1	1	0		0	0	1	0		0	0	0		
	All Dmgd / Unsrvcbl evnts=						2	All Inpprprat evnts=				1	All Uncrtfd =			0	
				TOTAL EQUIPMENT EVENTS FOR ALL CASES													3

Appendix F
Specific Failure analysis of 58 maintenance- related helicopter safety occurrences (Continued)

HFACS-ME	FIRST ORDER FACTORS	WORKING CONDITIONS (Continued)																	
	SECOND ORDER WORKSPACE																	Each	Each
	Confining					Obstructed						Inaccessible						Case	Case
	SPECIFIC FAILURES (141 TO 154)																	Workspace	Working Cond.
	141	142	143	144	Sum	145	146	147	148	149	Sum	150	151	152	153	154	Sum	Sum	Sum
Case 1		1			1			1			1		1				1	3	4
Case 2					0						0						0	0	1
Case 3					0						0						0	0	0
Case 4					0						0						0	0	0
Case 5					0						0						0	0	0
Case 6					0						0						0	0	0
Case 7					0						0						0	0	0
Case 8					0						0						0	0	0
Case 9	1				1						0						0	1	1
Case 10					0						0						0	0	0
Case 11					0					1	1						0	1	1
Case 12					0						0						0	0	0
Case 13					0						0						0	0	0
Case 14					0						0						0	0	0
Case 15					0						0						0	0	0
Case 16					0						0						0	0	2
Case 17					0						0						0	0	0
Case 18					0						0						0	0	0
Case 19					0						0						0	0	0
Case 20					0		1				1						0	1	1
Case 21					0			1			1						0	1	3
Case 22					0						0						0	0	0
Case 23					0						0						0	0	0
Case 24					0						0						0	0	1
Case 25					0						0						0	0	0
Case 26					0						0						0	0	0
Case 27					0						0						0	0	0
Case 28					0						0						0	0	0
Case 29					0						0						0	0	0
Case 30					0						0					1	1	1	1
Case 31					0						0						0	0	0
Case 32					0						0						0	0	0
Case 33					0						0						0	0	0
Case 34					0						0						0	0	0
Case 35					0		1				1				1		1	2	2
Case 36					0						0						0	0	0
Case 37					0						0						0	0	0
Case 38					0						0						0	0	0
Case 39					0		2	2			4						0	4	5
Case 40					0				1		1						0	1	1
Case 41					0						0						0	0	0
Case 42					0						0						0	0	0
Case 43					0						0						0	0	0
Case 44					0						0						0	0	0
Case 45					0		1				1						0	1	1
Case 46					0						0						0	0	0
Case 47					0		1				1						0	1	1
Case 48					0						0						0	0	0
Case 49					0						0						0	0	0
Case 50					0						0						0	0	0
Case 51					0						0						0	0	0
Case 52					0						0						0	0	0
Case 53					0						0						0	0	0
Case 54					0						0						0	0	0
Case 55					0						0						0	0	0
Case 56					0						0						0	0	0
Case 57					0						0						0	0	0
Case 58					0						0						0	0	0
	1	1	0	0		0	6	4	1	1		0	1	0	1	1			
	All Cnfining evnts=				2	All Obstrctd evnts=					12	All Inaccessbl evnts=					3		
	TOTAL WORKSPACE EVENTS FOR ALL CASES =																	17	
					TOTAL WORKING CONDITIONS EVENTS FOR ALL CASES =														25

Appendix F
Specific Failure analysis of 58 maintenance- related helicopter safety occurrences
(Continued)

HFACS-ME FIRST ORDER FACTORS MAINTAINERS' ACTS																									
	SECOND ORDER MAINTAINER ERRORS																								Each
	Attention/ Memory								Judg./Decision making						Knowledge				Skill/ Techniques						Case
	SPECIFIC FAILURES (155 TO 174)																								M. Error
	155	156	157	158	159	160	161	Sum	162	163	164	165	166	Sum	167	168	169	Sum	170	171	172	173	174	Sum	Sum
Case 1		2		2	1		1	6		1		1	1	3				0					2	2	11
Case 2					1			1						0				0			1			1	2
Case 3								0						0				0						0	0
Case 4								0						0				0						0	0
Case 5								0						0				0						0	0
Case 6							1	1						0				0						0	1
Case 7				1				1			1			1				0						0	2
Case 8								0						0				0						0	0
Case 9					1			1		1				1	1		1	2						0	4
Case 10								0			1			1			1	1					1	1	3
Case 11								0						0				0						0	0
Case 12								0						0				0			1			1	1
Case 13				2				2						0			1	1						0	3
Case 14								0						0				0						0	0
Case 15								0						0				0						0	0
Case 16	1		4	2				7						0				0						0	7
Case 17					1			1						0	2			2						0	3
Case 18								0						0	1			1						0	1
Case 19								0			1			1				0						0	1
Case 20								0						0				0						0	0
Case 21		2	3	1		1		7		1		1	2	4				0						0	11
Case 22				1				1						0				0			2	1		3	4
Case 23				1				1						0				0						0	1
Case 24				1	1			2						0				0						0	2
Case 25				1				1						0				0				1		1	2
Case 26				1				1						0	1			1						0	2
Case 27								0						0				0						0	0
Case 28								0				1		1				0				1		1	2
Case 29				2				2						0				0				1	1	2	4
Case 30	1	1		1				3		1	1	1		3		1	1	2			3	1	2	6	14
Case 31								0					1	1	1			1			2			2	4
Case 32					1			1						0				0					1	1	2
Case 33					2			2						0				0				1		1	3
Case 34								0		1		1		2				0						0	2
Case 35								0						0	1		1	2				2		2	4
Case 36					1			1						0				0					1	1	2
Case 37								0						0			1	1					1	1	2
Case 38								0						0				0						0	0
Case 39				1				1						0				0						0	1
Case 40				1				1						0			1	1			2			2	4
Case 41								0						0	1			1			1	1		2	3
Case 42								0						0				0						0	0
Case 43		1		1				2			1			1				0						0	3
Case 44								0						0				0						0	0
Case 45								0		1				1				0			2	1		3	4
Case 46								0		1				1				0						0	1
Case 47								0						0		1		1						0	1
Case 48					1			1						0				0					1	1	2
Case 49					1			1						0				0					1	1	2
Case 50					1			1						0				0						0	1
Case 51								0						0	1	1		2			1	1	1	3	5
Case 52								0						0				0						0	0
Case 53		1		1				2						0		1		1						0	3
Case 54								0						0		1		1			1	1		2	3
Case 55		1					1	2						0				0						0	2
Case 56				1				1						0	1			1						0	2
Case 57							1	1					1	1				0			1	1		2	4
Case 58								0					1	1	1			1			1		1	2	4
	2	8	7	21	12	1	4		0	7	5	5	6		11	5	7		0	0	18	13	13		
	All Attention/ Memory events =							55	All Judg/ Dcision events=					23	All Knldg evnt=			23	All Skll/Techng. evnts=					44	
					TOTAL MAINTAINER ERRORS EVENTS FOR ALL CASES =																				145

Appendix F
Specific Failure analysis of 58 maintenance- related helicopter safety occurrences
(Continued)

HFACS-ME FIRST ORDER FACTORS MAINTAINERS' ACTS (Continued)																													
	SECOND ORDER MAINTAINER VIOLATIONS																											Each	Each
	Routine/ norm							Infraction						Exceptional							Flagrant							Case	Case
	SPECIFIC FAILURES (175 TO 197)																											Violat.	M. Acts
	175	176	177	178	179	180	181	Sum	182	183	184	185	186	Sum	187	188	189	190	191	192	Sum	193	194	195	196	197	Sum	Sum	Sum
Case 1								0						0		2					2						0	2	13
Case 2		1						1						0							0						0	1	3
Case 3								0					1	1						1	1						0	2	2
Case 4								0						0							0						0	0	0
Case 5								0						0							0						0	0	0
Case 6								0						0							0						0	0	1
Case 7						2		2						0							0						0	2	4
Case 8								0						0							0						0	0	0
Case 9								0						0							0						0	0	4
Case 10								0						0							0						0	0	3
Case 11		1						1						0							0						0	1	1
Case 12		1						1					1	1							0						0	2	3
Case 13		1						1						0							0						0	1	4
Case 14								0						0							0						0	0	0
Case 15								0						0							0						0	0	0
Case 16								0						0					1		1						0	1	8
Case 17	1	2						3			1			1							0						0	4	7
Case 18								0						0						1	1						0	1	2
Case 19						1		1						0							0						0	1	2
Case 20		1						1						0							0		1		1		2	3	3
Case 21								0						0					1		1						0	1	12
Case 22		1				1		2						0							0						0	2	6
Case 23		1					1	2						0							0						0	2	3
Case 24								0						0							0						0	0	2
Case 25								0						0							0						0	0	2
Case 26								0						0							0						0	0	2
Case 27							1	1						0							0						0	1	1
Case 28								0						0							0						0	0	2
Case 29								0						0							0						0	0	4
Case 30		1			1			2				2		2	1	1			1		3						0	7	21
Case 31		2						2			1			1							0						0	3	7
Case 32								0						0							0						0	0	2
Case 33								0						0							0						0	0	3
Case 34		1						1		1				1							0						0	2	4
Case 35		1						1						0							0						0	1	5
Case 36								0						0							0						0	0	2
Case 37					1			1						0					1		1						0	2	4
Case 38								0						0							0						0	0	0
Case 39								0						0							0						0	0	1
Case 40								0				1		1							0						0	1	5
Case 41								0						0							0						0	0	3
Case 42								0						0							0						0	0	0
Case 43							1	1						0							0						0	1	4
Case 44								0					1	1							0						0	1	1
Case 45								0						0							0						0	0	4
Case 46								0						0							0						0	0	1
Case 47							1	1						0							0						0	1	2
Case 48								0						0							0						0	0	2
Case 49								0						0							0						0	0	2
Case 50								0						0							0						0	0	1
Case 51								0						0							0						0	0	5
Case 52								0						0							0						0	0	0
Case 53								0						0							0						0	0	3
Case 54								0					1	1							0						0	1	4
Case 55						1		1						0							0						0	1	3
Case 56								0						0							0				1		1	1	3
Case 57								0						0							0						0	0	4
Case 58								0						0							0						0	0	4
	1	14	0	0	2	5	4		0	1	2	3	4		1	3	0	0	4	2		0	1	0	2	0			
	All Routine / Norm events =							26	All Infrction evnts=					10	All Exceptional events=						10	All Flagrant events =					3		
					TOTAL MAINTAINER VIOLATIONS EVENTS FOR ALL CASES =																							49	
											TOTAL MAINTAINER ACTS FOR ALL CASES =																		194

Appendix G
HFACE-ME 3rd Order analysis of 58 maintenance- related helicopter safety occurrences

	MANAGEMENT CONDITIONS							
	Organizational conditions				Supervisory conditions			
	A1	A2	A3	A4	A5	A6	A7	A8
	Processes	Documents	Design	Resources	Operations	Supervision	Problems	Misconduct
Case 1	1	1	0	1	0	1	1	1
Case 2	1	1	1	0	0	0	0	0
Case 3	0	0	0	0	0	0	0	0
Case 4	1	0	0	0	0	0	0	0
Case 5	1	1	0	0	0	0	0	0
Case 6	1	1	0	0	0	1	0	0
Case 7	0	0	0	0	0	1	0	0
Case 8	0	1	1	0	0	0	0	0
Case 9	0	1	0	0	1	1	0	0
Case 10	0	1	0	0	0	0	0	0
Case 11	1	0	1	0	0	0	0	0
Case 12	1	0	0	0	0	0	0	0
Case 13	0	0	0	0	0	1	0	0
Case 14	1	0	1	0	0	0	0	0
Case 15	0	1	1	0	0	0	0	0
Case 16	0	0	0	1	1	0	0	0
Case 17	1	1	1	0	0	0	0	0
Case 18	1	0	0	1	0	0	0	0
Case 19	1	1	0	0	0	0	0	0
Case 20	1	1	0	1	0	0	0	0
Case 21	1	0	0	0	0	0	0	1
Case 22	0	0	0	0	0	1	0	0
Case 23	0	0	1	0	0	0	0	0
Case 24	1	1	1	0	0	1	0	0
Case 25	0	1	0	0	0	0	0	0
Case 26	1	1	1	0	1	0	1	0
Case 27	1	0	0	0	0	1	0	0
Case 28	0	0	1	0	0	0	0	0
Case 29	0	0	0	0	0	1	0	0
Case 30	1	1	1	1	0	0	1	1
Case 31	1	2	0	1	0	0	0	0
Case 32	0	0	1	0	0	0	0	0
Case 33	1	1	1	0	0	0	0	0
Case 34	1	0	0	0	0	0	0	0
Case 35	0	1	1	0	0	0	1	0
Case 36	1	1	0	0	0	0	0	0
Case 37	1	1	0	0	0	1	0	0
Case 38	1	0	0	0	0	0	0	0
Case 39	1	1	1	1	0	0	1	0
Case 40	0	0	0	0	0	0	0	0
Case 41	1	1	1	0	0	0	0	0
Case 42	1	0	1	0	0	0	0	0
Case 43	1	1	0	0	0	0	0	0
Case 44	0	1	1	0	0	0	0	0
Case 45	1	0	0	0	0	0	0	0
Case 46	1	0	1	0	0	0	0	0
Case 47	1	0	0	0	0	1	0	0
Case 48	0	1	1	0	0	1	0	0
Case 49	0	1	0	0	0	0	0	0
Case 50	1	0	1	0	0	1	0	0
Case 51	1	1	0	0	0	0	1	0
Case 52	1	0	0	0	0	0	0	0
Case 53	1	1	0	0	0	1	0	0
Case 54	1	1	0	0	0	0	0	0
Case 55	1	1	0	0	0	0	0	0
Case 56	0	0	0	1	0	1	0	1
Case 57	0	0	0	0	0	0	0	0
Case 58	0	0	0	0	0	0	0	0
	36	31	21	8	3	15	6	4
	Organizational conditions =			96	Supervisory conditions =			28
		Total Management Conditions Failure Enteries =					124	

Appendix G
HFACE-ME 3rd Order analysis of 58 maintenance- related helicopter safety occurrences (Continued)

	MAINTAINER CONDITIONS								
	Medical conditions			Crew coordination			Readiness		
	A9	A10	A11	A12	A13	A14	A15	A16	A17
	Mental	Physical	Limitations	Communicat	Assertivens	Adapt/ Flexi	Train/ Prepar	Certification	Infrigment
Case 1	0	0	0	0	0	0	0	0	0
Case 2	0	0	0	0	0	0	0	0	0
Case 3	0	0	0	0	0	0	0	0	0
Case 4	0	0	0	0	0	0	0	0	0
Case 5	0	0	0	0	0	0	0	0	0
Case 6	0	0	0	0	0	0	0	0	0
Case 7	0	0	0	0	0	0	0	0	0
Case 8	0	0	0	0	0	0	0	0	1
Case 9	0	0	0	0	0	0	0	0	0
Case 10	0	0	0	0	0	0	0	0	0
Case 11	0	0	0	0	0	0	0	0	0
Case 12	0	0	0	0	0	0	0	0	0
Case 13	0	0	0	0	0	0	0	0	0
Case 14	0	0	0	0	0	0	0	0	0
Case 15	0	0	0	0	0	0	0	0	0
Case 16	1	0	0	1	0	0	0	0	1
Case 17	0	0	0	0	0	0	0	0	0
Case 18	0	0	0	0	0	0	0	0	0
Case 19	0	0	0	0	0	0	0	0	0
Case 20	0	0	0	0	0	0	0	0	0
Case 21	0	0	0	1	0	1	0	1	1
Case 22	0	0	0	0	0	0	0	0	0
Case 23	0	0	0	0	0	0	0	0	0
Case 24	0	0	0	0	0	0	0	0	0
Case 25	0	0	0	0	0	0	0	0	0
Case 26	1	0	0	0	0	0	0	0	0
Case 27	0	0	0	0	0	0	0	0	0
Case 28	0	0	0	0	0	0	0	0	0
Case 29	0	0	0	0	0	0	0	0	0
Case 30	0	0	0	1	0	0	1	0	0
Case 31	0	0	0	0	0	0	1	0	0
Case 32	0	0	0	0	0	0	0	0	0
Case 33	0	0	0	0	0	0	0	0	0
Case 34	0	0	0	0	0	0	0	0	1
Case 35	0	0	0	0	0	0	0	0	0
Case 36	0	0	0	0	0	0	0	0	0
Case 37	0	0	0	0	0	0	1	0	0
Case 38	0	0	0	0	0	0	0	0	0
Case 39	0	0	0	0	0	0	0	0	0
Case 40	0	0	0	0	0	0	0	0	0
Case 41	0	0	0	0	0	0	0	0	0
Case 42	0	0	0	0	0	0	0	0	0
Case 43	0	0	0	0	0	0	0	0	0
Case 44	0	0	0	0	0	0	0	0	0
Case 45	0	0	0	0	0	0	0	0	0
Case 46	0	0	0	0	0	0	0	0	0
Case 47	0	0	0	0	0	0	0	0	0
Case 48	0	0	0	0	0	0	0	0	0
Case 49	0	0	0	0	0	0	0	0	0
Case 50	0	0	0	0	0	0	0	0	0
Case 51	0	0	0	0	0	0	0	0	0
Case 52	0	0	0	0	0	0	0	0	0
Case 53	0	0	0	0	0	0	0	0	0
Case 54	0	0	0	0	0	0	0	0	0
Case 55	1	0	0	0	0	0	0	0	0
Case 56	0	0	0	0	0	0	1	1	0
Case 57	0	0	0	0	0	0	1	1	0
Case 58	0	0	0	0	0	0	0	0	0
	3	0	0	3	0	1	5	3	4
	Medical conditions =		3	Crew coordination =		4	Readiness =		12
		Total Maintainer Conditions Failure Enteries =						19	

Appendix G
HFACE-ME 3rd Order analysis of 58 maintenance- related helicopter safety occurrences (Continued)

	WORKING CONDITIONS								
	Environment			Equipment			Workspace		
	A18	A19	A20	A21	A22	A23	A24	A25	A26
	Lighting	Weather	Hazards	Damaged/us	Unavailable	Uncertified	Confining	Obstructed	Inaccessible
Case 1	1	0	0	0	0	0	1	1	1
Case 2	0	0	0	0	0	0	0	0	0
Case 3	0	0	0	0	0	0	0	0	0
Case 4	0	0	0	0	0	0	0	0	0
Case 5	0	0	0	0	0	0	0	0	0
Case 6	0	0	0	0	0	0	0	0	0
Case 7	0	0	0	0	0	0	0	0	0
Case 8	0	0	0	0	0	0	0	0	0
Case 9	0	0	0	0	0	0	1	0	0
Case 10	0	0	0	0	0	0	0	0	0
Case 11	0	0	0	0	0	0	0	1	0
Case 12	0	0	0	0	0	0	0	0	0
Case 13	0	0	0	0	0	0	0	0	0
Case 14	0	0	0	0	0	0	0	0	0
Case 15	0	0	0	0	0	0	0	0	0
Case 16	1	1	0	0	0	0	0	0	0
Case 17	0	0	0	0	0	0	0	0	0
Case 18	0	0	0	0	0	0	0	0	0
Case 19	0	0	0	0	0	0	0	0	0
Case 20	0	0	0	0	0	0	0	1	0
Case 21	0	0	0	1	1	0	1	1	0
Case 22	0	0	0	0	0	0	0	0	0
Case 23	0	0	0	0	0	0	0	0	0
Case 24	1	0	0	0	0	0	0	0	0
Case 25	0	0	0	0	0	0	0	0	0
Case 26	0	0	0	0	0	0	0	0	0
Case 27	0	0	0	0	0	0	0	0	0
Case 28	0	0	0	0	0	0	0	0	0
Case 29	0	0	0	0	0	0	0	0	0
Case 30	0	0	0	0	0	0	0	0	1
Case 31	0	0	0	0	0	0	0	0	0
Case 32	0	0	0	0	0	0	0	0	0
Case 33	0	0	0	0	0	0	0	0	0
Case 34	0	0	0	0	0	0	0	0	0
Case 35	0	0	0	1	0	0	0	1	1
Case 36	0	0	0	0	0	0	0	0	0
Case 37	0	0	0	0	0	0	0	0	0
Case 38	0	0	0	0	0	0	0	0	0
Case 39	0	1	0	0	0	0	0	1	0
Case 40	0	0	0	0	0	0	0	1	0
Case 41	0	0	0	0	0	0	0	0	0
Case 42	0	0	0	0	0	0	0	0	0
Case 43	0	0	0	0	0	0	0	0	0
Case 44	0	0	0	0	0	0	0	0	0
Case 45	0	0	0	0	0	0	0	1	0
Case 46	0	0	0	0	0	0	0	0	0
Case 47	0	0	0	0	0	0	0	1	0
Case 48	0	0	0	0	0	0	0	0	0
Case 49	0	0	0	0	0	0	0	0	0
Case 50	0	0	0	0	0	0	0	0	0
Case 51	0	0	0	0	0	0	0	0	0
Case 52	0	0	0	0	0	0	0	0	0
Case 53	0	0	0	0	0	0	0	0	0
Case 54	0	0	0	0	0	0	0	0	0
Case 55	0	0	0	0	0	0	0	0	0
Case 56	0	0	0	0	0	0	0	0	0
Case 57	0	0	0	0	0	0	0	0	0
Case 58	0	0	0	0	0	0	0	0	0
	3	2	0	2	1	0	3	9	3
	Environment =		5	Equipment =		3	Workspace =		15
		Total Working Conditions Failure Enteries =						23	

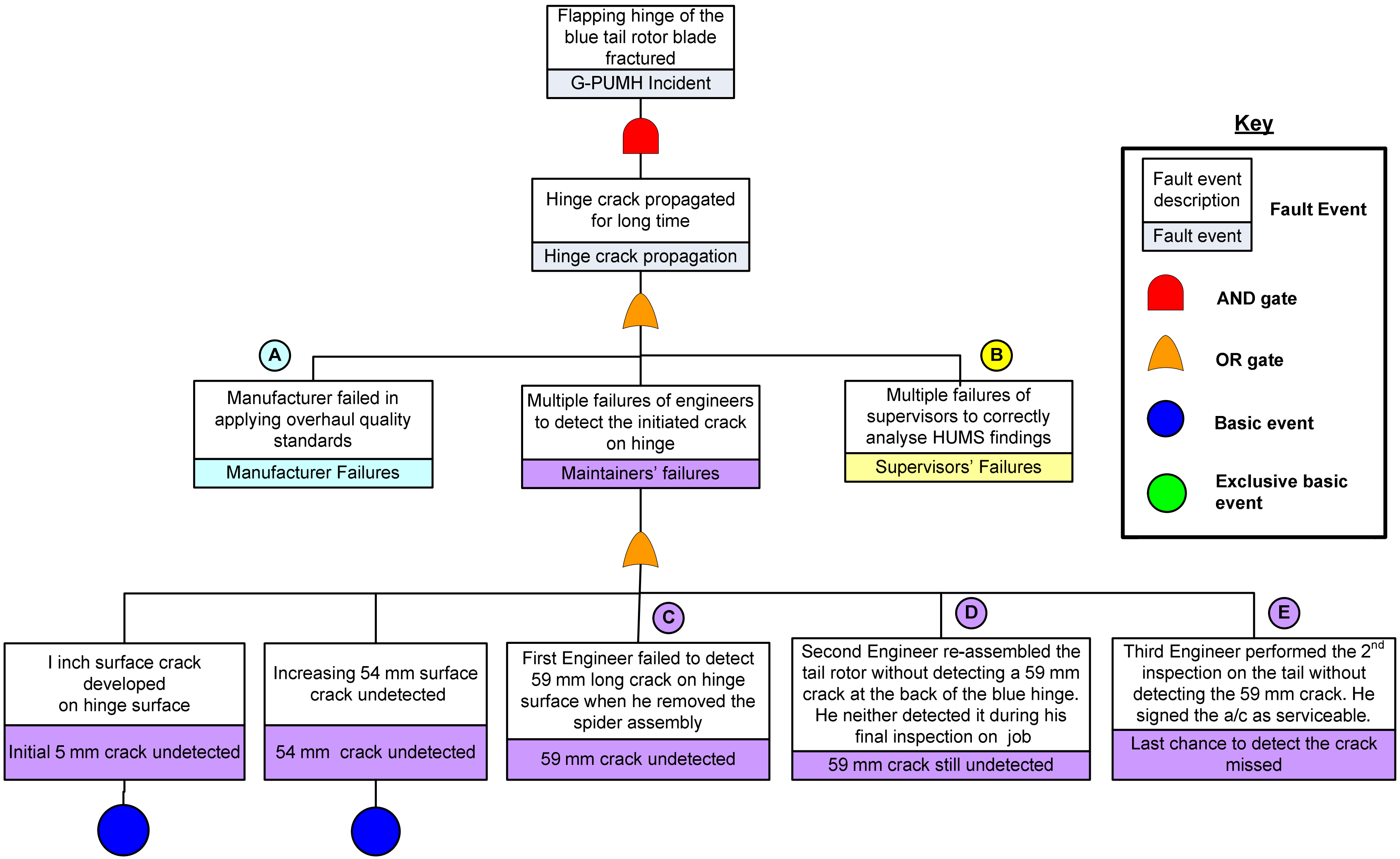
Appendix G

HFACE-ME 3rd Order analysis of 58 maintenance- related helicopter safety occurrences (Continued)

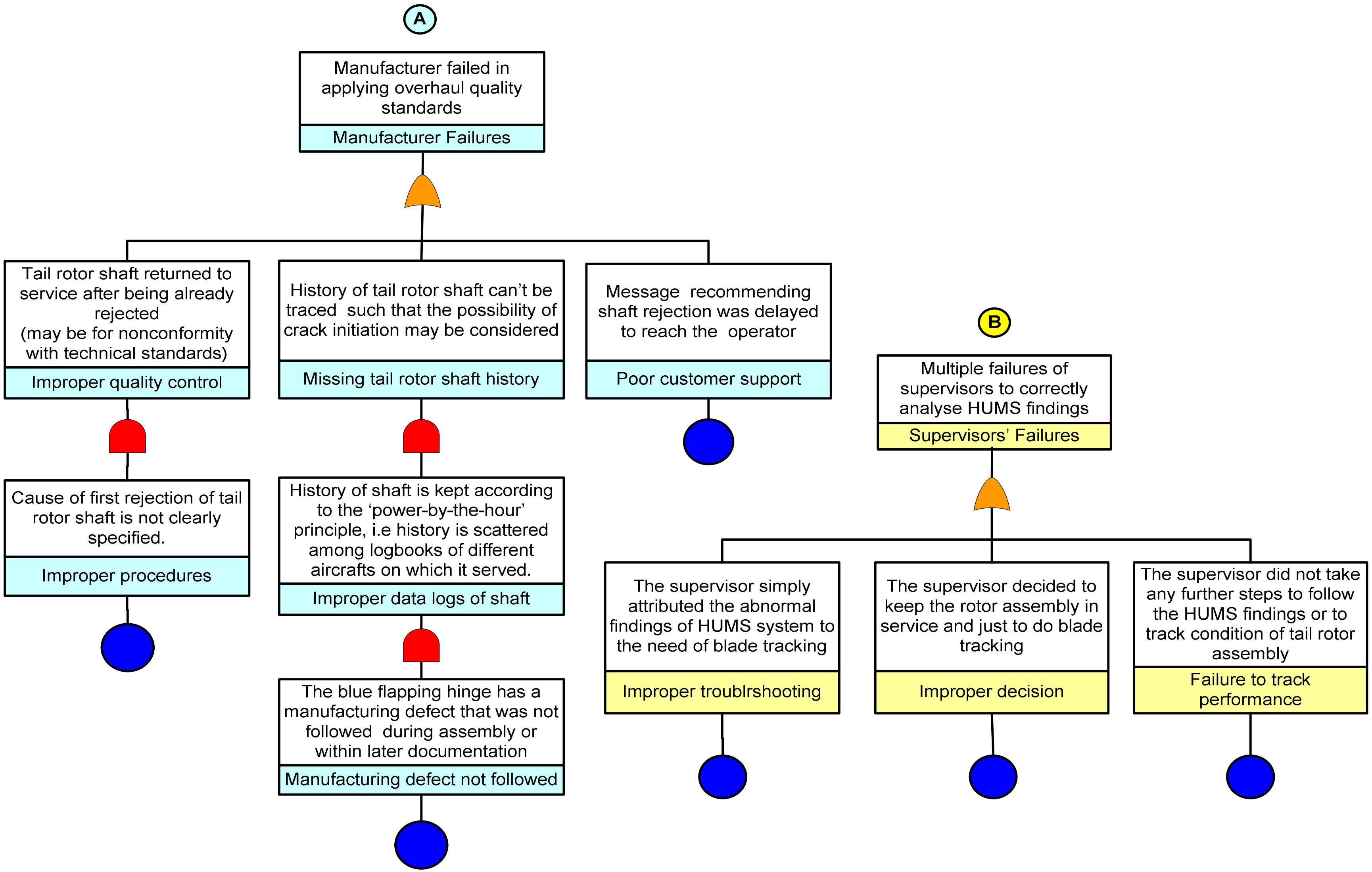
	MAINTAINER ACTS							
	Error				Violation			
	A27	A28	A29	A30	A31	A32	A33	A34
	Atntion/Mem	Judg/Decisn	Knowledge	Skill/ Technq	Routin/Norm	Infraction	Exceptional	Flagrant
Case 1	1	1	0	1	0	0	0	0
Case 2	1	0	0	1	0	0	0	0
Case 3	0	0	0	0	0	1	1	0
Case 4	0	0	0	0	0	0	0	0
Case 5	0	0	0	0	0	0	0	0
Case 6	1	0	0	0	0	0	0	0
Case 7	1	1	0	0	1	0	0	0
Case 8	0	0	0	0	0	0	0	0
Case 9	1	1	1	0	0	0	0	0
Case 10	0	1	1	0	1	0	0	0
Case 11	0	0	0	0	1	0	0	0
Case 12	0	0	0	1	1	1	0	0
Case 13	1	0	1	0	1	0	0	0
Case 14	0	0	0	0	0	0	0	0
Case 15	0	0	0	0	0	0	0	0
Case 16	1	0	0	0	0	0	1	0
Case 17	1	0	1	0	1	1	0	0
Case 18	0	0	1	0	0	0	1	0
Case 19	0	1	0	0	1	0	0	0
Case 20	0	0	0	0	1	0	0	1
Case 21	1	1	0	0	0	0	1	0
Case 22	1	0	0	1	1	0	0	0
Case 23	1	0	0	0	1	0	0	0
Case 24	1	0	0	0	0	0	0	0
Case 25	1	0	0	1	0	0	0	0
Case 26	1	0	1	0	0	0	0	0
Case 27	0	0	0	0	1	0	0	0
Case 28	0	1	0	1	0	0	0	0
Case 29	1	0	0	1	0	0	0	0
Case 30	1	1	1	1	1	1	1	0
Case 31	0	1	1	1	1	1	0	0
Case 32	1	0	0	1	0	0	0	0
Case 33	1	0	0	1	0	0	0	0
Case 34	0	0	0	0	1	2	0	0
Case 35	0	0	1	1	0	0	0	0
Case 36	1	0	0	1	0	0	0	0
Case 37	0	0	0	1	1	0	1	0
Case 38	0	0	0	0	0	0	0	0
Case 39	1	0	0	0	0	0	0	0
Case 40	1	0	1	1	0	1	0	0
Case 41	0	0	1	1	0	0	0	0
Case 42	0	0	0	0	0	0	0	0
Case 43	1	1	0	0	1	0	0	0
Case 44	0	0	0	0	0	1	0	0
Case 45	0	1	0	1	0	0	0	0
Case 46	0	1	0	0	0	0	0	0
Case 47	0	0	1	0	1	0	0	0
Case 48	1	0	0	1	0	0	0	0
Case 49	0	0	0	0	0	0	0	0
Case 50	1	0	0	0	0	0	0	0
Case 51	0	0	1	1	0	0	0	0
Case 52	0	0	0	0	0	0	0	0
Case 53	1	0	1	0	0	0	0	0
Case 54	0	0	1	1	0	1	0	0
Case 55	1	0	0	0	0	0	0	0
Case 56	1	0	1	0	0	0	0	1
Case 57	1	0	0	1	0	0	0	0
Case 58	0	1	0	1	0	0	0	0
	28	13	16	22	17	10	6	2
	Maintainer Errors =			79	Maintainer Violations =			35
		Total maintainer Acts Failure Enteries =					114	

Total Failure Enteries for the whole 58 accidents/ incidents =	**280**

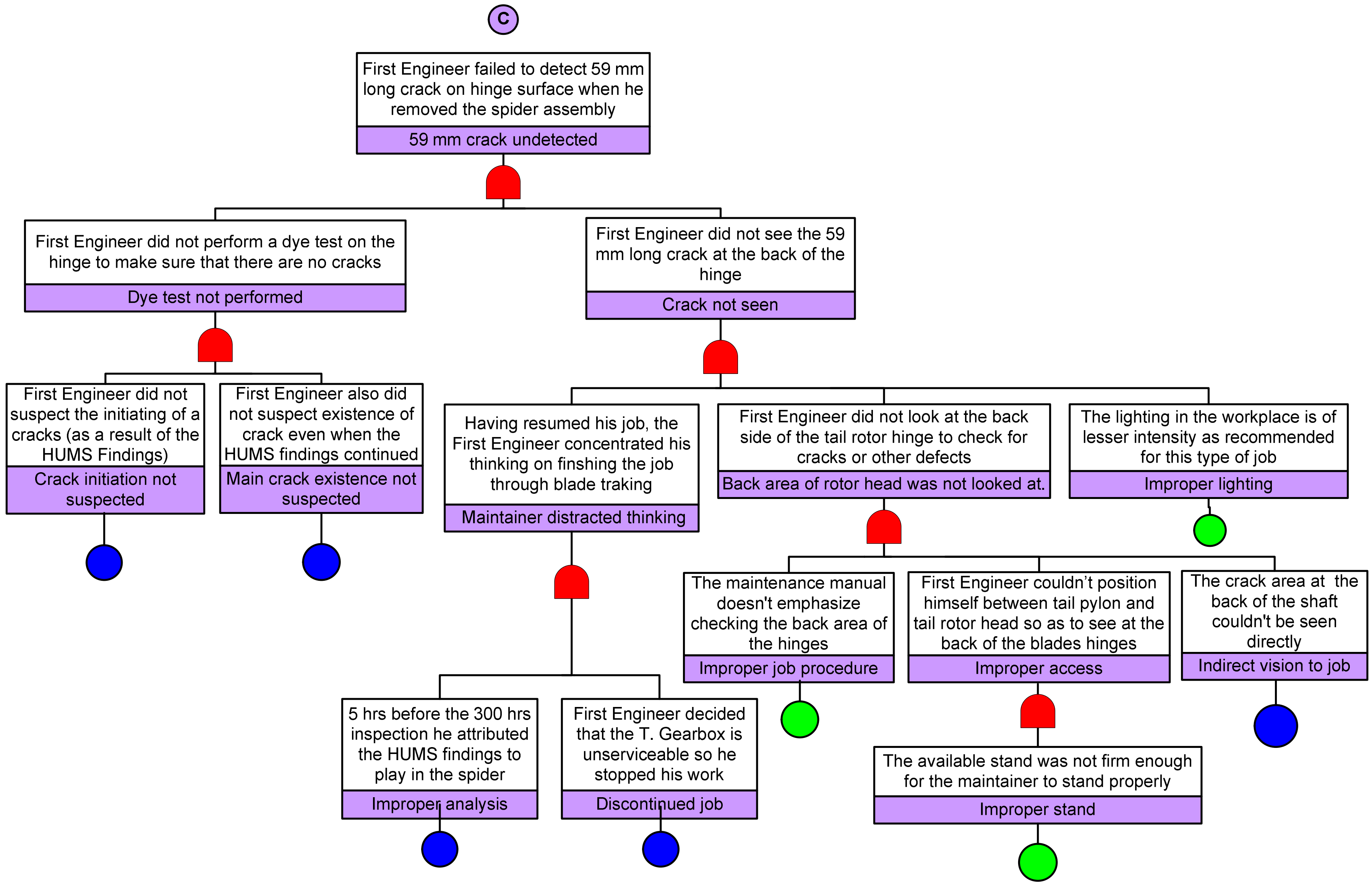
Appendix H
Fault Tree Diagram of Puma G-PUMH Helicopter Accident over the North Sea



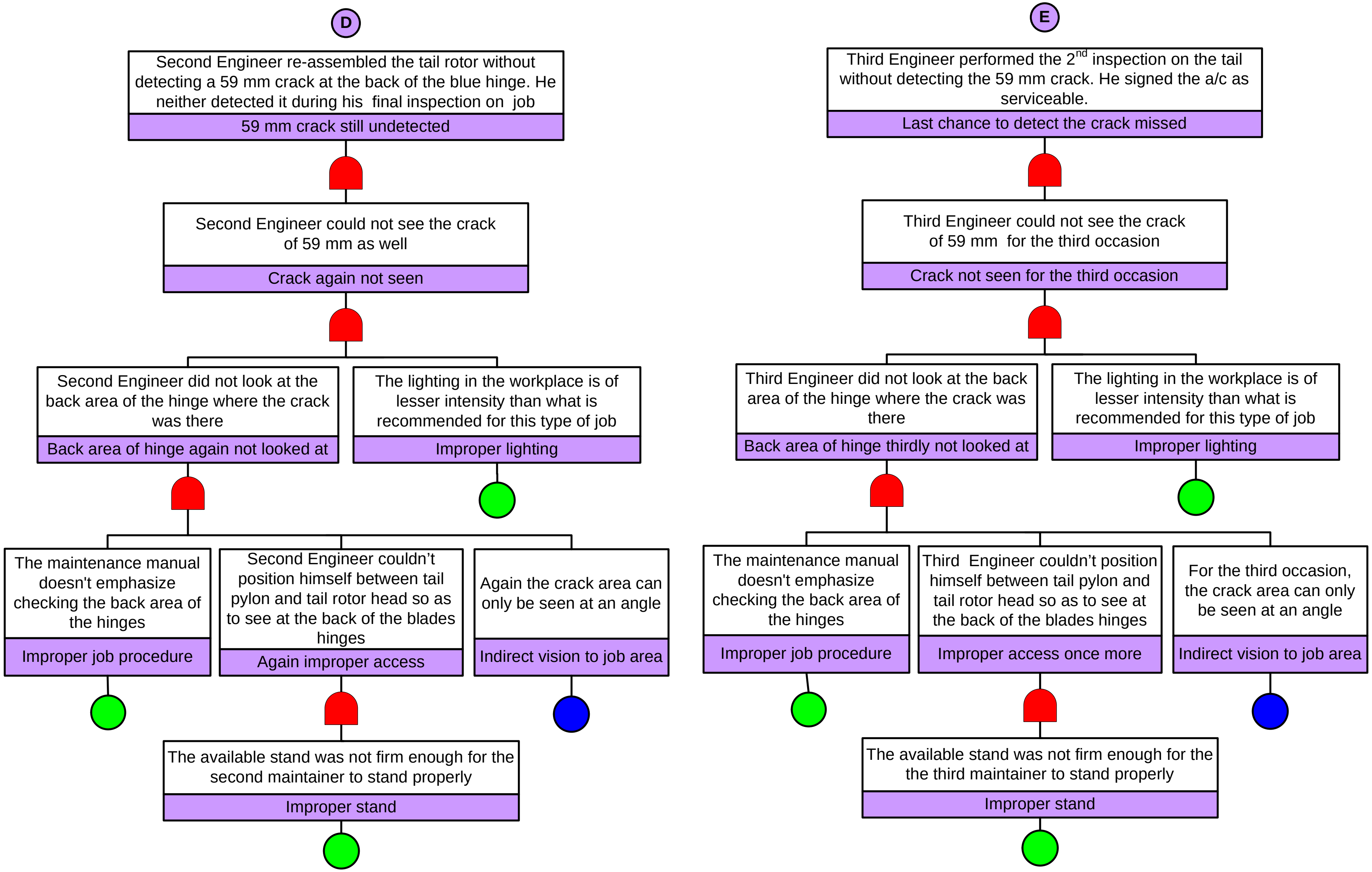
Appendix H Fault Tree Diagram of Puma G-PUMH Helicopter Accident over the North Sea (Continued)



Appendix H Fault Tree Diagram of Puma G-PUMH Helicopter Accident over the North Sea (Continued)



Appendix H Fault Tree Diagram of Puma G-PUMH Helicopter Accident over the North Sea (Continued)



Appendix I Specific Failures for the analysed 58 helicopter safety occurrences

Specific Failures	Frequency
1. Fail to enforce regulations	12
2. Fail to provide oversight	16
3. Fail to track performance	14
4. Inadequate guidance	6
5. Poor planning	9
6. Task complex/ confusion	5
7. Procedures incomplete	7
8. Non existing procedures	19
9. No/ poor documentation	19
10 .Documents not updated	18
11. Alerts/ Service B. not provided	1
12. Documents/ CD's unusable	1
13. Conflicting information	9
14. Insufficient information	1
15. Documents not understandable	2
16. Practical step(s) omission	10
17. Information not available	25
18. Procedure sequence	1
19. Delayed informing response	1
20. Purchasing failure	1
21. Deficiency not corrected	4
22. Modified equipment	1
23. Unserviceable/ deformed component	2
24. Design error	6
25. Poor layout/ Configuration	10
26. Poor/ no accessibility	0
27. Easy to be incorrectly installed	6
28. Organizational Improper manning	2
29. Lack/ constrains of funding	0

Specific Failures	Frequency
30. Lack of parts/ equipment	5
31. Inadequate facilities/ materials	3
32. Insufficient operational resources	0
33. Inadequate brief times	0
34. Supervisory improper manning	1
35. Inadequate schedule	0
36. Improper task prioritization	0
37. Non useful information	0
38. Unrealistic expectations	2
39. Failure to provide guidance	0
40. Failure to provide oversight	0
41. Failure to provide training	0
42. Failure to track performance	2
43. Failure to track qualifications	0
44. Failure to inspect	13
45. Task planning / organization	2
46. Task delegation / assignment	1
47. Amount of supervision	0
48. No corrective actions	4
49. Documents not updated	0
50. Unsafe condition not reported	1
51. Parts/ tools incorrectly labelled	0
52. Known hazards not controlled	2
53. Corrective action delayed	1
54. Ignoring risks	3
55. Failure to enforce rules/ SOP's	0
56. Use of unsafe equipment	0
57. Use of untrained personnel	0
58. Failure to follow rules/ SOP's	1

Appendix I Specific Failures for the analysed 58 helicopter safety occurrences (Continued)

Specific Failures	Frequency
59. Assigned unqualified worker	1
60. Complacency	0
61. Distracted	2
61. Mental fatigue	0
63. Life stress	2
64. Misplaced motivation	0
65. Task saturation	1
66. Canalized attention	0
67. Peer pressure vulnerability	0
68. General health	0
69. Medical illness	0
70. Physical fatigue	0
71. Circadian rhythm	0
72. Hearing limitations	0
73. Visual limitations	0
74. Insufficient reaction time	0
75. Incompatible aptitude	0
76. Physical capability/ strength	0
77. Physical reach/ size	0
78. Terms not standardized	0
79. Hand signal not standardized	0
80. Documentation/ log failure	0
81. Documentation delays	0
82. Equipment failure (radio)	0
83. Equipment use (light / whistle)	0
84. Inadequate brief / pass down	3
85. Inadequate shift turn-over	2
86. Maintainer new in group	0
87. Fail to brief / make suggestions	0

Specific Failures	Frequency
88. Fail to correct discrepancies	0
89. Fail to confirm messages	0
90. Inattention to feedback	0
91. Waiver when confronted	0
92. Peer pressure	0
93. Maintainer emergency response	0
94. Maintainer system failure response	0
95. Changes to routine	1
96. Different from similar tasks	0
97. Team member changes	0
98. Disregard of constraint	0
99. Not trained for task	2
100. Inadequate knowledge	0
101. Unrealistic training	0
102. Insufficient On Job Training	1
103. Inadequate skills	1
104. New for task	2
105. Not certified in task	1
106. Not certified in model	1
107. Qualification expired	0
108. Not licensed to operate	1
109. Intoxicated at work	0
110. Hung over	0
111. Inadequate rest	2
112. Drug / medicine use	0
113. Night shift/ work	2
114. Night visibility	0
115. Workspace illumination	2
116. Inadequate flashlights	0

Appendix I Specific Failures for the analysed 58 helicopter safety occurrences (Continued)

Specific Failures	Frequency
117. Inadequate natural light	1
118. Extreme temperatures	1
119. Ice on equipment/ precipitation	0
120. Visibility in rain/ snow / fog	0
121. Equipment / manning changes	0
122. Inadequate clothing	0
123. Wind	1
124. High noise level	0
125. House keeping/ cleanliness	0
126. Hazardous/ toxic substances	0
127. Trip/ fall hazards	0
128. Equipment is of limited usability	0
129. Equipment unusable(damaged/ sub serviced)	0
130. Equipment gauge/ calibration error	0
131. Unsafe equipment (brakes / electrical)	1
132. Unreliable / faulty equipment	1
133. inoperative / uncontrollable equipment	0
134. Equipment used elsewhere	0
135. Equipment not in inventory	0
136. Equipment unusable (inappropriate)	1
137. Power sources inadequate	0
138. Calibration expired	0
139. Open purchase / uncertified	0
140. Extended beyond service life	0
141. Insufficient workspace	1
142. Constrained position	1
143. Constrained equipment use	0
144. Insufficient manoeuvrability	0
145. Vision obstructed (fog / smoke)	0

Specific Failures	Frequency
146. Vision blocked (obstacles)	6
147. Not directly visible	4
148. Maintenance hindered	1
149. Not easily seen / detected	1
150. Inadequate aircraft design	0
151. Inadequate support equipment	1
152. workspace totally inaccessible	0
153. Workspace partially accessible	1
154. Workspace not directly accessible	1
155. Maintainer missed communication	2
156. Loss of situational awareness	8
157. Maintainer distracted / interrupted	7
158. Maintainer fail to recognise condition	21
159. Maintainer procedural mistakes	12
160. Maintainer sequence errors	1
161. Maintainer omitted procedural step	4
162. Maintainer exceeded ability	0
163. maintainer poor decision	7
164. Maintainer misjudgement /misperceived	5
165. Maintainer misdiagnosed situation	5
166. Maintainer improper procedures	6
167. Maintainer inadequate task knowledge	11
168. Maintainer inadequate process knowledge	5
169. Maintainer inadequate aircraft knowledge	7
170. Maintainer delayed response	0
171. Maintainer overuse of controls	0
172. Maintainer inadequate skills	18
173. Maintainer poor techniques	13
174. Maintainer improper cross check	13

Appendix I Specific Failures for the analysed 58 helicopter safety occurrences (Continued)

Specific Failures	Frequency
175. Maintainer did not follow brief	1
176. Maintainer bending of regulations/SOP's	14
177. Use of incorrect equipment (as norm)	0
178. Maintainer violated training rules	0
179. Maintainer doesn't utilize checklists	2
180. Maintainer skipped procedures	5
181. Use of incorrect parts/ materials	4
182. Maintainer violated single event to safe time	0
183. Maintainer violated to expedite mission	1
184. Use of incorrect equipment(isolated act)	2
185. Maintainer skip publication cross check	3
186. Use of incorrect parts / materials	4
187. Maintainer falsifying qualifications	1
188. Maintainer falsifying inspections	3
189. Maintainer not using required equipment	0
190. Maintainer violated under pressure	0
191. Maintainer signed off without inspection	4
192. Critical procedure skipped	2
193. Maintainer falsifying qualification (blatant)	0
194. Maintainer falsifying inspections (blatant)	1
195. Not using required equipment (blatant)	0
196. Maintainer other blatant violations	2
197. Maintainer thrill seeking	0

Appendix J
Maintenance Error Root Causes Existence Scale (RCES) – 870 Assessment Criteria – Design Practice (Excerpts)

Main Task		Sub Task		Assessment Criteria	
A	Preparation for maintenance	A-1	Task assignment / Responsibility allocation	1	Type of maintenance: scheduled / unscheduled
				2	Initial fault reports / critical readings, phenomena notes
				3	Task delegation / assignment : written, verbal
				4	Single maintainer / team work
				5	Single shift / multi-shift task
				6	Familiar task / first time task
				7	Time constraints / pressure
				8	Second opinion needed , expected, provided
				9	Task assignment overlaps / Non fixed responsibility
				10	Tasks conflicts / parallel multi- system maintenance

Main Task		Sub Task		Assessment Criteria	
A	Preparation for maintenance	A-2	Aircraft documents/ Task jobcards	1	Relative a/c manuals , CD's availability / usability
				2	Relative a/c manuals, CD's text clarity / meanings
				3	Illustrations/ Flowcharts/ Circuit diagrams/ Tables
				4	Service bulletins / A. Directives application / updating
				5	Maintenance procedures, steps sequence
				6	A/c logs updates / Maintenance history availability
				7	H & S monitoring data / Performance data records
				8	Current snags, faults clearly stated
				9	Specific job cards assigned
				10	Hand writing quality / Correct data entry

Appendix J
Maintenance Error Root Causes Existence Scale (RCES) – 870 Assessment Criteria – Design Practice (Excerpts) (Continued)

Main Task		Sub Task		Assessment Criteria	
A	Preparation for maintenance	A-3	Aircraft location / Orientation / Levelling	1	On station / off station / dig-out location
				2	In hangar / off hangar / In workshop / under shelter
				3	On runway / on taxi way / on tarmac / ground run area
				4	Floor: concrete / asphalt / rocky / dusty soil / mud
				5	Cleaning area / paint removing area / painting area
				6	Restricted zone / open area
				7	In-wind , side-wind, back-wind a/c orientation
				8	A/c levelled, inclined as required, not levelled
				9	Weather: temperature / wind / rain / ice / humidity
				10	Space suitability for functional tests

Main Task		Sub Task		Assessment Criteria	
A	Preparation for maintenance	A-4	Required Standard tools / Special tools	1	Specify, provide required standard tools
				2	Specify, provide required special tools
				3	Criteria, know how of using special tools
				4	Possibility to overlook , replace certain recommended tools
				5	Tool control standards application
				6	Possibility of snag carry-on due to lack of tools
				7	Tools quality / standardization
				8	Part(s) damage criticality if inappropriate tools are used
				9	Overall number of different tools needed for the given task
				10	Average number of cycles of using a single tool for this given task

Appendix J
Maintenance Error Root Causes Existence Scale (RCES) – 870 Assessment Criteria – Design Practice (Excerpts) (Continued)

Main Task		Sub Task		Assessment Criteria	
A	Preparation for maintenance	A-5	Required Equipment / Devices / Testers	1	Specify, provide required serviceable equipment, devices, testers
				2	Knowledge, skills required to use equipment, devices, testers
				3	Possibility to overlook , replace certain recommended equip, devices, .
				4	Number of individuals required to operate equip, devices, testers
				5	Possibility of snag carry-on due to lack of equip, devices, testers
				6	Equipment , devices, testers quality / standardization / calibration
				7	Part(s) damage criticality if inappropriate equip, devices, are used
				8	Overall number of different equip, devices needed for the given task
				9	Average number of cycles of using a equip, device for this given task
				10	Errors expected when using same equip, devices in various a/c types

Main Task		Sub Task		Assessment Criteria	
A	Preparation for maintenance	A-6	Workshops / Shelves / Parts Stands / Hoists	1	Specify, provide required workshop benches, fixtures
				2	Specify, provide appropriate stands, shelves for new / removed parts
				3	Provide appropriate hoisting, handling
				4	Standardized tag, label control for part(s)
				5	Standardized multi-shift interface with part(s) on shelves
				6	Criticality of not using required stands for larger part(s)
				7	Provide required air, water, multi-voltages lines and terminals
				8	Workplace gas/dust / paint stripping sucking, ventilation
				9	Workplace sealing
				10	Multi-workers handling, hoisting operations expected

Appendix J
Maintenance Error Root Causes Existence Scale (RCES) – 870 Assessment Criteria – Design Practice (Excerpts) (Continued)

Main Task		Sub Task		Assessment Criteria	
B	Maintenance preliminary steps	B-1	Identification of a/c targeted systems / parts	1	Target systems/ parts are identifiable using documented / verbal info.
				2	Target components are to be identified through trial and error checks
				3	Target components are to be identified using man senses e.g. visually.
				4	Target a/c components are single part(s)/ multi-component systems
				5	Target components are frequently / moderately / rarely maintained
				6	Interfering with target a/c parts will influence other parts / systems
				7	Time / efforts spent to identify the target parts, e.g. leaking points
				8	Possibility of snag carry-on if target part(s) are not identified
				9	Identification requires more than one maintainer working in parallel
				10	Difficult/ critical identification e.g. eng. temperature overshoot period

Main Task		Sub Task		Assessment Criteria	
B	Maintenance preliminary steps	B-2	Aircraft Jacking / Hoisting / Supports	1	Appropriate area for a/c (or a/c part) jacking, hoisting, support
				2	Possibility to carry maintenance without a/c jacking, hoisting, support
				3	A/c must be fully/ partially jacked, hoisted, supported
				4	Required a/c levelling, inclination during jacking, hoisting, supporting
				5	Use of dummy undercarriage / wheels, supports
				6	Number of maintainers to a/c jacking, hoisting
				7	Coordination, standard procedures during a/c jacking, hoisting
				8	Relevant safety measures in place
				9	Possibility of other parallel works to be done on jacked / hoisted a/c
				10	Length of time for the a/c to be on jacks/ hoist

Appendix J
Maintenance Error Root Causes Existence Scale (RCES) – 870 Assessment Criteria – Design Practice (Excerpts) (Continued)

Main Task		Sub Task		Assessment Criteria	
B	Maintenance preliminary steps	B-3	Required hydraulic/ pneumatic power facilities	1	Specify , provide required hydraulic / pneumatic power, air line
				2	Fluctuating / inappropriate hydraulic, pneumatic power supply
				3	Possibility of conducting maintenance without hydraulic / pneumatic power supply
				4	Criticality of snag carry on due to lack of hydraulic / pneumatic power supply
				5	hydraulic / pneumatic gauges/ indicators are accurate / clearly readable
				6	Influence of applying hydraulic / pneumatic power on other parallel maintenance
				7	Noise / vibration / heat produced by hydraulic / pneumatic generators
				8	Total number of co-workers required for this task utilising hydraulic / pneumatic
				9	Period of using hydraulic / pneumatic supply on a/c adjustments/ maintenance
				10	Efforts paid on hydraulic / pneumatic control rather than actual a/c maintenance

Main Task		Sub Task		Assessment Criteria	
B	Maintenance preliminary steps	B-4	Required electrical / radio / navigation maintenance facilities	1	Specify , provide required electrical / radio/ navigation maintenance devices
				2	Fluctuating / inappropriate electrical supply / radio, navigation testing signals
				3	Potentiality of conducting maintenance without electric, radio, navigation supplies
				4	Obligation to perform maintenance without 'snag carry on' due to lack of electric, ..
				5	Electric, radio, navigation gauges/ indicators are accurate / clearly readable
				6	Influence of applying electric, radio, navigation devices on other parallel maintenance.
				7	Noise / vibration / heat produced by electric, radio, navigation generators/ devices
				8	Number of co-workers required for this task utilising electric, radio, navigation devices..
				9	Period of using electric, radio, navigation devices on a/c adjustments/ maintenance.
				10	Efforts paid on electric, radio, navigation control rather than actual a/c maintenance.

Appendix J

Maintenance Error Root Causes Existence Scale (RCES) – 870 Assessment Criteria – Design Practice (Excerpts) (Continued)

Main Task		Sub Task		Assessment Criteria	
B	Maintenance preliminary steps	B-5	Needed liquids, lubricants, fuels, gases (llfg)	1	Specify, provide required llfg & their appropriate handling devices/ connectors
				2	Fluctuating, inappropriate llfg supplies / hoses, connectors
				3	Potentiality of ignoring llfg facilities and carry on maintenance without them
				4	Obligation to perform immediate maintenance . restriction to 'carry on snag'
				5	Gauges, meters, indicators are clearly readable
				6	Containers, cylinders , connectors are clearly identifiable,/can't be confused
				7	Llfg contamination, expire possibility during maintenance activity
				8	Number of cycles of maintenance using llfg devices
				9	Degree of difficulty, complexity of using llfg facilities during maintenance
				10	Number of co-workers required

Main Task		Sub Task		Assessment Criteria	
B	Maintenance preliminary steps	B-6	Getting position, using stands/ walkways	1	Influence of maintainer position on performing maintenance / inspection
				2	Potentiality to not using recommended stands, walkways, proper access points
				3	Impact of fixing stands, walkways on other parallel maintenance
				4	Difficulty of fixing/ moving stands, walkways as a motive to not using them
				5	Very confined spaces: difficult for personnel positioning /restricted movement
				6	Very confined spaces: need for additional light / additional ventilation
				7	Very confined spaces: difficulty to control lose items / 'on-the-way' items
				8	Very confined spaces: Influence of reduced ability to work there for long time
				9	Non direct positioning : need to use tool extensions, mirrors / single hand job
				10	Very high / remote/ hidden parts of a/c: impact on proper maintenance/ inspection

Appendix J
Maintenance Error Root Causes Existence Scale (RCES) – 870 Assessment Criteria – Design Practice (Excerpts) (Continued)

Main Task		Sub Task		Assessment Criteria	
B	Maintenance preliminary steps	B-7	Getting access: cowlings / covers/ access points (ccap)	1	Specify ccap required to be opened / removed to facilitate access to target areas
				2	Impact of ccap design (shape, weight) on the decision to / not to open, remove it
				3	Impact of ccap design (no of fasteners / screws) to be opened on that decision
				4	Potentiality of the task to be done / finalized without opening ccap as required
				5	Number of co-workers needed to open / support the required ccap
				6	Influence of opening ccap on other parallel maintenance
				7	Total efforts required to get access if compared with actual maintenance task
				8	Potentiality of opening the wrong ccap and its influence on required maintenance
				9	Applying required caution / attention / warning indicators to show removed ccap
				10	Recording opened ccap / removed covers

Main Task		Sub Task		Assessment Criteria	
B	Maintenance preliminary steps	B-8	Initial inspection/ observations/ measurements/ checks/ hand feel/ readings (ior)	1	Sensitivity of initial ior when done according to scheduled / non scheduled maintenance.
				2	Potentiality of error during visual inspection due to distance, orientation, light, ..
				3	Potentiality of error during gauge / indicators reading due to distance, light, …
				4	Potentiality of error during hand feel, noise level perception, cable tension sense .
				5	Potentiality of error during flight controls movements / resistance sensing
				6	Potentiality of error during initial identification of leak / vibration / smell sources
				7	Potentiality of misperception of pilot-reported snags
				8	Potentiality of error during initial diagnostic performance / functional tests
				9	Difficulty / complexity of performing initial checks
				10	Number of maintainers needed to perform initial checks

Appendix J
Maintenance Error Root Causes Existence Scale (RCES) – 870 Assessment Criteria – Design Practice (Excerpts) (Continued)

Main Task		Sub Task		Assessment Criteria	
C	Parts Removal / Paints, Sealants Stripping	C-1	Liquids/ gases discharge, power / signals on-off(dpo)	1	Importance/ influence of dpo on the given maintenance job
				2	Potentiality of skipping dpo due to location of/ access to relative parts, switches...
				3	Complexity of performing the dpo process. / or dpo involves readings, measures..
				4	Number of workers needed to perform the dpo
				5	Importance of tools or equipment needed
				6	Complexity of re-charging / power or signals re-set as cause to skip doing dpo
				7	Potentiality of discharging/ setting (off/ on) wrong systems or subsystems
				8	Potentiality of error if only partial dpo is required
				9	Influence of dpo on other parallel maintenance activities/ other trades tasks
				10	Time needed to perform dpo process. Number of units to be discharged…

Main Task		Sub Task		Assessment Criteria	
C	Parts Removal / Paints, Sealants Stripping	C-2	Removing the 'on-the-way' items (otw)	1	Potentiality of error during deciding minimum otw items to be removed
				2	Difficulty / complexity of removing otw items / number of nuts, screws, glue, …
				3	Total effort required to remove the otw items as motive to ignore removing them
				4	Obligation to remove otw items to facilitate performing main maintenance
				5	Potentiality of errors on other systems due to removing the otw items
				6	Potentiality of errors during removing otw items due to tools, space, positioning..
				7	Potentiality of removed otw items to be forgotten if not recorded / indicated
				8	Number of maintainers needed to remove otw items / multi-trade interference
				9	Potentiality of error when not using guiding marks /pre-adjustments records
				10	

Appendix J
Maintenance Error Root Causes Existence Scale (RCES) – 870 Assessment Criteria – Design Practice (Excerpts) (Continued)

Main Task		Sub Task		Assessment Criteria	
C	Parts Removal / Paints, Sealants Stripping	C-3	Removing targeted items (parts / cables / pipes / lines) (ti)	1	Potentiality of error during deciding minimum ti to be removed
				2	Difficulty / complexity of removing ti. / number of fasteners/ nuts / screws / glue
				3	Total effort required to remove ti as motive to ignore removing them if possible
				4	Obligation to remove ti to facilitate performing main maintenance
				5	Potentiality of errors on other systems due to removing the ti.
				6	Potentiality of errors during removing ti due to tools, space, positioning, design
				7	Potentiality of removed ti items to be forgotten if not recorded / indicated
				8	Number of maintainers needed to remove ti / multi-trade interference
				9	Potentiality of later errors if guiding marks / pre-adjustments records are not used
				10	

Main Task		Sub Task		Assessment Criteria	
C	Parts Removal / Paints, Sealants Stripping	C-4	Stripping paint / sealants (ps)	1	Potentiality of error during deciding minimum area of paint / seal to be stripped
				2	Difficulty / complexity of stripping ps / use of chemicals, physical means
				3	Total effort required to strip ps as motive to ignore stripping them if possible
				4	Obligation to strip ps to facilitate performing main maintenance
				5	Potentiality of errors on other systems, parts due to stripping the ps.
				6	Potentiality of errors during stripping ps due to tools, space, positioning, design
				7	Potentiality of stripped areas to be forgotten if not recorded / indicated
				8	Number of maintainers needed to do the stripping / multi-trade interference
				9	Potentiality of later errors due to stripping errors e.g surface scratched before NDI
				10	Potentiality of stripping errors if non-authorised chemicals, solvents are used

Appendix J
Maintenance Error Root Causes Existence Scale (RCES) – 870 Assessment Criteria – Design Practice (Excerpts) (Continued)

Main Task		Sub Task		Assessment Criteria	
C	Parts Removal / Paints, Sealants Stripping	C-5	Applying covers/ seals/ fixtures/ supports (csfs)	1	Potentiality to ignore applying csfs due to difficulty/ short maintenance time, …
				2	Potentiality to forget applying csfs due to remoteness/ hidden / smallness of parts
				3	Number of maintainers needed to apply csfs
				4	Possibility of error during selecting right type of csfs
				5	Total efforts required to apply csfs as motive to skip applying them
				6	Potentiality of applied csfs to be forgotten if not indicated or recorded
				7	Possibility of not applying csfs if not clearly stated in procedures
				8	Potentiality of the seal / cover to be sucked, dropped accidentally into the system
				9	Possibility of using non-authorised types of csfs
				10	Potentiality of affecting other systems / other parallel maintenance

Main Task		Sub Task		Assessment Criteria	
C	Parts Removal / Paints, Sealants Stripping	C-6	Applying red indicators / removed parts warnings (iw)	1	Potentiality to ignore applying iw due to difficulty/ short maintenance time, …
				2	Potentiality to forget applying iw due to remoteness/ hidden / smallness of parts
				3	Error when deciding if separate iw are needed in addition to (red) csfs
				4	Possibility of the applied iw to be loosened, dropped , wind-washed away
				5	Total efforts required to apply iw as motive to skip applying them
				6	Potentiality of applied iw to be forgotten if not recorded
				7	Possibility of not applying iw if not clearly stated in procedures
				8	Potentiality of the iw to be sucked, dropped accidentally into the system
				9	Possibility of using non-authorised types of iw
				10	Potentiality of affecting other systems / other parallel maintenance

Appendix J

Maintenance Error Root Causes Existence Scale (RCES) – 870 Assessment Criteria – Design Practice (Excerpts) (Continued)

Main Task		Sub Task		Assessment Criteria	
C	Parts Removal / Paints, Sealants Stripping	C-7	Apply shelf control / use bags, tags, labels (btl)	1	Potentiality to ignore using btl if number of removed items e.g nuts, bolts is small
				2	Potentiality to ignore using btl if expected time before re-installation is small
				3	Potentiality to issue bad quality btl if the target parts involve oily/greasy context
				4	Potentiality of ignoring btl in very confined, remote, high sections of the a/c
				5	Potentiality of not using btl when probability of parts inter-confusion is low
				6	Potentiality of not using btl if target parts are v. familiar (frequently maintained)
				7	Potentiality of leaving loose screws, bolts attached to removed cowlings/ parts
				8	Potentiality of not using proper shelf control if maintenance is done out of hanger
				9	Potentiality of ignoring btl if the target parts are to go immediately to other step
				10	Impact of task complexity/ length (multi-shift) in small parts/ btl confusion

Main Task		Sub Task		Assessment Criteria	
C	Parts Removal / Paints, Sealants Stripping	C-8	Recording removed / loosened /altered parts (rrl)	1	Potentiality of not recording v familiar frequently removed parts.
				2	Potentiality to forget recording if maintenance is to be performed off- hangar
				3	Potentiality to forget recording if a by side-part is only to be partially loosened
				4	Potentiality not to record removed item if only slight work is to be done on it
				5	Number of small removed parts as motive not to record all of them
				6	Potentiality not to record if there is no provision for reporting in the a/c log pages
				7	Local oily / greasy / compact context as a motive to delay then forget recording
				8	Mutual misunderstanding of who is to record if task is a team work job
				9	Potentiality of keeping 'only' voluntary personal notes if task is so complicated
				10	Tendency to ignore recording small removed items if not fully stated in procedure

Appendix K

Theory of Fuzzy Sets

Definitions:

A. Fuzzy set:

- Nahmias (1978) cited the definition of a fuzzy set, first given by Zadeh (1965), as: "A generalized characteristic function, that is, one which varies uniformly between zero and one rather than merely assuming the two values of zero and one. Intermediate values give grades of membership of various points in the set, higher values implying a higher grade of membership."
- Cox (1999) graphically defines a fuzzy set as: "A curve that encodes the imprecision or fuzziness associated with a phenomenon through its surface. The shape of the curve , in fact, represents the semantics of the actual concept." Graphically this can be illustrated in Figure 8.1.
- A more current definition of a fuzzy set is given by Mares (2006) as: " A mathematical model of vague qualitative or quantitative data, frequently generated by means of the natural language. The model is based on the generalization of the classical concepts of set and its characteristic function."

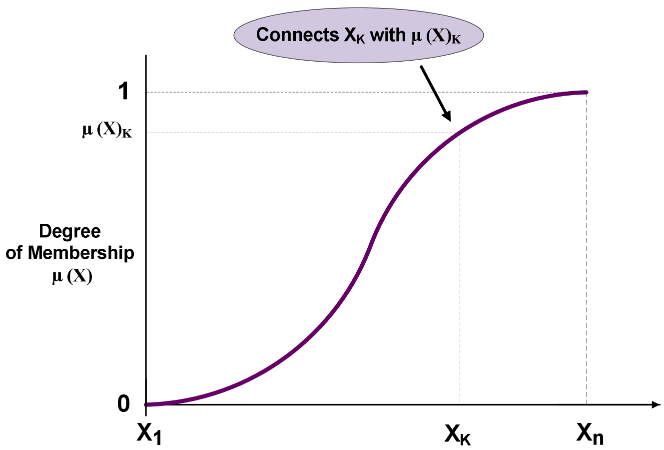


Figure 1 The structure of a fuzzy set (Cox 1999)

- "A fuzzy set is a class of objects with a continuum of grades of membership. Such a set is characterized by a membership (characteristic) function, which assigns to each object a grade of membership ranging between zero and one" (Kahraman et al. 2003). It can be seen from Figure 1 that a fuzzy set is generally composed of:
  i. A horizontal axis representing the domain of monotonically increasing real numbers which map the fuzzy population.
  ii. A vertical axis of values between 0 and 1.0 that give the amplitude (degree) of the membership in the given fuzzy set.

iii. The surface of the fuzzy set itself represented by the set curve which connects an element in the domain with its corresponding degree of membership in the set.

B. Membership function μ(x):

Also known as the characteristic or truth function of a fuzzy set.

- Cox (1999) interpreted the membership function of a fuzzy set as: " A measure of the compatibility between a value from the domain and the idea underlying the fuzzy set" .

C: Interval of confidence:

Kaufmann and Gopta (1985) wrote: "The interval of confidence is one way of reducing the uncertainty of using lower and upper bounds". This concept can thus be used to "treat the uncertainty with whatever information is available", Objective (e.g. a sought dimension is surely to be between two measured values) or subjective (e.g. when information is based on experience or expert opinion). The interval of confidence, as a concept can be further illustrated by Figure 2. This vital concept simply implies that the value of the given uncertain phenomenon, which is represented by the fuzzy set in the figure, lies definitely in an interval of confidence between the values of 'a' and 'c', with the most probable exact value describing this phenomenon expected at point 'b'.

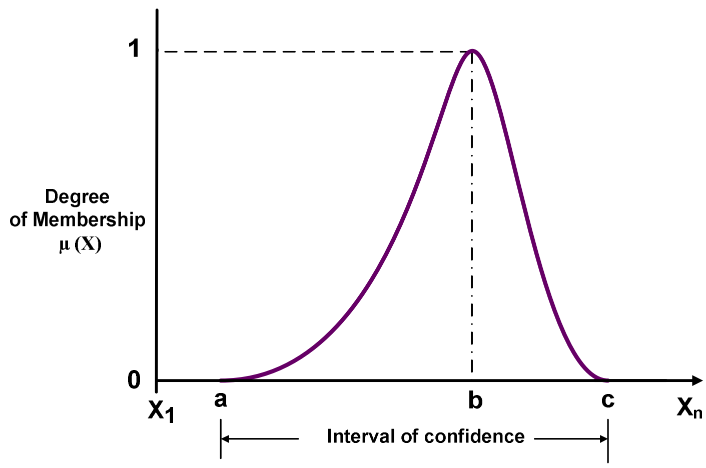


Figure 2 Interval of confidence of a fuzzy set

D: Normal fuzzy sets

- Kaufmann and Gopta (1988) Defined a normal fuzzy set as: 'A fuzzy set $A \subset R$ is normal if it maximum membership function value is 1,

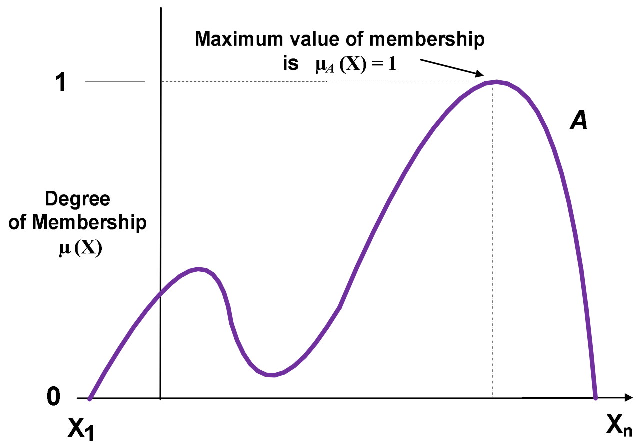


Figure 3 A typical normal fuzzy set

where R is the set of natural numbers'. This is given mathematically as:

$\vee\, \mu_A(x) = 1$, also written as: Max ($\mu_A(x)$) = 1 . This is shown in Figure 3.

E: Convex fuzzy sets:

Kaufmann and Gopta (1985) Defined a convex fuzzy set as :

"A fuzzy set $A \subset R$ is convex if and only if every ordinary subset (within the fuzzy set) that is given by $S_\alpha = \{x: \mu_S(x) \geq \alpha\}$, $\alpha \in [0,1]$ is convex, that is, if it is a closed interval of R. This is given graphically by Figure 4. It can be observed from the figure that a convex fuzzy set may or may not be a normal fuzzy set.

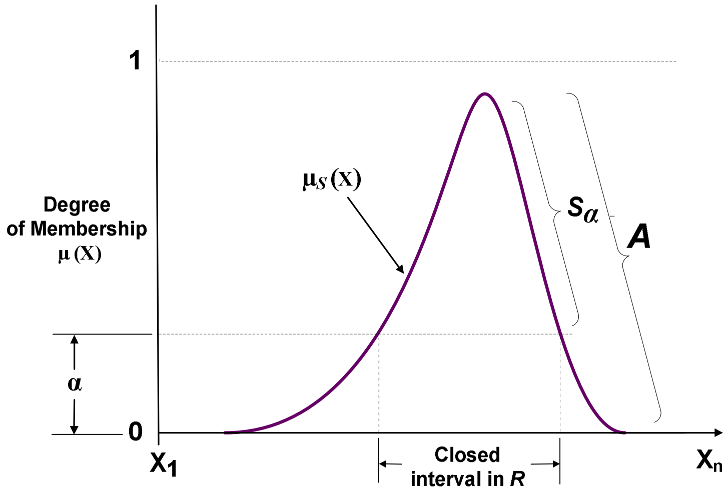


Figure 4 A typical convex fuzzy set

F: Fuzzy Numbers

- " Fuzzy numbers are sets that represent an approximate numeric quantity. These are convex fuzzy sets".(Cox 1999)
- "A fuzzy number is a fuzzy subset in R which is both normal and convex" (Kaufmann and Gopta 1988). Figure 5 represent a typical fuzzy number.

It is thus seen that a fuzzy number A represents a given uncertain phenomena in accordance with the curve described by a membership function $\mu_A(x)$, the interval of confidence being a value in R between 'a' and 'c', and the most expected value of A is sought at 'b'.

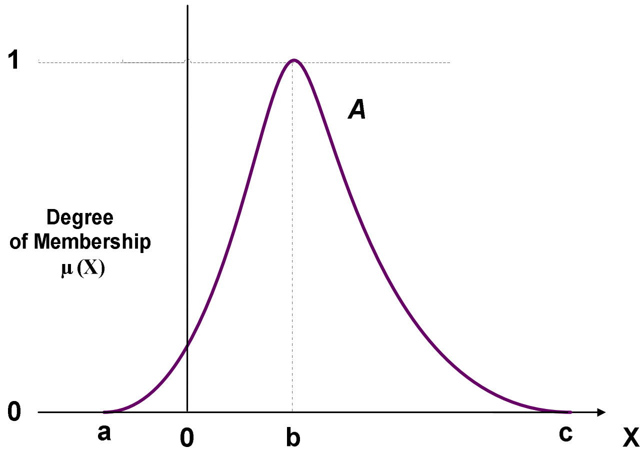


Figure 5 A typical fussy number *A*

Appendix L:

First Page of ErroDetect V.1.12 – Workplace Software as Being Applied Within Industry at The Selected MRO Organization

Maintenance Error Main Causal Factor A : Organizational Processes

Enter Initial Assessment of Criteria As Being OF:
1.V. Weak Influence 2.Weak Influence 3.Moderate Influence 4.High Influence 5.Absolute Influence
Give Initial Assessment Only To Those Criteria That Apply To The Maintenance Line Under Investigation

Sub-Causal Factor A-1: Regulations Enforcement

	Enter Criteria's Degree Of Influence Here ▼	KI	K2	K3	
POE due to non-conformity with international regulations governing maintenance activities within workplace	1	0.5	1	1.5	
POE due to non-conformity with internal regulations governing maintenance activities within workplace	2	1	1.5	2	
POE because maintainers don't quite understand regulations	3	1.5	2	2.5	
POE because regulations are not readily available within workplace zone for the maintainers to observe	4	2	2.5	3	
POE because regulations are not regularly explained to maintainers (e.g. in separate training sessions)	3	1.5	2	2.5	
POE because there are no definite regulation-enforcement activities that are active part of the quality / SMS	3	1.5	2	2.5	
POE because there is no definite independent unit responsible for regulation-enforcement within workplace	1	0.5	1	1.5	
POE because some regulations may be overlooked by maintainers sometimes as parts of common norms	2	1	1.5	2	
No previous cases of definite punishments (various levels) against regulations-breakers so others may learn	1	0.5	1	1.5	
No definite innovative initiatives/ updating activities regarding regulation enforcement are there (managmnt)	3	1.5	2	2.5	
Total number of criteria checked for this subtask	10	11.5	16.5	21.5	
Average representative fuzzy number for this subtask		1.15	1.65	2.15	
Primary index of error potentiality for this subtask (1st order)					1.65
		1.15	1.65	2.15	

Sub-Causal Factor A-2: Oversight Provision

	Degree of Influence	KI	K2	K3	
Lack of the overall understanding of the importance of oversight (within management and even maintainers)	2	1	1.5	2	
Oversight provision is not assigned as a definite responsibility to a definite unite/ team within the line/MRO	3	1.5	2	2.5	
Oversight activities are conducted as part of the regulations only, no further overtopping initiatives are there	3	1.5	2	2.5	
Lack of quality assurance activities (e.g. quality audits, technical records, standards, etc)	1	0.5	1	1.5	
Lack of quality control (A/c inspections, shop inspections, material inspections, NDT/ NDI calibrations, etc)	1	0.5	1	1.5	
Lack of program reliability (data control, preliminary investigations, alerts notices, results monitoring,etc)	1	0.5	1	1.5	
Lack of maintenance safety (safety program, health matters, safety equipment,etc)	2	1	1.5	2	
Lack or inconsistence of periodic oversight activities from external bodies (regulators, higher management)	2	1	1.5	2	
Lack or inconsistence of random oversight activities from external bodies (regulators, higher management)	2	1	1.5	2	
Lack of oversight results feedback to middle-management and to maintainers in order to learn and develop	3	1.5	2	2.5	
Total number of criteria checked for this subtask	10	10	15	20	
Average representative fuzzy number for this subtask		1	1.5	2	
Primary index of error potentiality for this subtask (1st order)					1.5
		1	1.5	2	