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Doctoral Thesis

Designing for Naturalistic Decision-Making

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Abstract

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Designing for Naturalistic Decision-Making

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Emergencies are safety critical situations where decision-makers make rapid and quick decisions. It is essential that decision-makers maintain a high level of performance whilst resolving the incident. Knowledge of human factors influences on decision-maker performance is critical to understand when designing technologies to support naturalistic decision-making.

Previous work has largely focused on the influence of a single human factor on naturalistic decision-making. However in naturalistic decision-making environments, such as resolving an emergency, often requires the interaction of multiple human factors with a resulting cumulative impact on the decision-making process outcome. This thesis presents a set of studies that investigates multiple, co-occurring human factors influences for naturalistic decision-making and investigates integration of the factors in the design of technologies to support effective outcomes in emergency situations. Findings contribute further understanding of the multi-factor influences on naturalistic decision-making, and provide a novel and practical set of design principles to support the design of naturalistic decision-making technologies.

A literature review confirmed that a majority of research presents single factor influences on decision-making, which is out of step for real-world naturalistic decision-making. In addition, findings showed that multiple factor influences co-occur in naturalistic decision-making environments, and are associated with decision-making performance. Seven factors were identified; situation awareness, mental models, workload, human error, uncertainty, teamwork and communication. Two studies using real-world decision-makers from the aviation domain and fire and rescue domain, investigated the multi-factor issues and the association with decision-making performance, through a set of real-world incident case studies. Results demonstrate the occurrence of the seven factors, and the cumulative impact on decision-making performance.

In collaboration with Airbus Defence and Space an experimental study with pilots contributed the design of a novel single pilot operated aircraft interface built using the understanding of the seven human factors. The interface was implemented in a flight simulator, where fourteen pilots performed three emergency related tasks. Results showed that the design had similar performance to that of a system based on the current design methodology, in spite of the fact the pilots had little experience with the system. Based on all findings, twenty-two cognition informed system design principles were created, with an aim to provide naturalistic decision-making system designers with a guide of how to integrate the seven factors into the design of systems to support effective decision-making. A final validation study, with human factors experts as participants, was carried out which identified the usability, validity and applicability of the design principles.

The thesis contributes findings that have both theoretical and practical implications. This research has addressed gaps within the naturalistic decision-making literature and contributed new understanding to the complex field of naturalistic decision-making for emergency situations. Findings suggest that seven factors influence naturalistic decision-making, thus potentially affecting the decision-maker's performance. In addition, this research contributes an understanding of the guidance that is required by designers to create technology. Technology created using this methodology allows decision-makers to improve decision-making performance by supporting their complex decisions, thereby maintaining and improving safety in naturalistic decision-making domains.

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Chapter 1

Introduction

1.1 Background Research

Responding to emergencies is often challenging; surprising events can occur carrying with them uncertainty. Operators are required to respond rapidly before the situation deteriorates. Designing interfaces that support optimal (or even just more effective) decision-making in these settings is challenging. A first step towards overcoming these challenges is to have a model of the human cognition and activities involved in the design stage.

Classical decision-making (ClasDM) theories use axiomatic models that imply operators rigorously determine the best option based on specific criteria, where information is systematically acquired and competing alternative courses of action generated, weighted and assessed, leading to the final course of action (Cole, 2004). Designing for this style of decision-making can be relatively straightforward, an interface would capture all relevant information and support generating alternative courses of action (Li, 2008). The system might also imply the relative merits of different courses of action if the situation is sufficiently constrained and choices obvious (to both the automation involved and the operator themselves).

Whilst ClasDM has merits as an account of decision-making in constrained, but typically high information/low time pressure situations, it fails to offer a satisfactory account of urgent emergency decision-making. Consequently, interfaces built around this model of operation run the risk of failing to support what actually happens in favour of a normative account of what should happen. This may be evident from detailed elicitation from decision-makers (Klein et al. (1986), Klein and Klinger (1991), Klein (1999)) but may also be evident simply from the structure of the situation, for example, where clear criteria for assessing the objective quality of alternative courses of action do not exist, or the time

pressures essentially rule out deliberate option generation and assessment as plausible. Nonetheless, decisions are made and in retrospect are recognised as being good decisions leading to concern amongst ergonomists that theory was failing to match reality.

An alternative to ClasDM is the naturalistic decision-making (NDM) paradigm which investigates the cognitive processes decision-makers perform in real-world environments. NDM provides a descriptive account, where decision-makers rely on situation assessment and identify a single solution to resolve the situation. NDM research supports dynamic conditions, time pressure, high-stakes, uncertain information and multiple players (Orasanu and Connolly, 1993a). Decision-makers can make decisions based on an incomplete view of the situation, deal with a high degree of uncertainty by identifying key features from the environment to develop a course of action. Expertise is instrumental when resolving an incident, the decision-maker develops the course of action based on their previous experience and knowledge. A novice will most likely use a more deliberate decision-making approach. Designing for NDM environments is relatively more difficult when compared to designing for ClasDM. If the system had access to all the information and all possible options, it would not have the time or the understanding to highlight the best choice.

To understand and design systems for NDM environments the Recognition Primed Decision (RPD) model can be used. It describes how experienced operators make good decisions without ever comparing options (Klein, 1993a). The RPD model states:

> *"...decision-makers recognise the dynamics of a situation, enabling them to identify a reasonable course of action, and this CoA [Course of Action] is evaluated by imagining how it will be implemented."* (Klein, 1993a)

RDP describes the decision strategy, which explains how operators use experience to make difficult and challenging decisions and establishes that decisions can be made without using a rational choice strategy.

In NDM you have to consider the NDM process while additionally considering factors that impact the decision-making process when designing for real-world environments (Lipshitz et al., 2001). The factors include situation awareness (Endsley, 1995b, Salas et al., 2005), mental models (Rutherford and Wilson, 1991b, Stout et al., 1999a), workload (Urban et al., 1996), uncertainty (Lipshitz and Strauss, 1997, Rutherford and Wilson, 1991b), error Klein (1993b), team (Lipshitz et al., 2001, Salas et al., 2005, Volpe et al., 1996b) and communication (Helmreich et al., 1999).

Whilst NDM provides an account of real-world decision-making, there is limited literature which identifies how decision-maker's behaviour should be supported when designing technology. Klein (1993a) highlights that if designers do not have a clear picture of the

key decisions, or how operators make these decisions, then it is difficult for them to build systems and human centred interfaces. Methods such as user centred design attempt to directly support all the tasks users need to accomplish (Constantine and Lockwood, 2001), alternatively ecological interface design focuses on understanding the domain and environment the end user must work in Vicente et al. (1992). However, these approaches do not consider the real-world decision-making process by investigating NDM. Decision centered design is better suited to investigate NDM and focuses on the decision requirements and uncovers expertise (Militello and Klein., 2013). Some authors have attempted to extract the requirements and use the findings as a basis for design guidelines. For example, Gualtieri et al. (2012) present design guidelines for human systems interfaces based on decision centered design, but with a focus on the electric power industry.

Two weaknesses have been identified with NDM literature. First, whilst decision centered design focuses on uncovering key decisions, there is limited research that investigates NDM and the key factors that can impact the decision-making process. Secondly, there is limited literature, which supports designers in creating systems for real-world decision-making. The work presented in this thesis investigates the decision-making and the key human factors issues that must be supported in NDM contexts. The focus of this research is to integrate both the decision-making and human factors issues more deeply into the design process and develop guidance for system developers. The thesis will contribute to both the human factors and system engineering domains by bridging the gap between the human factors that impact the operator in NDM domains and developers who create systems supporting operators.

1.2 Motivation for This Thesis

This PhD was part sponsored by Horizon: Centre for Doctoral Training and part-sponsored by Airbus Innovation, a subsidiary of Airbus Group. The Horizon: Centre for Doctoral Training focuses on multi-disciplinary research to develop digital technology to support both economic and social benefits. Airbus Group is a leading aircraft manufacturer, developing technologies for aeronautics, space and defence-related services. The research described in this thesis was motivated by Airbus Group's requirements to gain further understanding into the human factors required to support the design of systems for decision-making in safety critical domains. The outputs of this thesis will inform the design of future systems developed at Airbus Group. First, a one month placement within Airbus Innovation was carried out to develop an understanding of the NDM domains of interest to Airbus. A further six month placement within Airbus Defence and Space, another subsidiary of Airbus Group, was carried out to further support and develop this thesis.

1.3 Thesis Research Questions and Aims

The research question and aims were developed in collaboration with Airbus Group. The thesis investigates the following research question:

"What guidance should be given to designers developing real-world decision-making systems?"

To address this question, three research aims were developed:

1. **Identify the typical human factors issues that affect NDM environments.**

   A literature review was undertaken to investigate real-world decision-making. Whilst NDM is well documented, the HF issues that affect the decision-making process required further investigation. The review identified a set of seven HF issues that were present in the NDM environment. The HF issues were split into cognition, interactions between individual and environment, and individual in a team environment. These HF issues were identified in collaboration with Airbus, of which decision-making was considered as a cognition HF issue. Based on these findings, a research framework was developed and used to investigate real-world environments. Furthermore, the findings contributed in the development of the principles, their descriptions and the points designers need to consider.

2. **Examine NDM and the human factors issues in real-world environments.**

   Two real world environments were investigated to identify NDM and confirm the HF issues associated to the decision-making process. The fire and rescue service and the aviation domains were explored to identify the constraints decision-maker's experience in real-world situations. A range of methods including ethnographic study, critical decision method, cognitive work analysis and decision centred design, were applied to investigate NDM and the associated factors. The examination of the NDM and HF issues identified operator tasks, which were decomposed into types of decision-making tasks, evidence of the HF issues and decision requirements for design. The findings from the different methods informed the development of guidance by providing case studies for the principles, and extracts of the interviews were used as examples to support each principle.

   Data collection methods were employed to support this aim, these included observation and interview techniques, focusing on ethnographic study, critical decision method and focus groups with subject matter experts. To analyse the domains two approaches were used: cognitive work analysis and decision centered design. This supports a further study of the development and evaluation of an aviation system

prototype. This study provided support for the "points to consider" section of the guidance when designing for real-world decision-making.

3. **Develop guidance to support NDM system designers.**

   The findings from the first two aims were synthesised into design principles. Uncertainties within the principles were identified, investigated and a study was implemented to further develop the design principles. Human factors experts were asked to apply the design principles to create a paper prototype for a fire and rescue service system. The findings from this activity identified how the principles were used and how the principles should be presented to support the designer's design process. This guidance is called Cognition Informed System Design which is presented in the form of an on-line tool.

1.4 Overview of Thesis

This thesis is presented in nine chapters. Figure 1.1 presents an overview of the relationship between the research aims, the thesis chapters and research activities that address each aim.

Thesis Aim	1 Introduction	2 Literature review	3 Methodological approach and research framework	4 Investigation of NDM in the fire and rescue domain	5 Investigation of NDM in the aviation domain	6 Application of findings to a design prototype in the aviation domain	7 Synthesis and evaluation of design principles	8 Final design principles	9 Discussion and Conclusion
1. Identify typical human factors that affect NDM in emergency contexts.	X	X	X	X	X				
2. Examine NDM and the human factors issues in real-world environments			X	X	X	X			
3. Develop guidance to support NDM system designers.		X	X	X	X	X	X	X	

FIGURE 1.1: Mapping of Thesis Aims with Thesis Chapters and Research Activities

Figure 1.1 is supported by figure 1.2, which presents an overview of the thesis structure and progression of the thesis chapters.

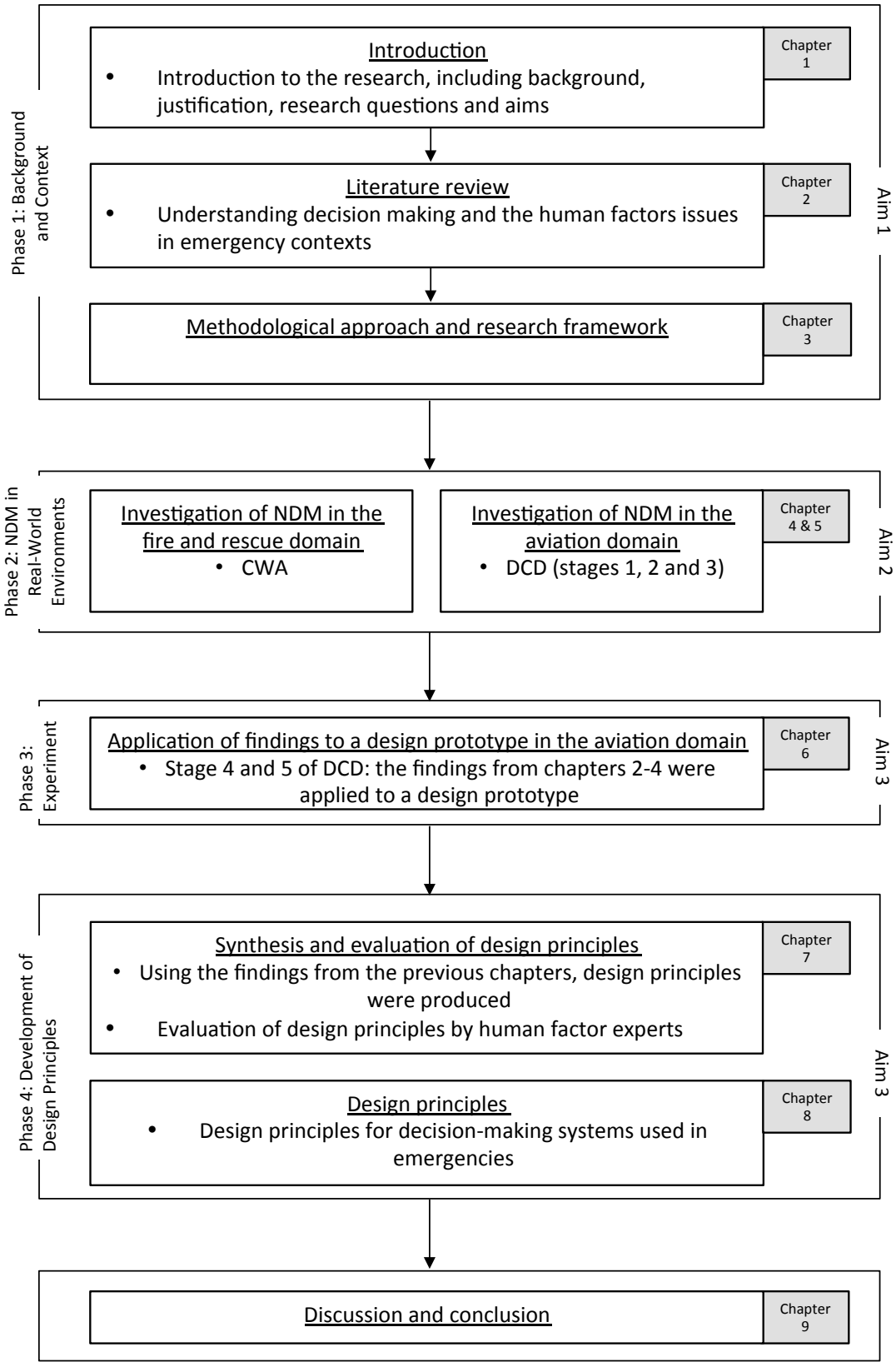


FIGURE 1.2: Thesis Structure and Research Framework

A summary for each chapter is provided giving context.

Chapter One: Introduction introduces the research, including background, justification, research aims and a summary of the structure of the thesis.

Chapter Two: Literature Review presents a review of NDM and identifies the key human factors issues that need to be supported for effective NDM in these types of domains. The human factors issues identified are split into cognition, interactions between the individual and the environment, and individuals in a team environment. Based on these findings, a research framework was developed and used as a basis to investigate real-world NDM environments.

Chapter Three: Methodological Approach and Research Framework presents the approach and research framework of the thesis.

Chapter Four: Applying Cognitive Work Analysis to Understand NDM in the Fire and Rescue Service contains an initial study to understand NDM using the cognitive work analysis approach, data collection methods include initial interviews, a focus group and critical decision method interviews. This chapter presents the five stages of cognitive work analysis and a set of case studies for the design principles.

Chapter Five: Exploring NDM in Aviation: Stages 1, 2 and 3 of Decision Centered Design provides a more detailed study using decision centered design to get a detailed understanding of NDM and the associated human factors issues. This chapter presents the findings from observations with a two pilot aircrew on a flight and critical decision method interviews with Airbus test pilots. The decision centered design approach is used to analyse the findings, and this chapter outlines the first three stages of the approach. Stage one investigates the domain, whilst stage two elicits the key decisions and stage three identifies the key decision requirements. The findings are used for stages four and five which are outlined in chapter six.

Chapter Six: Moving Towards Single Pilot Operations: Stages 4 and 5 of Decision Centered Design presents moving to single pilot operations, stages four and five of the approach. Stage four applies the requirements, to a prototype design and stage five evaluates the design. The prototype system is designed for a single pilot operated aircraft and the move from a two pilot aircrew, to a single pilot aircrew, is also investigated to influence the design of the system. Stage five evaluates the design of a decision-making system in the aviation domain using scenario-based evaluations.

Chapter Seven: Synthesis and Evaluation of Design Principles presents design principles based on chapters two to five. The design principles are outlined with an explanation, illustrative examples and questions to consider when developing systems. Areas of

uncertainty are highlighted for further exploration. These uncertainties are investigated by HF experts, who use and further develop the design principles.

Chapter Eight: Cognition Informed System Design integrate the findings from chapter seven to support the final draft of the principles. The design principles are presented on a website as a resource for other designers.

Chapter Nine: Discussion and Conclusion provides an overview of the research presented in this thesis. The chapter considers the findings from relevant studies in relation to each thesis aim. Limitations of the research are described, and areas of further research are recommended.

Chapter 2

Literature Review of Naturalistic Decision-Making and Human Factors Issues

2.1 Chapter Overview

The Naturalistic Decision-Making (NDM) domain attempts to understand how decisions are made in real-world contexts that are meaningful and familiar to the decision-maker (Lipshitz et al., 2001). This chapter presents a literature review which centres on NDM and describes the human factors (HF) issues that affect decision-making. The chapter is divided into three sections; figure 2.1 presents an overview of chapter two.

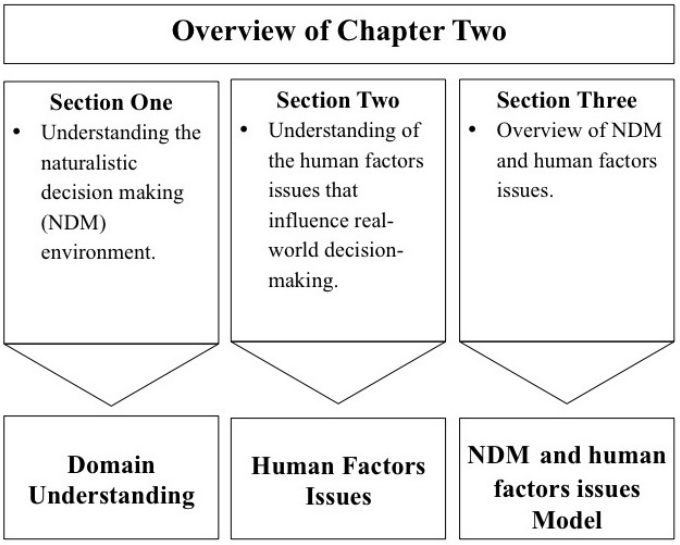


FIGURE 2.1: Overview of Chapter 2

Section one provides a review of the NDM domain, highlighting the key characteristics, existing research of the HF issues and decision-making models. Section two presents the factors which influence NDM; these are split into three themes: cognition, interactions between individual and environment and individuals in a team environment. These themes were identified in discussions with Airbus. The researcher then investigated existing literature to identify the main HF issues which affect NDM within the three themes.

These include:

- **Cognition;** Situation Awareness (Endsley and Hoffman, 2002, Endsley, 1995b, Salas and Klein, 2001, Salas et al., 2005) and Mental models (Jones et al., 2011, Norman, 1983a, Rutherford and Wilson, 1991b, Stout et al., 1999a)
- **Interactions between individual and environment;** Workload (Johnson and Proctor, 2004, Wilson and Sharples, 2015), Human Error (Flach et al., 2008, Lipshitz et al., 2001, Urban et al., 1996) and Uncertainty (Lipshitz and Strauss, 1997, Rutherford and Wilson, 1991b)
- **Individuals in a team environment;** Team (Lipshitz et al., 2001, Orasanu and Connolly, 1993b, Salas et al., 1992, 2005, Volpe et al., 1996b) and Communication (Helmreich et al., 1999)

The seven HF issues were presented to Airbus who deemed them satisfactory for investigation in this thesis.

Section three integrates the findings from sections one and two into a new model called Cognition Informed System Design. The purpose of the model is to present the decision-making process and the relationship of the HF issues which impact the decision-making process. This model reflects the elements that need to be supported when designing systems for NDM settings.

2.2 Section One: Naturalistic Decision-Making Domain

NDM is a descriptive decision theory, which understands and improves decision-making in field settings. Lipshitz et al. (2001) state that the NDM domain attempts to understand not only decisions but also how they make them in real-world contexts that are meaningful and familiar to them. Zsambok (1997) presents NDM from the point of the decision-maker, stating *"NDM is the way people use their experience to make decisions in field settings."* NDM supports the operator to quickly develop expertise and apply it to the challenges

they face (Klein, 2001). A more comprehensive definition is provided by Zsambok and Klein (2009):

> "The study of NDM asks how experienced people, working as individuals or groups in dynamic, uncertain, and fast-paced environments, identify and assess their situation, make decisions and take actions whose consequences are meaningful to them and to the larger organisation in which they operate" (Zsambok and Klein, 2009)

NDM method explicitly seeks to understand how operators manage complex tasks and environments, examining the context of the situation, where they are found and uses this to develop useful types of tools, training and support. The NDM environment has been studied in a number of domains including the emergency services (Klein, 1999, 1989), military (Hutchins et al., 1996), aviation (Orasanu and Martin, 1998), healthcare (Lighthall and Vazquez-Guillamet, 2015) and nuclear (Gualtieri et al., 2012).

To understand NDM it is important to consider classical decision-making (ClasDM), Cole (2004) states ClasDM is *"a process of identifying a problem, evaluating alternatives, and selecting one alternative."* Table 2.1 shows the characteristics of naturalistic vs. traditional decision-making research.

Naturalistic decision-making	**Traditional decision-making**
Ill-structured problems.	Well-defined problems.
Uncertain dynamic environments.	Relatively stable environments.
Shifting, ill-defined, or competing goals.	Single, well-understood goal.
Action / feedback loops.	Single decision event.
Time constraints.	Decisions deliberated.
Outcome with high stakes.	Research subjects less invested in outcome.
Multiple players.	Single decision-maker.
Organisational goals & norms.	Individual preference.

TABLE 2.1: Characteristics of Naturalistic vs. Traditional Decision-Making Research (Randel et al., 1996)

ClasDM highlights that people make the best choices among several options based on the current situation. Further ClasDM emphasises the concept of rationality and rational decisions during the process of discussions (Li, 2008). NDM emphasises an approach where people are not always "rational" decision-makers but they are proficient, where the decision-maker is using situation-action matching decision rules as opposed to choosing an alternative (Lipshitz and Strauss, 1997). Whilst ClasDM has been applied in business to reach decisions in organisations, ClasDM is less appropriate for NDM. Orasanu and

Connolly (1993a) claim decisions which are made whilst performing complex technical tasks do not align with the traditional, analytical decision-event models that are studied in laboratory situations. ClasDM fails to address the following elements of NDM including ill-structured problems, uncertain dynamic environments, shifting, ill-defined or competing goals, action/feedback loops, time pressure and high stakes. These classical strategies also fail when presented with time pressure as they take too long to implement. Even in low time pressure, classical strategies require extensive work and provide little flexibility for rapidly changing situations. Furthermore, it is difficult to account for ambiguity, vagueness and inaccuracies (Klein and Klinger, 1991).

Orasanu and Connolly (1993a) highlight that NDM environments can be challenging for the following reasons:

- **Ill-structured problems** – The decision-maker must generate hypotheses about what is happening and establish options that are an appropriate response. The decision-maker is required to relate observable features of the setting to one another by complex causal links, interactions between causes, feedback loops, etc.
- **Uncertain, dynamic environments** – The NDM environment is a dynamic and continually changing environment (Randel et al., 1996). Information in NDM domains is typically incomplete and imperfect; information that is available may be ambiguous or of poor quality.
- **Shifting, ill-defined or competing goals** – The decision-maker may be motivated by multiple goals, some of which may be unclear or conflicting. As a situation changes this may lead to a shift in the goals. Over the course of the situation various goals and sub-goals may need to be redefined as new information is received which in turn could impact the priorities of the goals and sub-goals.
- **Action/feedback loops** - In the NDM setting, typically a series of events occur, a string of actions over time that are intended to deal with the problem and/or to find more information about it, or both. When a decision-maker identifies a mistake, they have the opportunity to take corrective actions. The actions and results may only be loosely coupled, which may make it hard to attribute effects to causes.
- **Time constraints** – In NDM settings decisions are made under significant pressure, where the decision-maker only has minutes and seconds to make each decision. O'Hare (1992) states that the element of time criticality is one of the distinguishing features of decision-making in complex and dynamic systems. This has important implications as it can result in high levels of stress (including exhaustion and loss of

vigilance) and workload, which could see the decision-maker shifting their thinking to use less complicated reasoning strategies.

- **High stakes** – The outcomes of the decisions could have a significant impact on the participants involved e.g. loss of property, careers, or ultimately life itself.
- **Multiple players** – In the NDM setting, usually several operators will actively work together as a team. This could include one decision-maker and a single subordinate or a whole group of individuals. The multiple players work together towards the goal by sharing information to inform the decision process.

There are several claims for NDM environments, see table 2.2 .

Seven claims of naturalistic decision-making
1. In operational settings, people try to find the first course of action (CoA) that works, not the best one.
2. Decision-making consists of two aspects – assessing the situation, and selecting a CoA.
3. Experienced decision-makers can usually assess the situation quickly and accurately.
4. Once the situation is understood, the CoA decision is usually obvious.
5. Decision-makers often must be prepared to act without fully examining the parameters and contingencies.
6. Decision-making and problem solving are inter-related.
7. Decision-makers arrive at a CoA by generating pertinent options rather than filtering out unacceptable options.

Table 2.2: Seven Claims of Naturalistic Decision-Making (Klein, 1993a)

A key claim of NDM is that decision-makers do not generate alternative options, compare them, nor develop probability and utility estimates for different courses of actions (CoA) or generate decision trees (Klein et al., 2008). Klein and Klinger (1991) further support this, and state their research also shows that operators make effective decisions without performing analyses. Randel et al. (1996) found that experts base their decisions on the nature of the situation using their expertise; they have a large repertoire of past experiences to inform the current situation. The operators are acting and reacting on the basis of prior experience (Klein and Klinger, 1991). The decision-maker spends little effort in deciding how to react to a situation, once they have understood the situation; the reaction is often obvious. Further, Klein and Klinger (1991) find little evidence for extensive option generation, the operators wanted “workable,” “timely” and “cost effective” actions.

Lipshitz et al. (2001)'s review of NDM identifies that there are four main characteristics for NDM, these include process orientation, situation-action matching decision rules, context-bound informal modelling and empirical based prescription. Process orientation highlight NDM models outline the cognitive processes of a decision-maker rather than predicting which option will be implemented. NDM models describe the information requirements, how decision-makers interpret this and the decision rules they use. Situation-action matching decision rules describes that decision-makers make decisions based on matching, for example, *"Do A because it is appropriate for situation S"* (Lipshitz, 1994). Context-bound informal modelling shows that decision-making is driven by experienced tied knowledge. Empirical based prescription aims to enhance feasible decision-makers' characteristic modes of decision-making oppose to replacing them altogether, by basing them on expert performance.

There are two types of decision-making models; process models and typological models. Process models describe the sequence of phases in which decisions are made. Lipshitz (1993) identified that there are nine NDM models, these include five process models, model of situation assessment (Nobel, 1989), model of recognition-primed decisions (Klein, 1989), image theory (Beach and Mitchell, 1987), model of explanation-based decisions (Pennington, N., & Hastie, 1986) and dominance search model (Montgomery, 1983). Typological Models classify decision processes (e.g. intuitive or analytical) and discuss the contingencies under which type is ought to be used. These include model of cognitive control (Rasmussen, 1983), cognitive continuum theory (Hammond et al., 1987), model of decision cycles (Connolly, 1982) and model of argument-driven action (Lipshitz, 1989). Whilst these models were developed separately, they reached similar conclusions that people were not generating and comparing options. People were using their experience, also referred to as a schema, a prototype or a category to make a judgement (Klein et al., 2008). Lipshitz et al. (2001) describes that many of the models fall within the NDM framework and goes on to describe the Recognition Primed Decision (RPD) model (Klein, 1993a, 1999) serves as the prototypical NDM model. This research uses the RPD model as the basis of the research as the model was developed using experienced personnel who actually make decisions under time pressure. The model explains how people can use experience to make difficult decisions without rational choice strategy (Klein, 1999). Whilst other naturalistic decision-making models portray decision-making as a quick selection and further evaluation of a single alternative, the models do not suggest selection and evaluation based on suitability to current or projected conditions, nor the detection of an unsatisfactory alternative leads to its modification or replacement by others Klein et al. (1993). Furthermore, the RPD model has been tested and supported by different research teams working in a variety of settings (Klein, 1999).

The RPD Model is a descriptive model, which investigates how individuals effectively make decisions in complex situations (Klein, 1993a, 1999). The RPD model is based on cognitive task analyses of firefighters (Klein et al., 1989) and was originally conducted for a descriptive inquiry to prove that commanders do not generate a large set of response options when under time pressure. Using probe based interviews, the data suggested that no options were compared and they were in fact carrying out the first course of action.

The RPD model shows a number of things which includes decision-making under stress and time pressure and the decision-making process of experts and novices who have high levels of operator expertise (Klein, 1989). RPD involves non-optimising and non-compensatory strategies, which require minimal conscious deliberation. RPDs do not compare options, but instead involve recognition matching which highlights the most likely action (Klein and Klinger, 1991). Klein et al. (1989) highlight that the decision-maker develops a potential course of action, considers the constraints imposed by the situation and selects the first course of action which is not rejected.

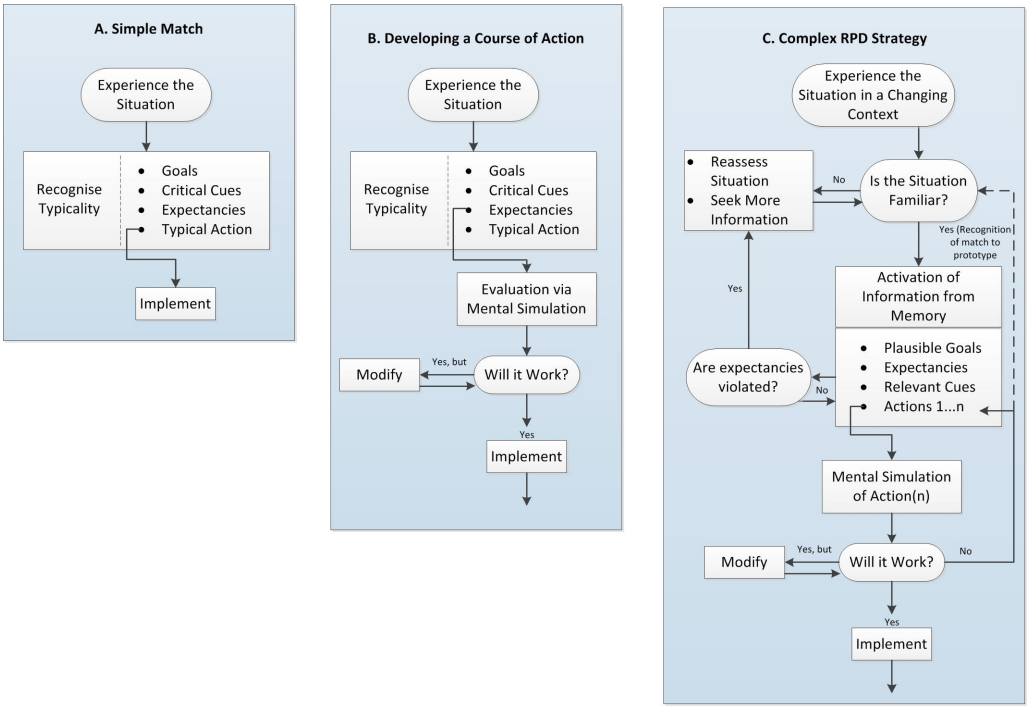


FIGURE 2.2: Recognition Primed Decision Model (Klein, 1999)

Figure 2.2 presents the RPD model in three variations. Variation (A) shows that the decision-maker sizes up a situation, recognises the situation and then generates the first feasible CoA. Here experience provides prototypes or functional categories (Lipshitz et al., 2001). If the decision-maker determines the situation as a typical case then he or she

will be able to implement the typical appropriate actions which are usually successful. To recognise a situation, the operator recognises the goals, cues and expectancies (Klein, 1999). A somewhat more complex case, variation (B), which emerged from commanders of Navy cruisers (Kaempf et al., 1996) describes a situation where the decision-maker consciously evaluates the reaction as the situation is not clear. In this variation the decision-maker devotes more attention to diagnosing the situation as the information may not clearly match a typical case (Klein, 1999). The decision-maker depends on a story or imagery (Klein and Klinger, 1991), where they mentally simulate the events leading up to the observed features of the situation (Klein and Crandall, 1995, Pennington and Hastie, 1993). In the most complex, variation (C), the models describes that decision-makers evaluate a CoA without comparing it to other possible actions. The evaluation of the CoA is mentally simulated to attain if it will work and identify if there are consequences that are not acceptable. The decision-maker will adjust the CoA when an anticipated difficulty is identified, in some cases the decision-maker may reject the course of action and look for another option (Klein, 1999).

The three variations of the RPD model heavily depend on expertise. In the first variation (A), expertise allows the decision-maker to categorise the situation, identify its typicality and recognise how to react as an aspect of the categorisation. In the second variation (B) of the model, expertise is required to construct the mental models required to find one explanation more plausible than another. In the third variation of RPD model (C), expertise is defined as an ability to mentally simulate a CoA in a situation, and anticipates how it will execute.

As mentioned above, RPD focuses on assessing the situation rather than assessing different CoA, thus the decision-makers spend more effort on understanding and assessing the situation, which distinguishes a good option as a CoA. If the first option needs to be rejected, the decision-maker will go on to distinguish the next best CoA in a serial fashion rather than concurrently evaluating a number of actions.

There are three main phases in the model, which need be considered to support the decision-maker (Klein, 1999):

1. **Situation Recognition**

   The RPD model shows that the decision-maker decides if the situation is typical or novel.

   - The decision-maker identifies the critical cues which distinguish the type of situation and casual factors which explain what is presently happening and what could happen.

- Based on the above, the decision-maker sets plausible goals and appropriate actions given the goals and expectations.

Typical and familiar situations will result in typical actions, which are usually well rehearsed. However, the operator needs support for novel situations, which they have not come across before as they are challenging and unfamiliar.

2. **Serial Option Evaluation**

   This stage states that the decision-maker evaluates the different course of actions until a valid one is found. Each action is selected from an action queue and arranged according to typicality.

3. **Mental Simulation**

   The final phase evaluates if an action is satisfactory, in this phase the decision-maker performs the course of action in his or her imagination; plays out the steps, the potential outcomes and the problems that might occur, and how these problems may be handled.

   - The decision-maker either implements the action, or modifies it, or rejects it and goes on to the next action.

   Mental simulation shows up in at least three places in the RPD model:

   (a) Diagnosing to form situation awareness - situation awareness can be acquired rapidly by intuitive matching of features of through mental simulation.

   (b) Developing expectancies to help generate situation awareness.

   (c) Evaluating a course of action.

When people are more experienced in a domain, they are more confident in their ability to size up the situation and consequently recognising a plausible course of action as the first solution they consider. Klein et al. (2008) states that the RPD model is a blend of *"intuition and analysis"*, where pattern matching is the intuitive part, and the mental simulation is the conscious, deliberate, and analytical part.

2.3 Section Two: Human Factors Issues

Naturalistic decision-making is affected by three main themes which include cognition, interaction between individual and environment and individuals in a team environment. Within these three themes, seven human factors issues were identified as factors that impact NDM. The HF issues include situation awareness, mental models, workload, error, uncertainty, team and communication. These seven HF issues were presented to Airbus who deemed the factors as satisfactory for further investigation in this thesis. This section investigates the identified human factors issues in detail.

2.3.1 Cognition

Two factors were identified which affect the individual's cognition when making real-world decisions; situation awareness and mental models, see figure 2.3.

Situation Awareness	**Mental Models**

Table 2.3: Cognition HF Issues

2.3.1.1 Situation Awareness

The NDM environment not only examines decision-making but also other cognitive functions such as situation awareness (SA) as it is the foundation for decision-making and performance in NDM domains (Endsley and Hoffman, 2002, Endsley, 1995b, Salas and Klein, 2001). A large body of research has found that adequate SA supports correct decision-making (Mogford, 1997) as SA supports the selection of the appropriate course of action with the support of additional processes. In order to match situations, the decision-maker must have an understanding of what is going on. SA is developed through the situation assessment process in the RPD model. Domains include aviation, firefighter and weather forecasting (Endsley and Hoffman, 2002).

Endsley (1988) defines SA as *"the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future"* or simply put *"knowing what is going on"*. SA gives the operator an understanding of what is happening around them and an understanding of what that information means in the future. SA is dynamic in nature and the repetition of the process continuously updates the decision-maker's understanding of the environment (Parasuraman et al., 2008).

Adams et al. (1995) argue when elements are not perceived, are misperceived or misunderstood, this results in "flawed" SA which can lead to error or wrong decisions. With incomplete or inaccurate SA, even well trained and experienced operators, such as pilots will make incorrect decisions (Endsley, 2000a). Contrary to this, inexperienced operators may have complete understanding and still not know what course of action to take. For this reason, SA should be explored separately from the decision-making and performance stages.

Endsley (1995b) presents three distinct levels of SA, based on the aviation domain. The first level, perception of the elements in the environment, involves understanding the status, attributes and dynamics of relevant elements in the environment. The operator must accurately perceive information about the aircraft and its systems. For example, airspeed, position, altitude, route, direction of flight, etc. Also, additional information which includes weather, air traffic control clearances, emergency information and other pertinent elements need to be understood. The second level, comprehension of the current situation, highlights an understanding of the level 1 elements taking into consideration the operator's goals. The operator will form a holistic picture of the environment based on the Level 1 elements and the patterns that emerge. The operator acquires an understanding of the significance of the information and events. For example, pilots must fuse data from a number of sources and determine the impact of a change in one system on another. The difference between a novice and experienced pilot is that whilst a novice pilot may be able to achieve the same Level 1 SA as an experienced pilot, they may not have the ability to integrate and comprehend the various data elements to support the goals. The third level, projection of future status, shows the operator's ability to project the future actions of the elements in the environment. Level three SA is achieved through knowledge of the status, dynamics of the elements and a comprehension of the situation (both level one and two SA). For example, in the event of a fuel leak, a pilot uses information from the fuel status to determine how long they can fly for. This gives the pilot the information necessary to decide on the most favourable CoA, such as which airport to making an emergency landing. Endsley's model of situation awareness in dynamic decision-making highlights each level, the internal and external factors that affect SA in order to develop a complete understanding of what SA is (Endsley, 1995b). The three levels of SA occur in working memory , where the stimuli are stored, processed and combined with previous knowledge in order to project what might happen in the future. Stored information in long-term memory guides the operator on what to expect, freeing up working memory resources (Wickens, 1984).

SA is more than information gathering, it is gathering the right information, being able to analyse it and then projecting what could happen based on this analysis. Thus, the

operator bringing meaning to the information. SA also requires the operator to pay attention to the correct information, not only in the early information processing stages but also during the decision-making process and CoA execution. In complex situations this can cause the limited attention capacity to be quickly reached (Endsley, 1995b). This can result in the operator not being able to attend to all the relevant information creating what Endsley and Jones (2011) call a bottleneck for SA where there is a limitation for the amount of information that can be perceived at any time. An operator having inadequate or complete loss of SA may negatively influence performance.

2.3.1.2 Mental Models

Mental models are created by operators; based on experiences, perception and understanding of the environment. They are understood as a cognitive structure, which forms the basis of reason and decision-making to sort and filter new information (Jones et al., 2011). Mental models are described as the internal psychological representations of an operator's conceptualisation and understanding of a system (Kieras, 1988, Nancy and Norcio, 1993, Norman, 1983a). Wickens et al. (1998), further extend the mental models definition as *"internal representations of objects, actions, situations or people. Built on experience and observation and are simulations which are run in mind to produce qualitative inferences in order to underpin our understanding of a system and allow us to describe, predict, and explain behaviour, and to test "what-ifs" and "what wills"".*

Endsley (2000b) finds that mental models illustrate stored long-term knowledge about a system which can be called to support problem solving and interaction with the relevant system. Although models grow and evolve with experience they mainly represent static knowledge about the system. The model may identify its significant features, how it functions, how different components affect others, and how its components will behave when confronted with various factors and influences. Moray (1998) describes a mental model as a mapping of the properties of the task to its representation in the mind of the operator. The importance of mental models is that it presents what people have in their heads and how this guides their use of things. The mental model enables the user to predict the operation of a target system (Norman, 1983a).

In the NDM setting as stated in the RPD model, operators use their experience in the form of a repertoire of patterns (Klein et al., 1989). Expertise constructs the mental models required to find one explanation more plausible than another. Mental models are important to SA levels two and three (comprehension and projection), as they are a mental blueprint of how something works. Where information is missing, the operator can fill in the blanks (Endsley and Jones, 2011).

Moray (1998) indicates that mental models should be understood in the context of different tasks and environments. Moray goes on to indicate that mental models are formed by mapping the external world into the operator's heads and subsequently by performing a series of mappings to form models from models. Mental models are regarded as inconsistent representations as they are context-dependent and often change according to the situation in which they are applied to. They have to be highly dynamic to adapt to continually changing circumstances and they evolve over time through learning (Jones et al., 2011). Table 2.4 presents the main characteristics of mental models.

Characteristic	**Description**
Dynamic.	Mental models change over time and include elements such as system components, how the systems works, how the components are related, what the internal processes are and how they affect the components (Carroll and Olson, 1988).
Can be erroneous, incomplete, unstable and fragments.	(Jones et al., 2011)
May have several mental models of a single system.	Different models may represent different facets of the system (Wilson and Rutherford, 1989).
Mental models can represent spatial relations, events and processes and the operations of complex systems.	Mental model can yield both inductive and deductive inferences (Johnson-Laird, 2001)
Visual.	Mental models are a very visual, structured proposition that rely on identified similarities between known and unknown systems. (Nancy and Norcio, 1993)

Table 2.4: Characteristics of Mental Models

Mental models exist within the mind, which makes it difficult for direct inspection and measurement (Jones et al., 2011, Nancy and Norcio, 1993). One of the main challenges of mental models is that there is no single established method of measurement of mental models and it is acknowledged that any method is likely to make preconceived assumptions about the form that the mental model holds (Dirk Ifenthaler and Specto, 2008). Rutherford and Wilson (1991a) highlights that problems lie with the methods by which we identify and represent mental models, they claim each method has its own weaknesses and potential biases. Wilson (2000) propose that no human scientist has been able to utilise mental

models, rather they have used the notion to advise designers or to provide descriptive accounts of human performance.

Norman (1983a) claim the following challenges for mental models, these are outlined in table 2.5.

Challenges of mental models
Mental models are incomplete
People's abilities to run their models are severely limited
Mental models are unstable: people forget details
Mental models do not have firm boundaries
Mental models are "unscientific"
Mental models are parsimonious: people will trade-off extra physical action for reduced mental complexity

TABLE 2.5: Challenges of Mental Models (Norman, 1983a)

As mental models are what people really have in their heads and it is what guides them when using something, we need to understand how people learn and reason about physical systems (Willams et al., 1983). Designers must create a clear design model in order to enhance the users' abilities to create appropriates mental models (Johnson-Laird, 2001). Janosky et al. (1986) added that designers must also anticipate users' models so that errors can be reduced. Mayhew (1991) suggests that we need to make invisible parts and processes visible to the user, provide feedback, building in consistency and presenting functionality through a familiar metaphor.

Norman (1983a) states that when constructing a system, the design should be based on a conceptual model. The model should govern the entire human interface with the system, where the image of the system is consistent, cohesive and intelligent. The author goes on to describe how the conceptual model should fulfil three criteria learnability, functionality and usability. Four elements need to be considered when supporting mental models (Norman, 1983a), including, the target system: the system that the person is learning or using. The conceptual model of the target system: invented to provide an appropriate representation of the target system. Invented by others. The user's mental model of the target system: evolving models through interaction with a target system and finally the scientist's conceptualisation of that mental model.

2.3.2 Interactions Between Individual and Environment

Three factors were identified for this section, including workload, human error and uncertainty, see table 2.6.

Workload	**Human Error**	**Uncertainty**

TABLE 2.6: Interactions Between Individual and Environment HF Issues

2.3.2.1 Workload

Workload (WL) has become a topic of increasing importance in the ergonomics domain as technology and tasks mature (Young et al., 2015). The operator's tasks have moved from being physical tasks to ones that are mental (Sharples and Megaw, 2015).

Despite over 40 years of research and the intuitive appeal in this topic, there is no universally accepted definition of workload (Cain, 2007). Early definitions by Kramer et al. (1987) define WL as *"... the cost of performing a task in terms of a reduction in the capacity to perform additional tasks that use the same processing resource."* Whilst Lysaght et al. (1989) define WL as *"... the relative capacity to respond, the emphasis is on predicting what the operator will be able to accomplish in the future."* Gopher and Donchin (1986) give a simple definition of WL which refers to the measurement of the mental processing demands placed on an operator during the performance of a task. This definition highlights that the operator requires mental resources in order to complete a task, however, the resources may not always match those required to successfully perform the task. Other definitions include:

- Hart and Wickens (1990) *"Workload is a general term used to describe the cost of accomplishing task requirements for the human element of man-machine systems"*
- Eggemeier et al. (1991) *"Mental workload refers to the portion of operator information processing capacity or resources that is actually required to meet system demands."*
- Young and Stanton (2001) *"The mental workload of a task represents the level of attentional resources required to meet both objective and subjective performance criteria, which may be mediated by task demands, external support, and past experience."* (p. 507)

There are commonalities among the various definitions, for example, Young et al. (2014) present two components; first, the authors present stress (i.e. task demands) and strain

(impact on the human). Stress can have multiple features including time pressure or task complexity. These can be supported by available resources such as team members or technology support. Young et al. (2014) claim the trade-off between stress and strain may have different effects on an operator. Lysaght et al. (1989) states that workload falls into three broad categories; the amount of work and number of things to do; time and the particular aspect of time one is concerned with; and, the subjective psychological experiences of the human operator. This research uses Parasuraman et al. (2008) definition of workload *"the relation between the function relating the mental resources demanded by a task and those resources available to be supplied by the human operator."*

Mental resources and capabilities are part of the human information processing system, figure 2.3. When stimuli arrive at the sensory receptors these are perceived and translated into three main stages: perception, decision-making/response selection and response programming/execution (Johnson and Proctor, 2004).

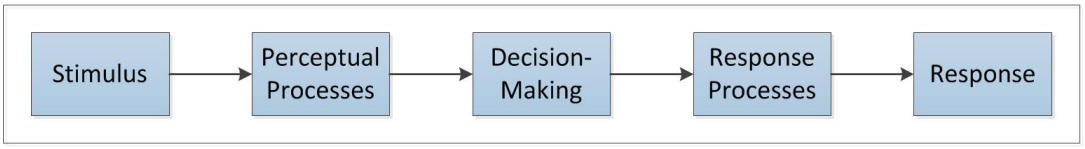


FIGURE 2.3: The Classic Information-Processing Framework (Johnson and Proctor, 2004)

As mentioned above, humans are characterised as having limited amount of information processing capacity which can deteriorate performance when a task exceeds their capacity (Welford, 1968). This concept was further developed by Kahneman (1973), Wickens (2008) and Wickens and Hollands (1999) who presented the term limited processing capacity to the term attentional resources. Depending on the task demands, the attentional resources are shared between a number of basic psychological processes such as perception, working memory and response execution (Wilson and Sharples, 2015, p. 520). The role of attentional resources in human information processing is illustrated in figure 2.4.

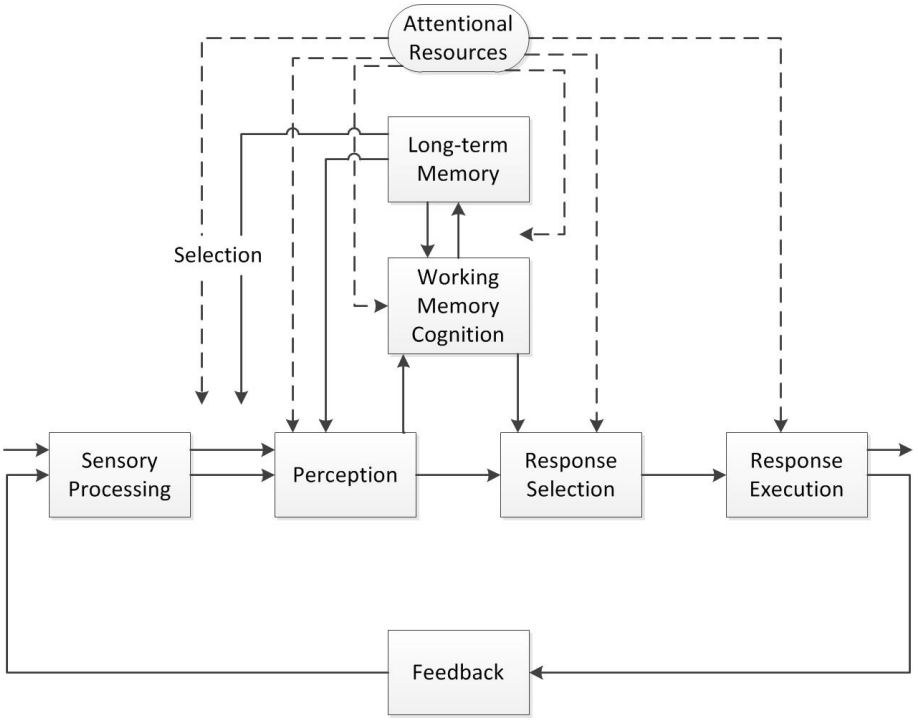


FIGURE 2.4: A General Model of Human Information Processing (Wilson and Sharples, 2015)

Resource theories explain workload through the concepts of attentional capacity and cognitive resources (Kahneman, 1973). The model of unitary-resource model of attention shows where the operator has a single resource of attention divided among different tasks in different amounts (Kahneman, 1973). When demand on attention exceeds the limited supply of attentional resource available the attention is voluntarily shifted. The unitary-resource model states that when demand for those attentional resources exceeds availability, performance will suffer. However, this model does not address when performance on one task degrades when difficulty levels increase on a concurrent task (Wickens, 1984), or when two tasks that interfere with other tasks do not affect each other when performed together (Johnson and Proctor, 2004).

Wickens (1984) developed the multiple resource theory, which proposes that operators do not have one single information processing source rather they use several different resources that can be used simultaneously. Multiple resource theory predicts the effects on performance when an operator carries out multiple tasks concurrently. This is particularly important in NDM contexts as it is a multi-task environment. Wickens (1984) identified four dimensions, each with two discrete levels (Figure 2.5). These include:

- The stages of processing dimension which describes that perceptual and cognitive (e.g. working memory) tasks use different resources from the selection and execution of action.
- The codes of processing dimension highlights that spatial activity uses different resources than verbal/linguistic activity.
- The modalities dimension outlines that auditory perception uses different resources than visual perception.
- Visual channels dimension outlines between focal and ambient vision, a nested dimension within visual resources.

The four dimensions defining the model have neurophysiological plausibility, where the dichotomies have parallels in brain anatomy (Wickens, 2008).

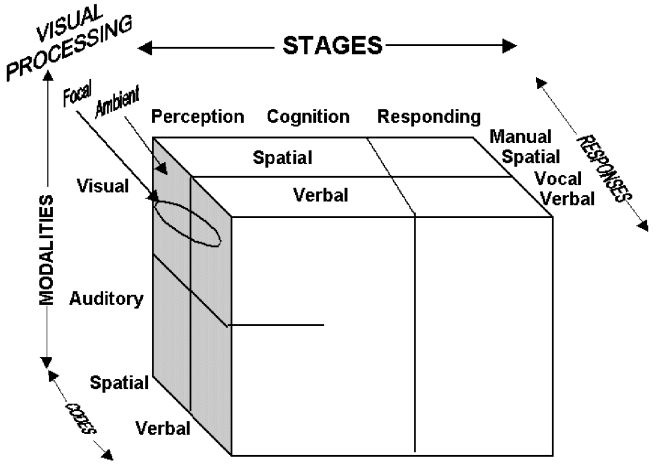


FIGURE 2.5: Wicken's Multiple Resource Model (Wickens, 2002)

When an operator experiences high workload, he or she is able to maintain performance levels at the expense of extra mental effort which can lead to fatigue and/or stress. The operator is able to manage high workload by making a strategy adjustment or strategy shift (Vidulich, 2003). This is where the operator changes his or her behaviour to a less effortful strategy to complete the task. The strategy may depend on three factors including individual characteristics (including training, motivation, age, health, etc.), task characteristics (i.e. its requirements, including work conditions) and workload levels (Sperandio, 1971). Another example of strategy shift is attentional narrowing, which highlights in stressful situations humans sometimes restrict their attention to some cues or information sources and ignoring others. It has been identified that operators experience attentional narrowing when they are told that they will experience a stressful situation, even before they have actually experienced it. This alone is enough to cause a significant reduction in

the number of attend stimuli (Weltman et al., 1971). A compensatory strategy known as the fatigue affect-effects may occur after a stressful task has been completed by an operator, where the operator may switch to low cost strategies in subsequent tasks (Schellekens et al., 2000). High workload demands can also result in speed-accuracy trade-offs where fast reaction times can be accompanied by high error rates vs. less errors but response time is increased (Sperandio, 1971). Gopher and Braune (1984) suggested that the workload concept was developed to explain the operator's inability to meet the requirements of a task.

As it is known that increasing workload reduces the ability of the operator to undertake efficient decision-making, the decision-maker needs to be supported when completing his/her tasks. These tasks include gathering information and identifying problems, reviewing causal factors with other team members and considering and sharing risks of alternative courses of action. Two forms of technological intervention are therefore possible; technology that reduces workload by automating – or more properly "offloading" – tasks that would otherwise consume mental effort (such as retaining information in memory or tracking states of environmental features mentally) or technology that supports the process of decision-making itself (i.e., decision support) (Rogers and Scaife, 1998).

2.3.2.2 Human Error

It is not surprising to learn that individuals make errors when using computer systems (Norman, 1983b). Errors are not only frustrating to the user but more seriously they can have severe consequences. Most errors are induced by inappropriate system design. This can be a result of system designers not considering the needs and functions of the users. Human error has been identified as a factor in a high proportion of incidents in complex and dynamic systems in NDM environments (Stanton et al., 2004). Human error has been investigated in many environments including aviation (McFadden and Towell, 1999), rail (Lawton and Ward, 2005) and healthcare (Helmreich, 2000).

Reason (1990) defines error as *"all those occasions in which a planned sequence of mental or physical activities fails to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some chance agency."* Latorella and Prabhu (2000) highlight human error is multifaceted and propose; *"(1) human operators are organic mechanisms with failure rates and tolerances analogous to hardware/software of a system, (2) that human is a pejorative term for normal behaviour in often unkind environments, where only the outcome determines if this behaviour is deleterious".*

Error is a key aspect in NDM environments, it alerts designers to areas where performance can be improved (Lipshitz et al., 2001). The NDM setting rejects the notion of faulty reasoning but instead attempts to understand why poor decisions were made. Klein (1993a) identifies weaknesses in NDM strategies linked to the three primary forms of inference used in NDM; feature matching, analogical reasoning and mental simulation. During feature matching the decision-maker may use the wrong features or may weigh the features incorrectly. When the decision-maker is undertaking analogical reasoning, he/she may select the wrong analogues or adjust the analogues incorrectly. During mental simulation, the decision-maker may build an inadequate mental simulation and fail to reject an inaccurate mental simulation. HF issues including workload and inadequate communication has been identified as *"major determiners of a human error"* (Park and Jung, 1996) as well as lack of experience (Lipshitz et al., 2001).

Literature investigates the types of errors, methods of predicting human error and methods for analysing errors in systems and tasks (Reason, 1990) . Types of errors are briefly discussed in this review, however methods for predicting error and analysing errors in systems and tasks are beyond the scope of this research.

Rasmussen (1982) presents skill, rule and knowledge based approach which identifies the types of error likely to occur in different operational situations, or within different aspects of the same task where different types of information processing demands on the individual may occur. Building on Rasmussen's work, Generic Error Modelling System was developed to describe how switching occurs between the different types of information processing (skill, rule, knowledge) in tasks (Reason, 1990). Reason (1990) finds that there are four error categories, which include; slips, lapses, mistakes and violations. Slips (attentional failure) refer to when the wrong control has been activated. Lapses (memory failure) refer to something that has been forgotten or a task step that has been missed. Mistakes (wrong intention) are those where the operator does the wrong thing due to a misunderstanding or misconception. Mistakes imply that the intended task was executed, but it was the wrong task given to the context. Violations are where the operator performs an action that they know is not allowed but they implement it anyway. (Wilson and Sharples, 2015, p. 796) stated that there are three overt error types that should be considered during any human error analysis; omission error, not carrying out a required act adequately and extraneous act. Omission error are those that the required act has not been taken. Not carrying out a required act adequately are those acts that are preformed without the required precision, at the incorrect time or in the wrong sequence. Extraneous acts are unrequired acts which are performed (also known as error of commission).

Dekker (2006) and Woods et al. (2010) also suggest human error needs to take the context of the system in which operators work into account. Human performance is shaped by both situational and environmental contexts. Multiple factors contribute to an error occurring, and the relevant characteristics of situations and environments are usually easier to modify than the relevant characteristics of operators (Allen and Rankin, 1995). Further gaining an understanding of why the decision-maker chose their action in past incidents is essential for future progress to ensure that the same mistakes are not made again (Flach et al., 2008).

A number of researchers have investigated the need for principles to support the design of systems to reduce error. Norman (1983b) presents design rules which provide support to system designers. The principles cover the need for better feedback, system configuration, consistency as well as the need to avoid overlapping in command sequences, memory reminders and reversible actions. Chen-Wing and Davey (1998) present human error prevention and reduction principles to support designers of plant designs to create solutions to decrease risk of human error occurrence and consequence.

2.3.2.3 Uncertainty

NDM environments have different types of uncertainty, these include; uncertainty about the information they have and uncertainty about the correct course of action which makes the decision-making process difficult.

There are numerous definitions for uncertainty (Griethe and Schumann, 2005, Hunter and Goodchild, 1993, MacEachren et al., 2005)), however this research uses Riveiro (2007)'s definition:

> *"Uncertainty is a complex concept and there are many kinds of uncertainty that decisions makers must face. It covers the broad range of concepts like inconsistency, doubtfulness, reliability, inaccuracy and error". (Riveiro, 2007)*

There are a number of factors that can cause uncertainty in data and can be introduced in any step of investigating and acquiring the data, filtering and mapping operations to the final representation (Griethe and Schumann, 2005).

Griethe and Schuhmann (2006) review a number of papers and sum up the different concepts that are encompassed in uncertainty, these include:

- Error: outlier or deviation from a true value

- Imprecision: resolution of a value compared to the needed resolution (e.g. values are highly accurately given for countries but are needed for states)
- Accuracy: size of the interval a value lies in
- Lineage: source of data (e.g. at first hand or at second hand)
- Subjectivity: degree of subjective influence in the data
- Non-specificity: lack of distinctions for objects (e.g. an attribute value is known to be one of several alternatives but not which one)
- Noise: undesired background influence

Pang et al. (1996) identify three types of uncertainty that can arise during decision-making. First, statistical, which is distribution of the data or estimated mean and standard deviation (confidence interval). Secondly, error, which is an absolute valued error among estimates or differences between a known correct datum and an estimate. Finally, range, an interval in which the data exists (and cannot be quantified into either the statistical or error definitions). Atoyan et al. (2011) present two types of uncertainties; objective and subjective uncertainties. The objective uncertainties include uncertainties with the input data, uncertainties connected with automated processes and uncertainties connected with fused output data. Subjective uncertainties are those uncertainties in the operator's mind. These types of uncertainties identify that people perceive and process information differently from one another and are based on the operator's expectations, mental model and trust.

Strategies that decision-makers apply to different types of uncertainty in NDM settings are presented by Lipshitz and Strauss (1997) as reduction, assumption-based reasoning, weighing pros and cons, suppression, and hedging heuristic. The authors found that there were three types of uncertainty; inadequate understanding, incomplete information, and undifferentiated alternatives. They found that decision-makers employ five coping strategies which include; reducing uncertainty, assumption-based reasoning, weighing pros and cons of competing alternatives, suppressing uncertainty, and forestalling. Inadequate understanding was primarily managed by reduction, incomplete information was primarily managed by assumption based reasoning, and conflict among alternatives was primarily managed by weighing pros and cons. Similar lists of coping strategies were reported by Allaire and Firsirotu (1989), Janis and Mann (1977), Klein (1999), Shapira (1995).

Visualising uncertainty in systems is important to guide decisions and to increase the decision-maker's situation awareness. Uncertainty is considered as scalar attribute values for example by estimating which measured values are missing or how probable a value

seems (Griethe and Schuhmann, 2006). Often, the given raw data already containing statements on its reliability, e.g. on the precision of used instruments (e.g. standard deviation) or on the completeness of a set of data (e.g. a number of missing values). Different types of visualisations of uncertainty were outlined in Griethe and Schuhmann (2006), Pang et al. (1996), Riveiro (2007). Atoyan et al. (2011) also present design guidelines to help operators cope with uncertainties in complex dynamic environments.

However, there are challenges when visualising uncertainty, such as controlling the explosion of output data (Griethe and Schuhmann, 2006). Riveiro (2007) emphasises *"that most of the developed techniques to present uncertainties do not include a perceptual and cognitive analysis or user evaluation that validates their usefulness"*. MacEachren et al. (2005) further echoes that little has been understood about the impact of visual depiction of uncertainties on decision-making process and decision outputs. They emphasised that "comprehensive guidelines for representing uncertainty do not yet exist" and that more research was needed to address all these questions.

2.3.3 Individuals in a Team Environment

There were two factors identified from individuals in a team environment these include team and communication, see table 2.7 .

Teamwork	**Communication**

Table 2.7: Individuals in a Team Environment HF Issues

2.3.3.1 Teamwork

Salas et al. (1992) outline teams are made up of two or more people who collaborate towards a common goal or objective, each person may be assigned an individual role which involves different functions of limited time duration. The authors go on to define a team as a *"distinguishable set of two or more people who interact dynamically, interdependently, and adaptively toward a common and valued goal/object/mission, who have each been assigned specific roles or functions to perform, and who have a limited life span of membership."*. This definition shows that the team is made up of individual team members who have individual roles (Salas et al., 1995). Kaber and Endsley (1998) state that members in a team have similar characteristics as those acting individually, the characteristics include; working towards a particular goal, performing a specific role/function in the task environment and completing the goal in a limited amount of time.

Research in the NDM investigates two key questions for teams:

- What is effective team decision-making (Orasanu and Connolly, 1993b)?
- What turns a team of experts into an expert team (Salas et al., 1997)?

The questions aim to understand how decision-making manifests in teams, investigating the teams distributed knowledge, information and expertise. There are a number of things that need to be taken into account when in a team, this includes team situation awareness, shared problem assessment, team mind and shared mental models (Lipshitz et al., 2001). The related concept of teamwork enables a group of individuals to effectively carry out team decision-making. It is the process in which operators seek, exchange and bring together information in order to decide a course of action (Lipshitz et al., 2001). Cannon-Bowers and Salas (1998) highlight that adaptability, shared situational awareness, performance monitoring and feedback, leadership and closed-loop communication contribute to effective team decision-making. In the aviation domain variables such as personality types, status differentials, and speech patterns have been examined to determine their effects on decision-making (Orasanu and Connolly, 1993b). The challenges of studying teams in the environment are; the expense to carry out the work, labour-intensive, difficult, frustrating and it can take a team to study teams in context (Lipshitz et al., 2001). Aviation psychology researchers identified that pilots' attitudes affected performance which could be modified through structured team training (Helmreich and Foushee, 1993, Stout et al., 1997).

The following investigates team situation awareness and shared mental models.

Team Situation Awareness

In the literature a distinction is made between individual SA and team SA. Team SA refers to a shared or distributed awareness or mental representation of the environment between team members. Lipshitz et al. (2001) outlines that team situation awareness is essential for effective decision-making, especially since obtaining and maintaining SA in teams is far more complex than in individuals. Team SA can be acquired when members of the team collect and exchange information and when the members engage in closed-loop communication (Orasanu, 1990). Salas et al. (1992) state that each member's role is a sub-goal, which contributes to the overall team goal and can dictate the SA elements that they focus on. Endsley (1995b) suggests that team SA is the total SA for each individual, independent of any overlap in SA requirements among operators. Endsley and Jones (1997) argue each member of the team need to have sufficient SA otherwise a "weak link" will occur. When a person does not have the same SA as the rest of the team, this could lead to performance errors.

Situation awareness in teams is a more complicated activity than simply combining the situation awareness of individual team members(Schwartz, 1990). Endsley and Jones (1997) state for a team to successfully function, all team members must possess a high level of the same SA on shared requirements. The authors go on to state there are many different states in which shared SA can occur within teams including *"(1) the situation assessments of all team members are correct, (2) all assessments are incorrect, or (3) all operators have a different assessment of the same situation with some being correct and others being incorrect."*

Endsley (1995b) indicates that her theory of the three levels of SA (perception, comprehension and project) focuses on individual SA, whereas team SA involve activities such as coordination and information sharing. With respect to factors influencing the achievement of shared SA between teams, they may be identical to those that drive shared SA within a team are included in table 2.8.

Drivers for shared SA
The organisational culture.
The ability of teams to meet requests for assistance.
By other teams.
The availability of high bandwidth communications.
The level of inter-team planning and strategy development.
The level of time stress to which separate teams are subjected.
The presence or absence of distributed mental models.
The verbalisation of information used in decision-making.
The level of feedback on actions between teams.

TABLE 2.8: Drivers for Shared Situation Awareness (Kaber and Endsley, 1998)

Further, differences between SA within a single team and among a distributed team are that members in a distributed team do not share a common environment which can impact SA as non-verbal communication cannot be carried out. This can impact team coordination as members are physically separated, which can interrupt the process of information flow. Endsley and Jones (1997) state that control teams are required to rely on voice communication and shared displays, which are used to relay information to the members of various teams.

Shared Mental Models

Shared mental models are *"knowledge structures held by members of a team that enable them to form accurate explanations and expectations for the task, and in turn, to coordinate*

their actions and adapt their behaviour to demands of the task and other team member" (Cannon-Bowers et al., 1993). According to Cannon-Bowers et al. (1993), shared mental models provide an understanding of how teams are able to cope with difficult and changing task conditions. Mathieu et al. (2000) suggest that team member who share mental models are able to anticipate each other's responses and coordinate effectively in time critical situations and when communication is limited.

Research has identified that high performance teams require the ability to adapt effectively (Cannon-Bowers et al., 1995, McIntyre and Salas., 1995). Shared mental models identifies the mechanisms of adaptability which highlights how teams can quickly and efficiently adjust their strategy. Shared mental models have been linked to enhanced team performance (Cooke et al., 2007). Lipshitz et al. (2001) indicates that having a shared understanding of the task allows the members to know who is responsible for what and the information needs and requirements. Having this understanding allows the team members to anticipate the others' needs, allowing them to have better communication, planning and better decision-making performance (Stout et al., 1999b, Volpe et al., 1996a).

The impact of expertise is that the decision-maker will have many well-formed mental models to cope with emergencies. Whilst different people have different mental models based on their individual experiences and knowledge in the teams they will also have similar mental models of how to handle the situation based on their domain experience and training.

Cannon-Bowers et al. (1993) propose that a team is most effective when they share four mental models which include the equipment model, task model, team interaction model and team model. The equipment model outlines the team members' shared understanding of the technology and equipment with which they carry out their team tasks. The task model highlights the team member's perceptions and understanding of team procedures, strategies, task contingencies and environmental conditions. The team interaction model captures team members' understanding of each member's responsibilities, norms and interaction patterns. Finally the team model reflects team member's understanding of each others' knowledge, skills, attitudes, strengths and weaknesses. Mathieu et al. (2000) argued that the four mental models proposed by Cannon-Bowers et al. (1993) reflect two content areas: task-work (subsuming Cannon-Bowers et al. (1993)'s first two models) and teamwork (subsuming Cannon-Bowers et al. (1993)'s last two models).

2.3.3.2 Communication

Communication can be considered as all the ways ones mind affects another, either verbal or non-verbal, intentional or unintentional (Eccles and Gershon, 2004). Hogg and Vaughan (2002) define communication as the /textit"transfer of meaningful information from one person to another", which involves the production and the reception of messages. The basic concept of communication requires a sender to send a message or information and for a receiver to receive this through a channel of communication. Isaac and Ruitenberg (1999) indicates that communication starts when a sender encodes an idea or message and sends it through one or more channels that can be either verbal or non-verbal. The receiver then decodes this message using long term memory to bring meaning to the message. The receiver may have different characteristics which include experience, culture and expectations which may affect decoding.

The impact of communication on team performance has been widely studied (Salas et al., 1995). Research shows that having either too little or too much communication could impact performance (Patrashkova-Volzdoska et al., 2003). A meta-analysis found that information sharing positively predicted team performance, particularly when unique information was shared (Mesmer-Magnus and Dechurch, 2009). Communication facilitates reaching and maintaining coordination (Ellingsen and Östling, 2010), other research has reported that it can resolve team conflict (Bornstein and Gilula, 2003).

Isaac and Ruitenberg (1999) make a distinction between verbal and non-verbal communication, where verbal forms include speech and written where speech pitch, tone and rhythm have an important role in communicating and supporting to the message and consequently the decoding (Huttunen et al., 2011). In contrast non-verbal communication includes forms such as gaze, gesturing and facial expressions. Non-verbal communication can occur independently or in combination with other forms of communication. Hogg and Vaughan (2002) state "speech rarely occurs in isolation from non-verbal cues."

Communication can also be differentiated via direct (message stated explicitly) or indirect (not intended for the individual who gains information). It can also be differentiated on addressed (message sent intentionally) or non-addressed (messages sent without the intention of the sender) communication. These types of communication influence the receipt and correct interpretation of the message by the receiver and thus the efficiency of the communication (Hogg and Vaughan, 2002). Communication is highly related to other team processes as they would not be possible without information sharing and transfer between team members (Waterson, 2015).

In order to support successful communication, domains such as aviation have developed communication training to support the decision-makers. For example, in aviation, crew resource management has been applied to the process of training to reduce pilot error through better use of human resources on the flight deck (Helmreich et al., 1999). The training was developed to increase aircraft safety as well as efficiency of flight. The crew resource management philosophy has proved popular with other domains, with healthcare adopting the approach (Lyndon, 2006).

Bowers et al. (1998) investigated communication styles and found that high-performing teams engaged in more planning statements, asked more questions, and repeated commands more frequently than low-performing teams. Effective teams require advanced planning, which correlates to the development of shared mental models of the situation and support for efficient communication during high-workload conditions (Stout et al., 1999b). In addition, target training has a positive impact on team performance, which can support operator attitudes, knowledge, and coordinated performance (Stout et al., 1997).

2.4 Section Three: Discussion

This chapter presents the naturalistic decision-making process and the recognition primed decision model which investigates how individuals effectively make decisions in complex situations. The model identifies that decision-makers identify a single solution based on the constraints in the environment. The chapter also presents seven human factors issues that affect this process which are split into cognition, interactions between an individual and the environment and individuals in a team environment. By understanding these factors, an understanding can be formed to understand how the decision-maker needs to be supported during real-world decision-making.

This research proposes a general framework based on the findings, which present the relationship of decision-making and the human factors issues, figure 2.6.

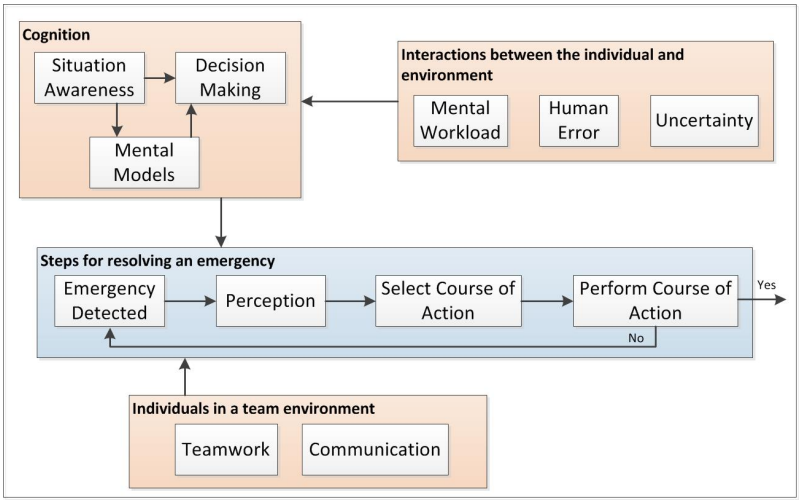


FIGURE 2.6: Overview of the Human Factors Issues that Contribute to Naturalistic Decision-Making

At the centre of the diagram the steps of resolving an emergency are presented adapted from figures 2.2 and 2.4. These include detecting an emergency, perception, selecting a course of action and performing a course of action. The main human factors issues that support the detection of an emergency include situation awareness, mental models and decision-making. Decision-making is also used to support the next task of selecting the course of action. There are also three key issues that influence the individual and environment this includes workload, human error and uncertainty. The next task is to perform the course of the action and to identify the outcomes. If the outcomes are successful usually there are limited actions that need to be completed. However, in the event that it has not been successful the diagram loops back to a problem being detected. Each of tasks are affected by HF issues in a team environment which include team (shared mental models and shared situation awareness) and communication.

The findings from this chapter have identified how the human issues affect the decision-maker and consequently identified the behaviours that need to be investigated further in real-world settings. Furthermore, these human factors issues need to be supported in the design of NDM system. Whilst each of the human factors have been well researched they have not been brought together when designing systems for NDM environments.

2.5 Chapter Summary

This chapter contributes to the first aim by identifying NDM and the human factors issues that affect NDM in emergency contexts. The chapter investigates decision-making theories

which include NDM and finds that decision-makers find a single solution based on constraints. The research presents seven human factors issues including situation awareness, mental models, workload, human error, uncertainty, team and communication. These are split into three main themes; cognition, interactions between individual and environment and individuals in a team environment.

NDM and the human factors issues will be investigated in the following chapters in real-world domains. It is proposed when designing systems to support effective NDM that not only the decision-making process needs to be considered but also the human factors issues. Whilst each of the human factors have been well researched they have not been brought together when designing systems for NDM. Whilst research has been done to investigate the decision requirements limited research has been undertaken to understand how the factors need to be included into the design.

Chapter 3

Methodological Approach and Research Framework

3.1 Chapter Overview

This chapter describes the research approach and framework of the thesis. The research approach outlined is the approach taken to address each of the three thesis aims. A strategic combination of methodologies were undertaken to understand naturalistic decision-making in emergency situations. The chapter then presents the research framework which outlines the four research phases to address the three thesis aims. The methods used for each research phase are described in order of completion and associated to the research aims.

3.2 Overall Research Approach

A combination of methods were utilised to address the aims of the thesis. Table 3.1 summarises the methods used to investigate the aims. The strength of this approach is that a comprehensive understanding of NDM from varying perspectives is generated to support the development of the design principles. The benefits of applying multiple methods include quantitatively confirming qualitative findings, contributing to experimental results, establishing statistical tests and integrating small-scale studies with a large-scale perspective (Robson, 2002).

The research approach began by investigating previous NDM research and examining previous research in the factors that influence the naturalistic decision-making process. In

Aim	Aim Description	Research Methods
1	Identify the typical HF issues that affect NDM.	Literature analysis. Interviews with decision-makers including using the critical decision method. Focus groups. Ethnographic study of a NDM environment.
2	Examine NDM and the HF issues in real-world environments	Cognitive work analysis. Decision Centered design. Experiment: design of a system for use in a NDM environment.
3	Develop guidance to support NDM system designers	Workshops with HF experts. Interviews to develop design guidance.

TABLE 3.1: Mapping Between Research Aims and Methods

discussions with Airbus, three main themes which affect the NDM process were identified; cognition, the environment and team. To address these three themes, seven human factors issues were identified; situation awareness, mental models, workload, human error, uncertainty, teamwork and communication. The seven factors were deemed satisfactory for further investigation by Airbus as the main issues influencing naturalistic decision-making.

Research was undertaken in both field and experimental settings. Two studies using real-world decision-makers from the aviation and fire & rescue domain were used to investigate the multi-factor issues and the association with decision-making performance, through a set of real-world incident case studies. Analytical methods, cognitive work analysis and decision centered design, were used to further investigate naturalistic decision-making process, the factors that affect the decision-making process and identify system design requirements. In collaboration with Airbus Defence and Space an experimental study with pilots contributed to the design of a novel single pilot operated aircraft interface built using the identified design requirements. The interface was implemented in a flight simulator, where fourteen pilots performed three emergency related tasks and investigated the pilot's performance. Based on all findings, 16 initial design principles were created, with an aim to provide naturalistic decision-making system designers with a guide of how to integrate the seven factors into the design of systems to support effective decision-making. A final validation study, with human factors experts as participants, was carried out which identified the usability, validity and applicability of the design principles. The final principles resulted in twenty-two cognition informed system design principles, including definitions, examples and points to consider when designing.

3.3 Research Framework

3.3.1 Overview of the Methods Used in This Thesis

The research framework (figure 1.2) provides an overview of the selected methodologies and descends vertically. Four research phases were implemented in order to investigate the three aims of the thesis. Research phases are presented on the left hand side of the figure, whilst the research aims are stated by each phase on the right hand side. The arrows show the progression of the research studies, however, there is no meaning to the length of the arrows or the size of the boxes; differences are only for presentation purposes.

3.3.2 Research Phase 1: Background and Context

The first research phase investigates NDM and identifies the typical HF issues that affect NDM. In collaboration with Airbus, three key themes which affect the decision-making process were identified. These factors included the operator's cognition, interactions between the individual and the environment and individuals in the team environment. From the literature the following HF issues were identified as factors that are part of the complex process of decision-making in naturalistic domains; situation awareness, mental models, workload, error, uncertainty, team and communication. The seven HF factors were presented to Airbus who deemed the factors as satisfactory for further investigation in the thesis.

3.3.2.1 Literature Review

A literature review investigated previous NDM research and the HF issues that influence decision-making in emergency environments (chapter 2). The seven HF issues formed the basis of the factors that need to be supported when designing for real-world decision-making. It is concluded that few research studies support the design process when creating these types of systems. In addition, the proposed guidance needs to support the HF issues that influence the NDM process. An initial model of the NDM steps and the seven HF issues was formulated to present an overview of factors involved in this complex environment.

3.3.2.2 Methodological Approach and Framework

The methodological approach and framework supported the development of research studies and informed the progression of the research (chapter 3). Most chapters take a progressive approach where findings from one study were used to contribute to the aims and design of subsequent studies. The exception is chapter 5 (aviation domain), which is a parallel activity with chapter 4 (F&RS domain). The findings from both these chapters are integrated into the design principles.

3.3.3 Research Phase 2: NDM in Real-World Environments

Two field studies were performed to give understanding of NDM in two environments. Two separate methodologies were applied to achieve the second aim, to examine NDM and the HF issues in real-world environments.

3.3.3.1 Fire & Rescue Service Environment

Data Collection: Kick off Interviews, Focus Group and Critical Decision Method

An exploratory study was implemented which included two types of interviews (chapter 4) to get an initial understanding of the NDM environment.

First, kick off interviews and a focus group were undertaken by visiting the F&RS. The focus group consisted of a semi-structured process, using open ended questions to investigate the challenges in the environment and types of incidents the firefighters attend. In addition, one-to-one semi-structured interviews with system specialists were performed. The interviews investigated in detail the technologies the operators use to make NDM decisions and resolve an emergency. The system specialists demonstrated the system and explained each of the datasets within the system.

Secondly, critical decision method interviews were undertaken as emergencies in the F&RS are complex and unpredictable. It was decided that a retrospective interview process would be used to investigate the environment as it was deemed unsafe for the researcher to attend an emergency. The critical decision method has been used in a number of emergency domains including fireground (Klein et al., 1986), aviation (O'Hare and Wiggins, 2004), medical (Patterson et al., 2003, Wong and Blandford, 2002) and disaster management (Mendonça, 2007, Smith and Dowell, 2000). Three detailed critical decision method interviews were performed with decisions makers to identify the NDM steps and the additional HF issues which support effective decision-making. The interviews are a retrospective

cognitive task analysis technique where individuals were asked to recall an incident that they had previously attended (Klein et al., 1989, O'Hare et al., 1998). The interviews were open-ended and exploratory, but aimed to address the specific actions taken to resolve the incident. The participants were then systematically probed to investigate their NDM process during the incident. The findings from the CDM interviews were reviewed to identify the HF issues affecting the NDM process.

Analysis: Cognitive Work Analysis

From the above data collection, a cognitive work analysis was performed to analyse, develop and evaluate the complex socio-technical systems. Cognitive work analysis is a multifaceted approach to analyse human information behaviour (Pettigrew et al., 2001). The goal of cognitive work analysis was to make the constraints and complex relationships in the work environment perceptually evident to the researcher. The analysis allowed the researcher to understand the environment the tasks are carried out in and the effect of the imposed constraints on the system's ability to perform its purpose. Sanderson (2003) stated that cognitive work analysis focused on identifying properties of the work environment and of the workers themselves that define possible boundaries on the ways that human-system interaction might reasonably precede, without explicitly identifying specific sequences of actions. The analysis answers a number of questions, which includes why the system exists, what activities are conducted within the domain, how this activity is achieved and who is performing it (Jenkins et al., 2009). As stated by Vicente (1999), cognitive work analysis is non-prescriptive, this flexibility is required as this was an initial approach used to get an understanding of a NDM environment.

Cognitive work analysis is made up of 5 defined phases; work domain analysis (WDA), control task analysis (ConTA), strategies analysis (StrA), social organisation and cooperation analysis (SOCA) and worker competencies analysis (WCA) (Vicente, 1999). WDA presents formative modelling, which starts by understanding how the system works and presents all the items present in the NDM environment. This leads to ConTA, which outlines an event and time independent description of the system. This phase identifies the inputs and end goal without describe the intermediary steps, identifying what needs to be done without describing how or by whom. This allowed the researcher to investigate the key decisions and types of questions and information the decision-maker uses in the decision-making process. StrA investigates how to complete the same task in a number of different ways, addressing how an activity can be completed. SOCA presents the constraints established by organisational structures and specific actor results. This presents the actors and which steps in the NDM process they typically complete. Finally, WCA investigates the behaviour required by the humans within the system required to

complete tasks. The analysis gave the researcher a whole system view of the social system and technical system as well as the interactions. The outputs of cognitive work analysis describe the strategies, decisions and activities of the system. The approach has been applied to a number of NDM domains including aviation (de Carvalho et al., 2009, McIlroy and Stanton, 2011), healthcare (Carayon and Buckle., 2010), military (Jenkins et al., 2008, Salmon et al., 2010), rail (Golightly et al., 2010, Read et al., 2016, Stanton et al., 2013) and submarines (Stanton and Bessell, 2014), highlighting its versatility.

CWA was used to analyse the NDM environment separate from the individual tasks the decision-maker completes. The outputs of the CWA framework provides the researcher with an understanding of the components of the environment, calculations made, the team involved including external parties, as well as, the NDM process in the form of decision ladders. An important output of the CWA are the questions the operators ask during the steps of resolving an incident. These questions indicate the type of information required by the decision-maker and the step in the RPD model, which could be developed into future technologies.

3.3.3.2 Aviation Environment

Decision Centered Design (Stages 1, 2 and 3)

A second NDM environment was investigated to get a further understanding of decision-making and the HF issues (chapter 5). Whilst CWA provided a rich understanding of NDM, a different method was implemented to investigate the aviation domain as the methods used to investigate the F&RS had a number of weaknesses. The combination of methods used in the F&RS provided limited investigation of the decision points required for NDM and minimal support to generate ideas to support the design of a NDM system. Furthermore, there was little support to investigate the domain during normal procedures. For these reasons the DCD framework was used to investigate NDM in the aviation domain. The Decision centered design method allowed the following:

- The aviation domain is made up of normal and non-normal situations. During normal situations, the pilots have procedures they must follow and have extensively trained for. However, during non-normal situations, such as emergencies, the pilot must deviate from the normal procedures, requiring NDM. Normal situations need to be investigated to get a full understanding of the environment.
- In collaboration with Airbus, a project was identified to apply the findings. The project aims included creating and evaluating a prototype for this NDM environment.

The approach focuses on understanding and supporting cognitive tasks. It allows for communication and understanding between designers and the individuals for whom interventions are being designed (Hutton et al., 2003). The approach is based on cognitive task analysis, which can identify the key decisions and overcome the associated sources of difficulty. There are five steps in this approach: preparation; knowledge elicitation; analysis & representation; application design and evaluation. Decision centered design was selected as it investigated NDM in a similar fashion as the F&RS environment (stages 1-2 of decision centered design) however, decision centered design focuses on designing to support naturalistic decision-making (stages 3 and 4), as well as, using the findings to generate a design and evaluate it (stages 5).

Like the F&RS two rounds of interviews were implemented, these are presented in the first two stages of the approach.

Stage 1: Preparation

Stage 1, the pilots' activities were investigated during normal operations by implementing an ethnographic study, which observed a two pilot aircrew in the flight deck. Post-flight interviews with the pilots were carried out to gain an understanding of their naturalistic decision-making process and the HF issues which influence this process. The factors identified in the literature review were used as a framework to report findings. This stage also identified that critical NDM occurred during emergency procedures on-board an aircraft.

Stage 2: Knowledge Elicitation

Stage 2 further investigated the tasks two pilot aircrews completed during emergency procedures using critical decision method; paying attention to the key decisions that must be made in order to resolve the emergency. This section investigates the steps in the RPD model, as well as, the factors that surround the complex NDM process. Like the F&RS it is difficult for HF experts to attend emergencies, as there is no way to pre-empt when an emergency will occur. A variety of non-normal situations were covered to outline the variety of NDM examples. The participants were asked to think about an incident that they had attended, which involved attending to an emergency in the aircraft. They were then systematically probed about the decisions and actions that they made during the incident. The procedure included the participants describing the incident and developing a task decomposition diagram like the F&RS. However, a further step was added where the researcher and participant identified the main decision points during the incident. These decision points were then systematically investigated using set questions, which provided a structured approach for deeper analysis of the decision points. This step identified two additional steps in-comparison to the RPD model; stabilise emergency and monitor the

course of action. These additional steps were included in the final cognition informed system design diagram and principles.

Stage 3: Analyse and Representation

Stage 3 presents analyse and representation, using the findings from stage two, the decision requirements are investigated to highlight design leverage points. The steps of resolving an emergency and the identified HF issues were the main input into the design requirements.

3.3.4 Research Phase 3: Experimental Investigation of HF in Design

Phase 3 applies the findings from the previous stages to design a system for a NDM environment. The system developed has been designed for single pilot operation in the aviation environment and was evaluated to investigate the impact on the decision-maker.

3.3.4.1 Decision Centered Design (Stages 4 and 5)

Using the findings from the previous stages, the final stages 4 and 5 of decision centered design were completed (Chapter 6).

Stage 4: Application Design

Stage four uses the design requirements from the previous stage to design a NDM system for single pilot operations in the aviation domain. This stage presents the design of a fuel system for a novel jet aircraft and identifies the main features of the design. The design prototype supports the NDM process and considers the complexity of NDM environment.

Stage 5: Evaluation

The final stage evaluates the design of the NDM system. This stage outlines the human factors methodology, the results and recommendations. An experiment was created to investigate three of the main factors (decision-making, situation awareness and workload) that impact the pilot as advised by Airbus D&S. Fourteen participants were studied to evaluate the system, the number of participants was restricted due to the confidentiality of the project, consequently, only Airbus pilots could be used for the evaluations.

Participants' behaviours were observed and recorded throughout the experiment. Findings contributed to identifying if the HF issues have a positive impact on the decision-maker. Both qualitative and quantitative methods were recorded for decision-making (correct

decisions and time taken to complete the scenario), situation awareness (situation present assessment method values and 3D situation awareness rating technique questionnaire) and workload (situation present assessment method and NASA task load index questionnaire), combining objective and subjective views. A usability questionnaire was also implemented at the end of the evaluation. Pilots were used to evaluate the new system using scenarios to complete events.

3.3.5 Research Phase 4: Development of Design Principles

This phase developed design principles to support system designers for NDM environments.

3.3.5.1 Synthesis of Design Principles

This study synthesises the findings from previous phases into design principles for designers creating real-world decision-making systems (chapter 7). The design principles were formulated based on the understanding gained of the naturalistic decision-making process and the identified 7 HF issues from the field studies. The summaries of the HF issues were used to identify examples for the designers of how the factor identifies in the real-world, providing the reader with validation of the factor and examples. Once the initial set of design principles were created, the researcher identified three key questions that needed to be addressed when developing the design principles. The questions investigated if the principles were usable, understandable, complete and if they could be applied to other domains.

3.3.5.2 Design Principles Evaluation

To address the questions outlined when developing the design principles, two workshops were carried out with ten HF experts who completed four activities to evaluate and further develop the design principles. The HF experts applied the principles to create a system for the F&RS, which allowed them to become familiarised with the principles. The experts were then interviewed using a semi-structured approach which provided comments and amendments to further develop the principles.

Four activities were completed, activity one asked each group to work as a design team and use the guidance to create a system to support the F&RS incident commander's decision-making process during an emergency incident. In activity two, the group indicated which design principles had been used to inform their prototype. For activity three, the group

ordered the principles according to how useful they were to design the prototype. Activity four, investigated feedback from the participants regarding their views of using the design principles through a semi-structured focus group.

3.3.5.3 Cognition Informed System Design

A set of 22 principles were created based on the findings from the evaluation study and were developed to form Cognition Informed System Design (chapter 8). The principles expose the complex steps of NDM and highlight the main steps that need to be supported for effective naturalistic decision-making. The principles, checklist and interviews were integrated into an on-line tool for designers of real-world decision-making systems.

3.3.6 Discussion and Conclusions

The discussion chapter (chapter 9) presents the results that were generated throughout the thesis. The chapter reflects on each research aim, the approach and methods applied. Further, contributions resulting from the thesis are highlighted. To conclude, the thesis limitations of the research and suggestions for future research, are discussed.

3.4 Chapter Summary

This chapter outlines the research approach used in the thesis and provides the overall research framework. A combination of methods was implemented to address each of the research aims. Furthermore, a combination of settings was used, including field and laboratory settings to address the research aims. The research framework illustrated the overall development of the research. The chapter concluded with a summary of each method used in the thesis and where appropriate, a description of methods building upon previous research findings.

Chapter 4

Applying Cognitive Work Analysis to Understand NDM in the Fire and Rescue Service

4.1 Chapter Overview

This chapter presents an exploratory study, which investigates how operators make real-world decisions in the Fire and Rescues Service (F&RS). Chapter 4 contributes to the second aim of this thesis, to examine NDM and the HF issues in NDM contexts. The chapter provides a description of the decision-maker's tasks, decision-making process and the HF issues that support the decision-making process.

Three activities are detailed in this chapter. Activity one presents the findings from a kick-off meeting with system managers and a focus group, which presents an initial understanding of the F&RS including a description of the F&RS domain as well as an insight into the team and technology. Activity two presents three critical decision method (CDM) interviews with two incident commanders (IC) and a second in command (SiC) who are main decision-makers at an emergency. The interviews present a detailed account of how decision-makers resolved an emergency, providing a step-by-step account of the actions the decision-maker completed. Activity three uses the findings from activities one and two; a cognitive work analysis (CWA) was performed. CWA identifies the properties of the work environment and of the workers themselves that define possible ways that human-system interaction might reasonably proceed, without explicitly identifying specific sequences of actions (Sanderson, 2003). The method identifies why the system exists, what activities

are conducted within the domain, how this activity is achieved and who is performing it.

4.2 Introduction

The emergency services are essential for public safety as they prevent incidents, respond to emergencies and protect the environment. There are 63 fire brigades in England, Wales, Scotland and Northern Ireland that consist of approximately 12,000 whole-time firefighters and 18,000 retained firefighters (Fireservice.co.uk, 2016). Whole-time firefighters are assigned to a watch on permanent shifts, whereas retained firefighters train for a few hours a week and attend the fire station when called out to an emergency. A firefighter's responsibilities may vary widely from attending fires and floods, issuing safety advice and guidance, attending road traffic collisions and chemical spills to participating with other services in response to major events. Typically, incidents can be thought of as time-limited, featuring dynamically changing environmental conditions, suffering from the potential for goal conflictions/tradeoffs and may require the understanding and integration of large amounts of information.

Gary Klein has spent decades investigating NDM and used the F&RS as one of his first domains to investigate decision-making (Klein, 1999). Klein found that experienced fireground commanders could judge a situation as prototypical and knew what actions to take. The commanders did not find the best solution as traditional decision-making theories stated; instead, they used the first solution that worked. Further studies documenting NDM in the F&RS highlights that firefighters use their expertise to identify the situation as typical (Klein et al., 1986), firefighters employ matching mode decision-making (Hoffman, 2007) and they evaluate the details rather than evaluating the overall situation (Rake and Njå, 2009). Research attempts to investigate system design to support the firefighter's decision-making process, as well as investigating the other factors such as communication that affect the decision-maker (Alexander et al., 2011, Andrienko and Andrienko, 2007, Jiang et al., 2004, Zlatanova et al., 2004). This research does not investigate the set of HF issues outline in chapter two nor what is required to support real-world decision-making across different NDM environments. This chapter investigates NDM and what needs to be supported in the design.

4.3 Activity One: Kick-off Meeting

4.3.1 Method

A kick-off meeting consisting of one-to-one interviews and a focus group was completed. The interviews were performed with system managers to provide the researcher with an initial understanding of the F&RS domain, including an understanding of the team and the technology they currently used. The focus group allowed the investigator to get an understanding of the domain and get first-hand opinions and experiences of attending an emergency and the associated information that is used to resolve a situation. The interviews were transcribed and formed the basis for the kick-off meeting findings.

4.3.2 Participants

One-to-one meetings with two officers in charge of the F&RS systems were implemented first, which took approximately three hours. This was followed by an informal focus group with six firefighters, lasting approximately an hour.

4.3.3 Kick-off Meeting Findings

4.3.3.1 Domain

The modern day F&RS has evolved following many years of development and improvements. Initially the F&RS focused on fire incidents but now extend their tasks to include planning and implementing preventative measures and plans, to attending an array of incidents including road traffic collisions. Firefighters spend considerable time in their day-to-day activities collecting and updating the information stored on the system ready to be used when attending an emergency incident.

In general, when an incident is mobilised, the officer in command, known as an incident commander, identifies the scenario upon arriving at the incident, and assesses the level of severity for potential life and property loss. The officer in command then gathers the key information from the scene. The decision-maker may query additional information from digital knowledge repositories, which contain information about residential occupancy, hydrants, automotive and chemical safety. An operational protocol is then formed as a framework for response to the emergency. Each incident is made up of a combination of elements including type of incident, location of the incident, the individuals involved, the resources available, and so on. The variability inherent in such features means that

even ostensibly similar incidents may in truth produce a range of different difficulties, constraints and trade-offs resulting in the firefighter processing and interpreting significant amounts of new information in order to have a picture of the situation.

Figure 4.1 illustrates the general process and information flow for firefighters attending an incident (adapted from Shen and Shaw (2004)).

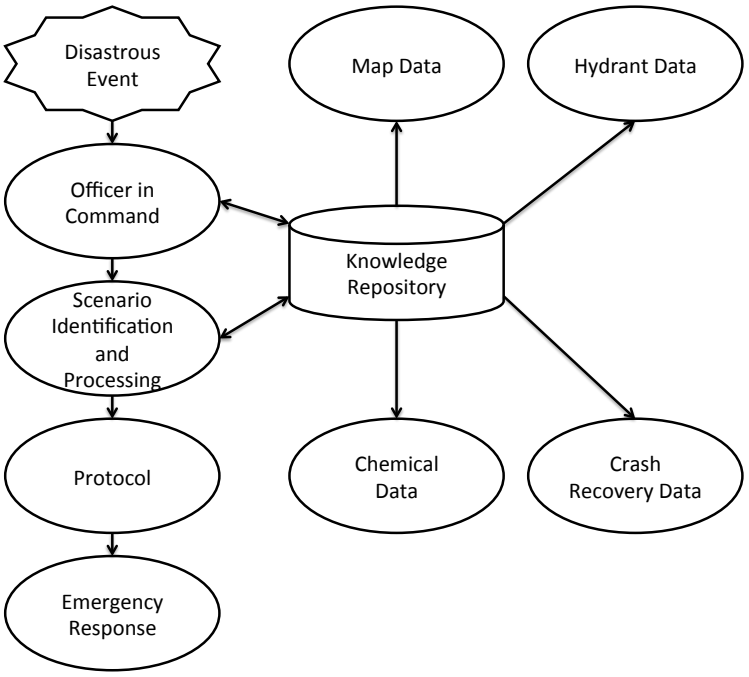


FIGURE 4.1: The General Process and Information Flow for Firefighters Attending an Incident (adapted from Shen and Shaw (2004)).

The officers described the emergency environment as varied and demanding. They went on to state that the environment can have the following properties:

- Limited time to resolve the emergency incident
- Changing and evolving scenario
- The environment in which an incident takes place can be chaotic and confusing
- Fast decision-making is required
- High uncertainty of the results of decisions taken
- High risk of casualties and property loss
- Dangerous environments for all individuals involved
- Incomplete information from a number of sources, which must be fused together to build up a picture of what is happening

- Questionable reliability of information

4.3.3.2 Team

The team consists of an IC, SiC and firefighters, as well as a supervisory officer for larger incidents, see figure 4.2. The IC is the main decision-maker and responsible for resolving an emergency, with the support of the SiC who also supports in the decision-making process. Firefighters implement procedures as delegated by the IC and SiC. The supervisory officer will be deployed to incidents which are more complex and monitor the incident to ensure that the emergency is resolved successfully and that the firefighters are following good practices. Control room staff receive information regarding the emergency, this is then passed on to the firefighters and third parties such as the police and ambulance service. The control room also identify and dispatch the necessary resources. The emergency itself may involve a number of casualties, the public in the surrounding area and the environment, which may be involved in the emergency.

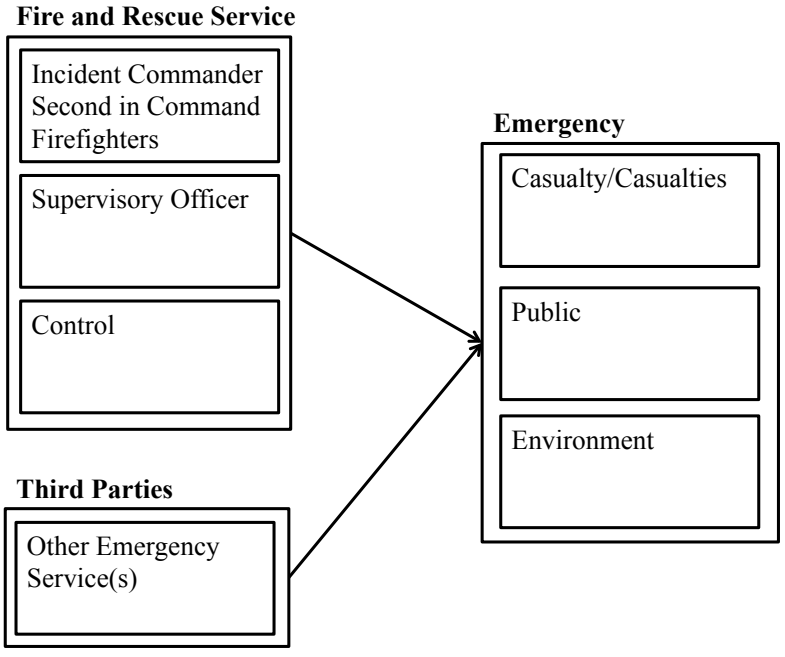


FIGURE 4.2: Overview of the F&RS Team

4.3.3.3 F&RS Technology

One of the main resources used at an incident by the F&RS is mobile data systems. The goal of the system is to provide the F&RS with a reliable information tool to aid critical decision-making and form a holistic view of the unfolding situation (that is, consolidate

situation awareness). In the event an incident were to occur the system aims to store information which has been input by the firefighters during the planning stages.

When additional information about the incident is needed the incident commander uses the system as a portable information bank. The system contains multiple datasets, which include best practices, building plans, geographical and building occupancy data. Maps are core to the system as they allow the user to pinpoint the location of the incident and get an understanding of the surrounding area in a visual representation. The maps are provided by Ordnance Survey Maps and additional information is overlaid.

The system is primarily used by the IC and firefighters on a mobile data terminal (MDT); the MDT allows the officer in charge to have a full view of the system whilst on the move and contains a complete set of data in the event of Internet connection failure, see figure 4.3. The MDT is a ruggedised "tough book" computer, which operates on Windows, and input is through the touch screen by using either a pen or finger. There are two types of MDTs; the first type is demountable from the cab and has Wi-Fi and GPRS Internet capabilities. The second type is fixed in the fire appliance and only has Wi-Fi capabilities. Both types of MDTs use the same software and are updated overnight whilst connected to the local area network. The screen works on pressure so can be used with gloved hands and is not set to be sensitive.



FIGURE 4.3: Mobile Data Terminal

At the interviewed F&RS, they have two types of stations. The first type are stations that are permanently manned, named "whole-time" and have demountable MDT's. A second type of station, - where crews are called in only when there is an incident, named "flexi-duty" or "retained" - have fixed systems. The demountable MDT can be moved to another cradle at the back of the fire appliance so that it can be used during an incident without the officer in charge or driver of the fire appliance having to return to the passenger seat.

When a whole-time appliance is mobilised, the appliance receives a mobilising message, which gives the officer in charge information about the incident. This includes address information, type of incident (e.g. a house fire, property fire), additional incident information, and then the corresponding risk card is unlocked for the incident. The information will typically be processed by either the IC, who will look at the system before arrival at the incident, or by the driver who will look at the system after he has completed the water supply set up at the incident.

The system is used to support three types of use:

1. To answer immediate and specific queries.
2. To support planning activity ahead of time (short-term planning en route to the incident or possibly even long term planning or training activity).
3. To aid in the assessment of an unfolding situation at the event site itself.

Example Scenario

An example scenario could be that the F&RS has been asked to attend a road traffic incident with a trapped passenger. The officer in charge would get key information regarding the incident, which includes location information, type of incident and any details taken during the emergency call. Whilst in the fire appliance, the officer in charge would usually have between 5-10 minutes to absorb as much information as possible from the MDT before arriving at the incident. The primary information of interest to the officer in charge would be the crash recovery data for the make and model of the car, which would be used to understand how to cut free the trapped passenger. Upon arrival at the incident the officer in command would try to get as much information as possible about the incident and may review the crash recovery data before taking action to free the passenger. Usually, the firefighters sit in the three back seats of the fire appliance. The officer in charge sits in the passenger seat and is the only one who can see the MDT.

Interviewees reported that viewing and processing information on the MDT could be difficult, especially in the fire engine. Reasons include:

- The fire engine is travelling at high speeds.
- Varying amounts of light, for example, the fire engine can be dark inside.
- The environment in the fire engine can be chaotic and bumpy.
- The officer in charge is trying to absorb the right information in a limited time.

- Firefighters will often be wearing personal protective equipment, including heavy gloves, visors and so on, which can make the portable devices difficult to use.

Thus workload is highest when, for example, an officer in charge who has not seen the MDT for a few weeks may be asked to get information about an incident at 3am in a bumpy, dark fire appliance with distractions from sirens, flashing lights and radio traffic.

4.3.3.4 Databases

The complex data system used in the F&RS contains a wealth of information for firefighters to use at an incident. Figure 4.4 illustrates the various datasets in the complex data system used by the F&RSs.

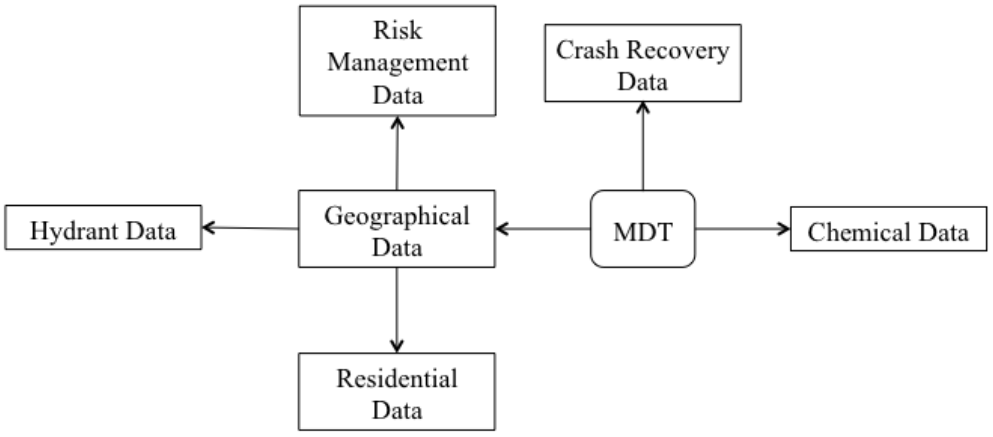


FIGURE 4.4: Overview of Mobile Data Terminal Databases

Each of the datasets are described below:

Risk Management Data

This dataset stores information about properties that are considered an exceptional risk in the area. These are predominantly commercial premises but the dataset also includes some private residences. An example property could be a hospital where the firefighters would need to know the location of the oxygen stores, lift shafts, dry risers and the wards for incapacitated people who cannot self evacuate. Each property is given a risk level, which is categorised as low, medium or high. Each risk is marked on the map with symbology and when an incident is identified at this location the associated risk card is activated for the fire fighter to view. A risk card is the combined information collected during a previous risk assessment and allows any firefighter to attend an incident and know the dangers before entering the property.

Data is collected by a firefighter who carries out an inspection in person at the premises before an incident has occurred. The firefighters carry out an assessment that is paper based. They ask questions and score the property according to what they see. The firefighter will draw up architectural plans of the property; take pictures of items of interest and pinpoint hydrants. Heritage buildings will also have a salvage of what to get out first. On completion of the assessment the information is input into the database and guidance is given regarding the property with suggestions being categorised into the dos, don'ts and considers. Currently, the F&RS does not have the resources to do the assessment digitally and the information is assembled by office staff using computer-aided design software. This dataset is updated every 1-3 years depending on the property's risk level.

Hydrant Data

The hydrant dataset contains information about the hydrants in the area. Hydrants are connection points for the fire hoses to the town's drinking water mains. They are underneath small manhole covers in footways, roads and verges, which can be missed or parked upon. There is an icon on the maps showing the location of each one. The firefighter uses this information to pinpoint where their closest water source is and the length of hose needed to reach the water supply. Location information of the hydrant could read *"outside house number 43."* Being able to calculate the distance from the incident and water source allows the firefighter to determine the number of hoses that are needed in order to get the water source. This is particularly useful, as the fire engine only carries limited resources and allows the firefighter to plan ahead. The dataset includes information about the size of the water main that the hydrant connects to and the water company responsible. The hydrant information is updated frequently as it can change daily.

Residential Information

Residential Information is a set of data, which includes information regarding building occupancy. The main information contributors are the local council. Houses in multiple occupancy, i.e several families in one houses, area a pertinent risk.

Chemical Data System

The chemical data system contains 99.9% of all known chemicals and gives basic information about how to approach the chemical, for example, what protective equipment should be worn. The system allows searching based on the chemical's name or symbol. This system has been borrowed from the chemical industry and integrated into the core system. In order to access the information the firefighter must leave the core system and start up the chemical data system. As the system is borrowed from the chemical industry it has not been designed for firefighters specifically and is not integrated into their systems.

Crash Recovery Data System

This system contains a blueprint of all known makes and models of cars in the United Kingdom and is borrowed from the automotive industry. This system is used when attending a road traffic accident and the firefighter needs to cut into a vehicle. In the past a firefighter could simply cut into a car and free the passenger, but as technology has enhanced there are several things that the firefighters has to consider, for example, boron rods that are used for strengthening, air bags, supplementary restraint systems, pistons in the seats, different types of fuels cells and so on. The crash recovery data gives the firefighter a bird's eye view of the car showing what the car contains, allowing the firefighter to plan how to cut safely into it. The system can select in two ways; either by typing in the registration number of the vehicle or directly searching for the model of the car.

4.3.3.5 Summary of Kick-off Meeting Findings

Activity one presents the challenging characteristics of the F&RS environment that firefighters work in. The work presents a general understanding of the F&RS by identifying their goals and the general steps a decision-maker must complete. The activity finds that the decision-maker gathers information from the scene, identifies the key information and develops a protocol.

The study identifies that the decision-maker works with the control room and firefighters in his team and will usually interact with people directly impacted by the incident. For larger and more complex incidents, the decision-maker will interact with a supervisory officer from the F&RS and third parties such as the ambulance service.

The interviews and focus group uncovered the use of a system that provides the F&RS with a reliable information tool to aid critical decision-making. The system holds information about the environment, water sources, residential information, chemicals and vehicles.

4.4 Activity Two: Critical Decision Method Interviews

A second set of interviews were implemented to get a detailed understanding of NDM in the F&RS using critical decision method (CDM). The following questions were adapted from past research by Wong and Blandford (2000), who investigated naturalistic decision-making in the ambulance service: How do firefighters make decisions? What strategies do they use when making such decisions? What information do they attend to and how do they consider and use the information? What knowledge do they bring to bear on the decision problem? What difficulties do they experience? A better understanding of these issues can lead to design of systems that are supportive of decision-making in such areas, and will contribute towards the development of alternative future systems.

4.4.1 Method

CDM was used as it was not possible to implement observations at the scene of an emergency. As mentioned in chapter 3, CDM is a retrospective cognitive task analysis technique, which asks individuals to recall an incident that they had previously attended. The interviews were open-ended and exploratory but aimed to address the specific actions taken to resolve the incident and identify the HF issues to investigate how they need to be supported. As part of the CDM process a task decomposition diagram was created to document the steps of the emergency, as well as, providing the participant with a talking prompt. The findings from the CDM interviews and task decomposition diagram were used to inform the cognitive work analysis (CWA) in activity three. CWA is a multifaceted approach to analyse human information behaviour, identifying the complexity, rather than centring on the social, which often uses social network theory, or on the cognitive, which focuses on the individual's behaviour, independent of context (Katopol, 2004).

4.4.2 Participants

Three interviews were carried out with 3 male participants; 2 IC and a crew manager. ICs are the main decision-makers with the support of crew managers (also known as second in charge).

4.4.3 Procedure

Each participant was asked to read an information sheet and complete a consent form. The researcher then briefed the participant regarding the aim of the research and the CDM

process. The participants were asked to identify an incident that they had attended which required them to make decisions. A set of CDM steps and questions were identified and loosely followed during the interview, see appendix A.

Once an incident was identified the participant was asked to give a description of the incident. The researcher then asked the participant to outline step-by-step the actions they had completed during the incident. These steps were then entered into a task decomposition diagram template in Microsoft Word, which the researcher had prepared before the interview. The task decomposition diagram template was mainly edited by the researcher in full view of the participant. In many instances the participant inserted and edited tasks.

Once the main tasks in the task decomposition diagram were identified, the main tasks were then broken down further into sub tasks, providing the researcher with greater detail regarding how the incident was resolved. The task decomposition diagram were constructed to document the steps that the participant had undertaken, as well as, provide the participant representation of the steps completed and as a prompt to talk about. For example, the researcher explored the types of information required to complete the task, investigating the HF issues, the people and technology involved. Each interview took between 1-2 hours and was audio recorded.

Once the interviews were completed the researcher then analysed the audio recording and transcribed each interview. The transcribed data was then summarised to give a whole description of the incident, using quotes from the transcriptions. The description of the incident and task decomposition diagram were used to complete an initial analysis to identify the general steps required to resolve an incident and the HF issues. The content of the CDM interviews and analysis was used as a basis to develop the cognitive work analysis for activity three.

4.4.4 CDM Interview 1: Road Traffic Collision

This interview was carried out with a male IC who described a road traffic collision that had occurred and a passenger was trapped.

The service control room were notified by the ambulance service that they needed the support of the F&RS at the scene of a road traffic collision. The control room activated the sounder in the fire station, sent out notifications to the firefighter's pagers and activated the mobile data terminals (MDT). The control room mobilised two appliances to the incident, and each appliance had four firefighters in the vehicle. A supervisory officer was also dispatched to the scene to ensure good practises were implemented and support the

IC. The IC went down to the office to get the turn out information (a paper print-out of core information given to the fire control) while the rest of the firefighters began to put their protective clothing on. The tip sheet provided the IC with information regarding the location of the incident and other information that had come through on the call, including the street name and the type of incident. This incident was a road traffic accident. The IC commented that there was no information about the vehicle, which is sometimes provided. The IC printed out two tip sheets as two appliances had been mobilised by the control room. The IC also collected a route card, which provided the crew with a road name and outlined the best route to get to the road. The participant stated that this is a *"paper version of a sat-nav [it] gives the best route considering the size of the vehicles, based on operational experience"*. The IC then put on his protective gear and got into the appliance. The MDTs were already in the appliances ready to go.

The IC and crew had a quick discussion about the address of the emergency as there was some ambiguity regarding the road name. Together the crew decided on the route to take to the emergency and then travelled to the incident. The IC stated that crew has a target 80 seconds to complete this and leave for the emergency. In the vehicle the IC mobilised by pressing a button on the MDT and sent a verbal transmission through the main scheme radio. The appliance with the IC left first and the second appliance followed. When travelling to the incident the IC explored the information on the MDT, focusing on the geographical data. As there was limited information the IC was not able to explore a lot of information on the MDT.

When arriving at the scene, the appliances switched around as the police had closed the road. The crew from the first appliance moved traffic cones to let the second appliance go through first and the first appliance followed. Both appliances parked in a safe position, then the IC sent a notification to the control room to acknowledge that they were at the incident. This was done by pressing a button on the MDT and via radio communication. The IC also sent a first impression to control giving an indication of the extra resources that might need to be sent to the scene.

The IC's first job on the scene was to liaise with the ambulance service and develop an understanding. The IC stated they wanted to know:

- "Does the casualty need to come out of the vehicle immediately?"
- "Do they have a life threatening injury?"
- "Do they have a compromised injury? Large trauma?"

This allowed the IC to gauge how much time they had before decisions needed to be made about extracting the casualty. In the event of an immediate extraction needing to be

made, the IC outlined that a *"snatch rescue"* would be completed. If a snatch rescue was required the IC would have taken a different approach as the IC outlined that for a snatch rescue *"we'll either cut corners or we'll use techniques to get a rapid extraction"*. In the event that the casualty has a head injury then the F&RS aim to get the casualty from the time of the accident to the hospital within 20 minutes to allow for the casualty to receive the right medical care. In this incident there was no urgency and the casualty was stable. However, the paramedics stated that the casualty had pre-existing medical conditions and that they needed to be careful of the c-spine. The ambulance crew went on to request that the F&RS take off the roof of the car. The IC was initially hesitant to take off the roof as the car had no damage to it and the IC was trying to reduce the financial loss of the vehicle. The IC asked if the ambulance crew had considered a CED, an extraction device, which is used by the ambulance service, also known as a splint. However, the casualty was too heavy for this device to be used. Another option could have been to extricate the casualty via a door removal, which would include removing the door and door-posts. However, this was not considered as the crew could not get above the casualty to lift her out.

The IC stated that there are six steps to complete a successful extrication, these include:

1. Scene safety.
2. Stabilisation.
3. Glass management.
4. Initial access to the casualty (initial primary survey of the casualty and to ensure that the airways are clear).
5. Full access.
6. Extrication.

Once a roof extraction was decided, the F&RS set up a command support point for central communication, known as the command support role. The driver was in charge of this and set up a control board. The fire appliance driver was responsible for gathering the information, and the control board displayed information regarding the *"tallies"*; this showed information about the people involved, and in particular, the casualty. The control board has a perspex roll-down where the crew fill out information, draw a plan, write down who is there, and any other agencies present. The driver was near the appliance in order to hear the main radio and have mobile phones as backup if the radio signal failed. The driver took the MDT from the passenger seat and put it at the back of the appliance.

The driver also put on a chequered tabard and put a red flashing light on the appliance to indicate the control point.

The firefighters started to set up the equipment including hydraulic cutters and spreaders, a toolbox, sharps protection and a hose reel in case a fire started. The firefighters also stabilised the vehicle using blocks and wedges to reduce any movement, which could have an impact on the casualty. At the same time the IC sent a firefighter to get the MDT off the appliance and find more details of the vehicle. The IC stated that it is not always clear what type of engine the car has as they are not always stated on the back of the cars. The IC remembered that there was a discussion as to whether the car had the smaller engine or the larger one. The IC got a schematic picture of the vehicle and took off the roof and the doors on the image so that he could see the sides. He identified where the battery was because severing the electrical connection *"reduces the risks from the airbags and other devices"*. He also identified where the airbags were because when the firefighter cuts through the roof they can sometimes go off in the casualty's face. The IC referred back to a previous incident that he had attended where they had struggled to cut through the airbag material. The IC stated he was trying to identify the easiest/best way to cut off the roof. The IC outlined that the roof removal is the most common way of getting a casualty out and the senior ambulance crew had already recommended that it should be done.

The IC stated that having the MDT allowed him to stay at a distance from the vehicle; getting close to the vehicle was difficult due to the number of people around the car. The IC said that there was some difficulty in distinguishing if the car involved was the same as the blueprint that he was investigating as although he had a blueprint there was no picture of what it looked like on the outside. Therefore, the IC spent some time distinguishing if it was indeed the correct car.

The IC said three main tasks were completed to manage risk:

1. A dynamic risk assessment, where the IC carried out a risk assessment. The assessment was completed visually, and was reported via radio, which lets the other officers on their way know what is happening.

2. The IC also filled out a risk assessment sheet, which is a tick-box sheet including:

    - Date and time
    - Potential hazards
    - What measures have been put in place to mitigate the hazard

3. As the F&RS had to be there for more than 20 minutes they had to carry out an analytical risk assessment, which was more detailed. They put a risk factor based on likelihood and severity, which then gives them a risk factor and associated control measures. They recorded this on paper with carbon copies. This is used to brief people and audit it later.

The IC then considered glass management to reduce the risk of further injury. In the example given by the IC the windows needed to be broken by a controlled method using adhesive plastic sheeting to manage any glass breakages. The IC informed the other crew members how to remove the roof and the crew then marked where they wanted to cut the vehicle. One firefighter was assigned to maintain communication with the casualty, to reassure the casualty and let the casualty know what was happening.

The IC stated that the crew manager dealt with what was required at the vehicle whereas the IC was *"standing back and getting an overview of the incident and liaising with the ambulance service"*. By standing back the IC was reconfirming the actions that they had set in motion, as well as, identifying potential hazards for the F&RS. The IC also checked if everyone was wearing the right personal protective equipment, that everyone was out of the risk area, and that car stabilisation was maintained, whilst keeping himself updated on the casualty. The IC stated that at this point he was *"pre-planning the next stage, once we have done the roof removal, how are we going to package casualty for removal?"* The IC emphasised that the IC of an emergency has to always forward-plan and be thinking about the next step that needs to be completed. There was also a senior officer on the scene who was monitoring the incident at the same time and ensuring that the F&RS are following good practice. The IC also liaised with this officer regarding the plan of action.

Once the roof was removed the F&RS liaised with the ambulance service regarding using a stiff board to get the casualty out. As the ambulance crew were less experienced (which was apparent as one of the paramedics was wearing a student paramedic uniform), the F&RS led the extraction. The IC also explained that the crew spent time explaining to the ambulance service what they were doing, as they were using this as a training incident for the student paramedic.

A firefighter gently eased the board in, and then coordinated the team to make a coordinated lift of the casualty on to the board whilst trying to minimise any stress and further injury. The casualty was put on to the board and then on to a trolley.

The IC stated that they use an incident recording system for the Government, with which the F&RS recorded the incident, and enter the related information such as the casualty's name, which can be used for the medical team.

The IC then did a "hot debrief" (a quick chat about the incident) with his crew. He wanted to know the problems that the crew had experienced. The IC and crew discussed the MDT as they were worried about whether they had the right model of the car. They also discussed the material that the car was made up of, as there had been some plastic parts, which was unusual. The IC stated that firefighters had to be careful of plastic as it could shatter or it could flex and be difficult to cut with the gear that the F&RS have. On this occasion there was no problem but it was something that they discussed. They also discussed how they liaised with the ambulance service and how they felt about that.

The IC stated that an experienced IC asks the following questions:

- "Is it time critical or not?"
- "What is the major ailment?"

The IC stated that questions need to be asked so that the IC can then offer the best way to get the casualty out. A novice IC or firefighter may not be confident in asking these questions and might complete the actions requested by the ambulance crew.

Task Decomposition Diagram

Figure 4.5 presents task decomposition diagram of road traffic collision.

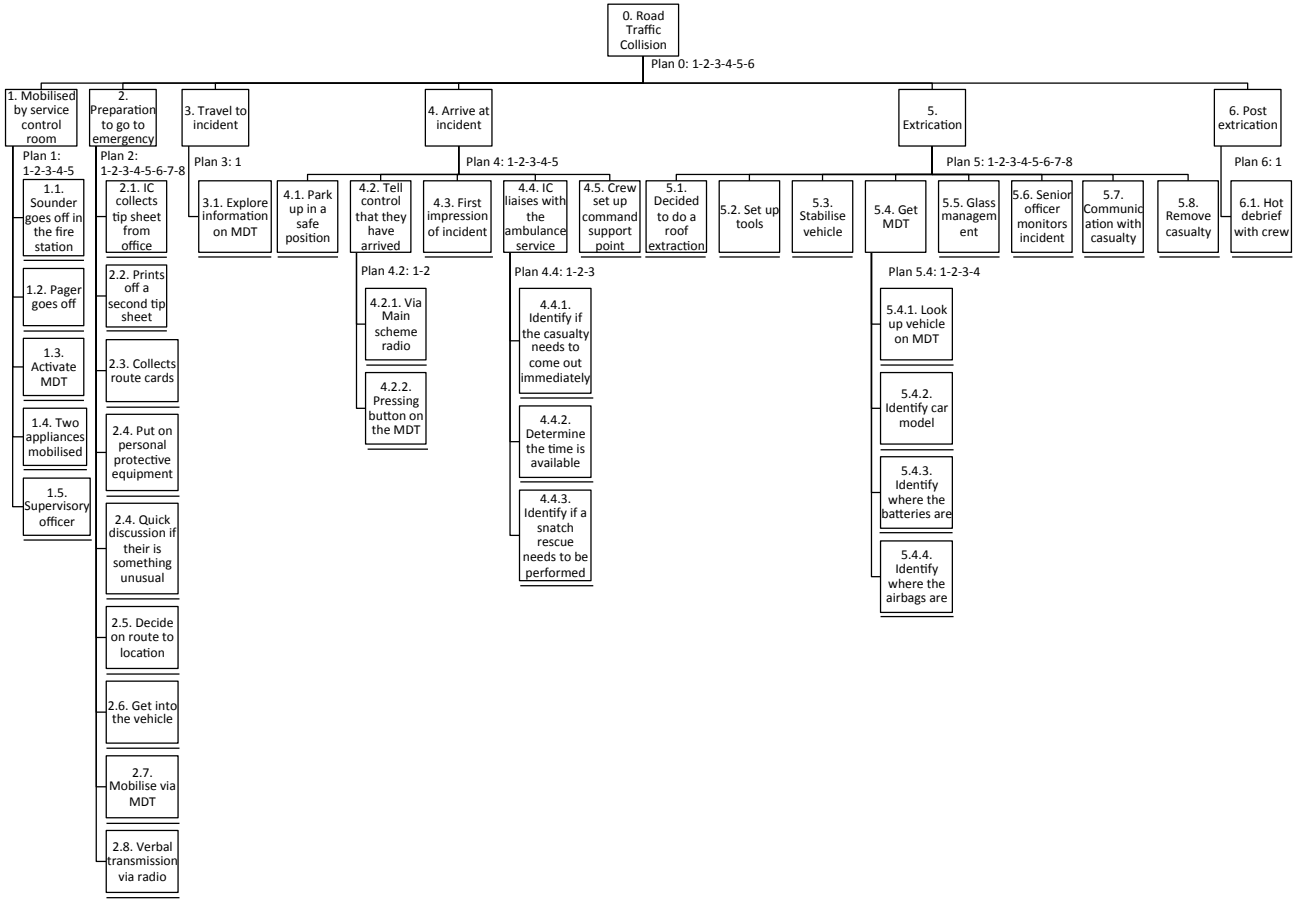


FIGURE 4.5: CDM Interview 1: Task Decomposition Diagram of Road Traffic Collision

4.4.5 CDM Interview 2: Residential Property Fire Incident

CDM Interview 2 was performed with a second male IC, who described a residential property fire incident. The IC identified an emergency that he had attended six months prior to the interview date, where a fire had started and gone in to the loft space at a semi-detached house. The occupier of the house rang the emergency services to alert them that a fire had started at his property. The call handler took his details and two appliances were indicated to attend the incident.

The sounder in the F&RS went off and the IC went down to the office and collected the tip sheet. The IC stated that the tip sheet gives the following: *"It gives me... address, what it is... house fire, road traffic collision, all that kind of thing and it said if I remember rightly it was a fire in the loft space. It also gives addition information, if this house [two doors down] has dialysis, we get told that... if he's got dogs, things like that."* He then went to put his personal protective equipment on with the rest of the crew who had started to put it on as soon as the sounder had gone off.

The two appliances were mobilised and the IC investigated the VMD, a system that is based in the appliance and is not mobile -which the IC stated he used for the following things:

- What type of property they are going to attend?
- Where are the hydrants?
- What are the standard operating procedures for road traffic collisions (For example, when speaking to the IC he outlined that whilst the procedures stated consider fire spread, the procedures do not tell you that you should send two firefighters to the scene).

The IC said he referred to a route book in the fire engine to look up the location. The appliances managed to get to the fire within five or six minutes. The IC got his crew to park the appliance at an angle to block the road. The IC explained: *"Because we need hose lines out and we want to protect our crews. It's only a small road, there is access round here and there is access down there. So blocking that road off is not a major problem but I like to make sure my crews are safe if we are going to be rushing around but also because I had called for the aerial ladder platform. I need that space there."* As the IC pulled up to the house there was smoke coming under the tiles, which suggested that it was a well-developed fire. The IC looked for the colour, its behaviour, and if it was a ventilated fire or not. The IC then visually surveyed the property and investigated the material the building was made of, the number of floors, the potential risk hazards and what control

measures would need to be put in place. This is what the IC called the "dynamic phase" where a lot of things happen at once.

On arrival the IC radioed for an aerial ladder platform and an extra pump. The IC sent the SiC to look at access points and where the gas and electric cut off points were. He was also looking for hazards and entrances, and tells the IC what the fire looks like at the back. The IC spoke with the occupier of the house who told him that he had a train set in his loft. The IC stated: *"the occupier had a train set in his loft and all-round the loft was train cupboards. So all that was cupboards and he'd got little trains put in there, £65,000 worth. In the middle he had a train set... so what he had done was, he was a smoker and he had put a cigarette out and put it in a bag and hung it on the landing. So that had caught fire to the loft ladder, gone up into the roof space."*

The IC also said that he asked the occupier for the best access points into the building and was informed there was access from both the front and back. He also asked if there was anything dangerous in the building that could hurt the crew.

At this point the SiC came back and briefed the IC regarding his findings. The IC outlined that he is *"triangulating information"* at this point from a number of sources.

At the same time the crew were setting up and doing the following:

- Finding the closest water source (hydrant)
- Getting the hoses off the appliances
- 2 jets were used and a safety jet

The closest water source was found by exploring the VMDs, and the IC stated that this is also used to get specific risk information about a building, which helps the IC understand the dangers and risks in an area.

Once the IC had all the information from all sources, he then made the decision of how to tackle the fire. The IC split the crew into two teams. The first team was sent into the house next to the incident to investigate if the house had been affected by the fire and stop the fire spreading to this house. The crew were sent in with breathing apparatus, a thermal camera and hose reel, so if the fire did spread they could react straight away. The second team of two firefighters were asked to put out the fire from the occupier's house (incident house). It took the crew four hours to put the fire out.

Once the crew started putting out the fire the firefighters came back to say *"yeah we're just putting it out, it's not gone into there yet [the next house]."* The IC then started to think about the next step. *"What other things do I need to consider?"* The SiC then

carried out an analytical risk assessment (ARA), which outlines the hazards, what risks are involved, the control measures being implemented and indicates the tactical mode (offensive, defensive or transitional). He communicated the risks to the crew and the associated control measures were put in place.

Once the fire had been put out the IC double-checked that everything was OK and that there were no hot spots. The IC was also checking that no damage had been caused to the houses next door. The IC then offered the occupier emergency support as the occupier could not go back in. The occupier went to an emergency support caravan, which allowed him to have a cup of tea, make arrangements and phone calls. The IC stated that the caravan provides essentials to the people affected by the fire.

Normally once the fire has been stopped the F&RS would determine how the fire started and need to answer the following questions: *"How did it start? What are the ignition sources? How can they stop it starting again?"* In this incident they did not need to do this investigation, as the occupier had already told them the source. The IC stated that the crew then went *"hot spotting"* where they dropped off leaflets to surrounding houses to say that there has been a fire in their area. The leaflet asks if they have smoke detectors and if they require a safety check.

Then the IC carried out a hot debrief, which was a chat about the incident. The IC said they discussed *"what went well? What did not go well? Did you know what you were doing? Did the IC tell you what they were supposed to be doing? Did you have any difficulties?"* The crew finished by collecting the equipment and headed back to the fire station. There was a second debrief carried out where the IC completes a debrief form and fills out the *"good bits and the bad bits"* and this is shared with the whole of the organisation.

Task Decomposition Diagram

Figure 4.6 presents a task decomposition diagram of residential property fire incident.

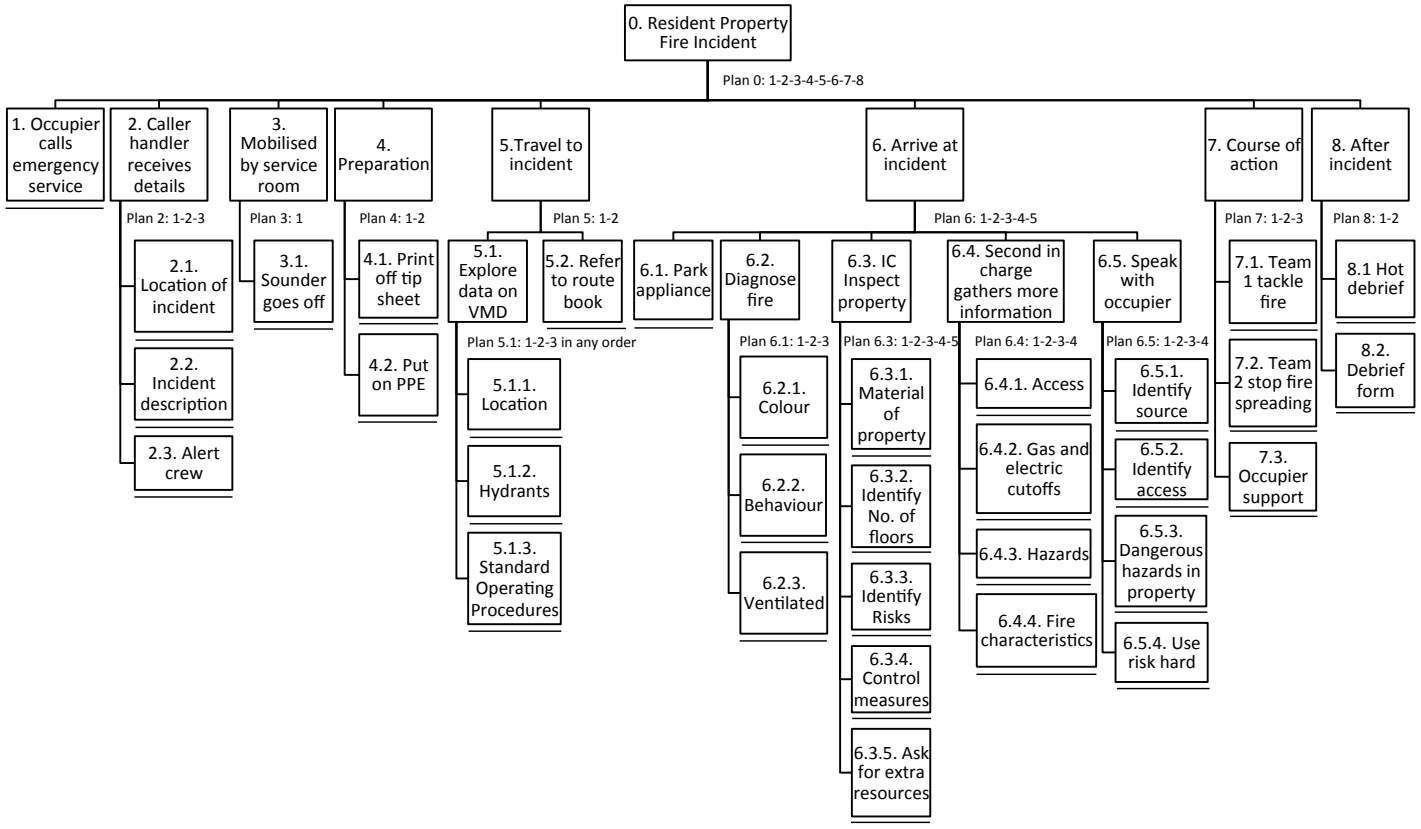


FIGURE 4.6: CDM Interview 2: Task Decomposition Diagram of Residential Property Fire Incident

4.4.6 CDM Interview 3: Commercial Property Fire Incident

The third participant was the SiC for a commercial property fire incident, where he attended a property fire at a mechanic's garage unit in an industrial park. There were eight or nine other units in the same industrial park. The call came in, the sounder went off and the IC went to get the tip sheet. *"The tip sheet just said that there was a commercial fire, name of the garage, name of the caller, potential for cylinders, vehicles stored on site, hydraulics, three phase electricity. A list of hazards that are known for that site."*

The MDT was collected and the SiC tapped the mobilise button on the MDT to say they were attending the emergency and radioed to the control room. There were two appliances sent. On route the SiC explored information on the MDT. He was exploring the information that control had sent and crosschecking if the information was the same as the tip sheet. He found that it was identical to the tip sheet. The SiC then turned around in the appliance and spoke to the other firefighters to ask about their local knowledge. He wanted to know *"have they been there before? Know where it is? [location of emergency], know what it is?"* [garage]. In this incident they had a good idea as a couple of the firefighters had used the garage and they discussed what kind of garage it was. The SiC outlined that they *"actively build up a picture of what they are turning up to."*

When arriving close to the incident the IC and SiC were looking for visual signs and saw a *"plume of black smoke."* This showed that there was urgency in the emergency, and whilst on the tip sheet there were no persons reported in the garage they were still aware that there was a possibility that there was someone inside. The first thing the IC had to decide was where to park the appliance. They were concerned with how much space was needed and how many other appliances might come and the space they might need.

On arrival the firefighters had to deal with the public, cordoning off the area, vehicles, the fire itself and identify water sources. On first visual assessment of the building, the crew could see *"it's an extensive fire and that there is partial collapse on one side"*. A dynamic risk assessment was completed, *"this is done in your head and you make an assessment, you look around, you are supposed to do a 360 of building but sometimes can be difficult. You are trying to gather as much information as possible about the incident to decide if it's safe for the crews to go inside the building to tackle the fire or if they need to remain inside and tackle the fire."*

The SiC outlined that he was trying to gather the following information:

- How developed is the fire?
- Information about the inside of the property

- The construction of the building
- How badly the fire is affecting the construction of the building?
- Is it safe or unsafe?
- Is it going to collapse or not?
- What's in the adjacent units?
- What is our priority?
- Is our priority to put out the fire or stopping the fire from getting three times worse?

The Sic stated that decisions were being made in split seconds.

At the same time two firefighters were getting ready with breathing apparatus and a main jet, which allowed more volume of water. Other questions that the IC and SiC investigated included:

- How much water do we have?
- How many more fire engines are coming?
- Establish what resources you need to support in the incident?
  - In this incident the IC asked for a further 3 appliances to attend the incident and an aerial appliance so that they could tackle the fire from above.

Water was a main priority, and the firefighters used the MDT to highlight where the closest hydrants were. For this incident they used two hydrants but quickly realised that the hydrants could not supply the firefighters with the amount of water they needed. The SiC supported the other firefighters to connect to the hydrants and the crew began tackling the fire. The SiC went back to assist in completing the ARA, a risk assessment, and the SiC investigated the potential hazards on the scene. The IC later read and signed the ARA assessment. The SiC stated that the initial problem was gaining access to the building, as the roller shut door had come down and he needed to find how to gain access to the building safely.

The SiC and IC needed to establish the extent of the fire and found that the whole building was on fire and that whilst they were initially putting the water on the fire, the water was evaporating faster than it arrived. It became apparent that the crew needed more water and that the crew didn't need to be in the risk area, which resulted in them withdrawing to a safe distance. The IC and SiC decided that the water droplet size would need to be changed to make the water they had more effective.

The IC also decided that a defensive approach would need to be taken. Both the IC and SiC then needed to determine where the fire was going as it was fully developed. The SiC needed to answer the following questions: *"Is the fire going up and across the roof and affecting the other buildings? Or is it isolated to the one building".* This led to the IC and SiC to investigate the buildings on either side of the fire. They needed to investigate what access there was to the adjacent buildings. The firefighters were able to gain front and back access by forcible entry and crews were sent to investigate. The crews found that there was only smoke logging and the fire had not progressed through.

The firefighters needed a second point of attack, so it was decided to get access on the rear of the property (through someone else's property). The SiC outlined that they needed to answer the following questions:

- Whose property is it?
- Do we have keys?
- Can we break into it?
- What's in there if we do break in?
- What hazards are in there?

An hour into the incident they were able to get more water from a housing estate across the way from the fire. Crews were constantly going in and out of the house and tackling the fire. They tackled the incident from the outside, and took a defensive approach. The fire was eventually put out after four hours. Once the fire was put out a debrief session took place.

Task Decomposition Diagram

Figure 4.7 presents a task decomposition diagram of commercial property fire incident.

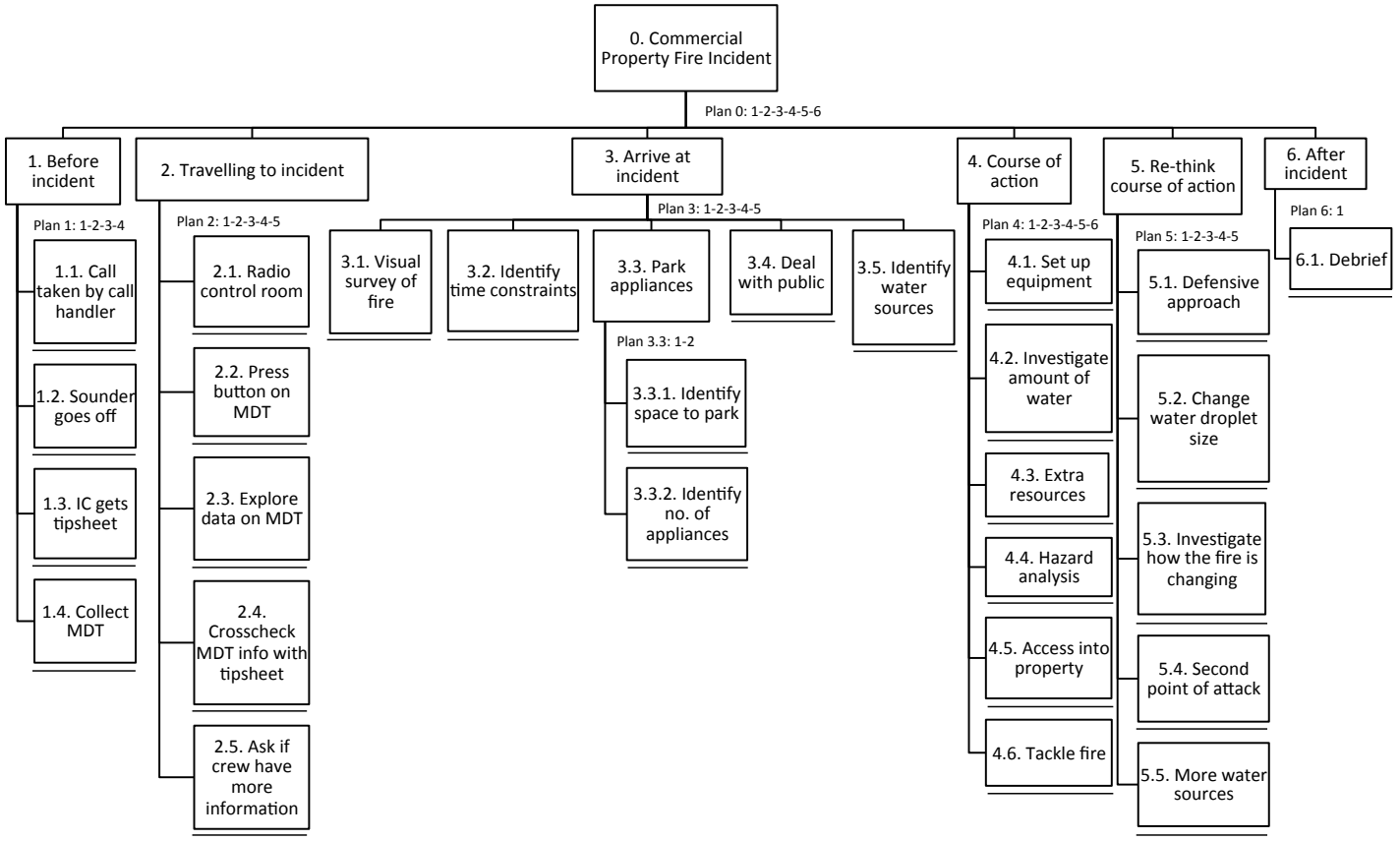


FIGURE 4.7: CDM Interview 3: Task Decomposition Diagram Commercial Property Fire Incident

4.4.7 Summary of CDM Interview Findings

The CDM interviews identify that there are seven steps that the IC and his/her team must complete in order to resolve an incident. These include:

1. **IC alerted to emergency:** this is usually via the control room that will send over the initial information, which will be printed on a tip sheet.
2. **Analyse and get an understanding of the emergency:** Collect as much available information as possible and build up a picture of the emergency, the environment and the people involved. This can occur before arriving at the emergency and then further understanding is developed at the emergency.
3. **Identify if the emergency is critical:** the IC needs to determine if the emergency is critical or not.
4. **Identify and implement course of action depending on the criticality of the emergency:**
   - If a critical emergency:
     - Identify an immediate course of action, for example, a snatch rescue.
     - Implement course of action to resolve the emergency.
     - Then carry out further investigation.
   - If not critical:
     - Gather as much detailed information about the emergency.
     - Visually inspect the emergency and environment.
     - Speak to as many people at the emergency as possible to gain further information. For example, third party emergency services, the public, the casualties involved.
     - Minimise potential risks and implement countermeasures.
     - Identity a course of action
     - Implement procedures for the course of action to resolve the emergency.
5. **Identify if the emergency has been completed**: the IC confirms that the course of action has resolved the emergency.

6. **Casualty after-care:** this is providing the individuals who are impacted by the emergency with support. For example, support in finding accommodation, advice regarding after-care of the property or informing the public.

7. **Debrief:** the IC will perform a debriefing session with the team. This could include a debrief with the third party emergency services.

Based on the CDM interviews the human factors are identified for each CDM interview in table 4.1:

Human Factor	**CDM 1: Road traffic collision**	**CDM 2: Residential property fire**	**CDM 3: Commercial property fire**
Decision-Making	Decided on the route to the incident. Decide on a course of action to resolve the incident in collaboration with the ambulance service to ensure the safety of the casualty.	The IC decided to split the team in two	Decide where to park the appliance. The need for more water and a change in droplet size. Defensive approach to be taken.
Situation Awareness	The IC developed an initial understanding of incident and if the situation was critical. The IC further investigated the incident to get a full understanding of the situation. Understanding of the car using the MDT.	Initial information came through on a tip-sheet. Use of the MDT to get an understanding of the incident. Visual inspection of the fire. Further collection of data from the owner of the Triangulating information from a number of sources. IC carried out an analytical risk assessment.	Initial information came through on the tip sheet. The SiC investigated the information to ensure that it was correct. Visual assessment of the fire and building. Dynamic risk assessment. Knowledge of where the water sources are.
Mental Model	The firefighters set up at a scene including the control board and the equipment that would be needed. The procedure of performing a roof extraction.	The firefighters set up at a scene including the equipment, identifying the water sources. Procedure to resolve the fire.	Procedure to resolve the fire.

Workload	Workload is shared between the IC, who takes the key decision-making role and the firefighters, who set up the equipment and implement the procedures once a course of action has been developed.	Workload shared between the team.	Workload shared between the IC, SiC and firefighters.
Human Error	The supervisory officer takes a monitoring role to ensure that best practises are taking place. The IC takes a monitoring role once the course of action has been decided.	The IC and firefighters monitored the fire. The IC confirmed that the fire had been put out successfully and that there are no hot spots. The IC confirmed that there was no damage to the other properties.	Monitoring the fire.
Uncertainty	Limited information on the tipsheet - No information about the vehicle involved. Ambiguity of the road name. Uncertainty if the model on the MDT was the same was what they had in front of them.	Uncertainty of the severity of the fire and if it had gone through to the next property.	If there were people inside the property. Identifying where the access points to the building. The severity of the fire. How the fire had affected the surrounding properties.
Teamwork	Knowledge of the area. Control board to display known information.	Shared mental model of the procedure to put out the fire.	Sharing their knowledge of the environment around the incident. The SiC and the team were actively building up a picture of what they may find when arriving at the incident.

Communication	Communication with control regarding the first impression of the incident. IC informs the firefighters regarding the course of action and coordinating with them regarding the set up, equipment and the procedures that need to be completed. Liaising with the Ambulance service to agree a course of action to get the casualty out safely. Further communication when removing the casualty out of the vehicle. Communication with the supervisory officer to ensure the correct course of action had been chosen. Debrief with the firefighters.	The IC and SiC worked together to get an understanding of the incident, including identifying the access points, cut-off points, hazards, entrances and fire information. IC communicated with the owner of the property. Communication between with the IC and team, particularly when implementing course of action and communicating the risks and countermeasures. The IC supports the occupier of the property. Debrief with the IC and firefighters.	Communication between control and the F&RS through MDT and radio. Debrief with the IC and firefighters.

Table 4.1: Human Factors in the F&RS

4.5 Activity Three: Cognitive Work Analysis

Based on the findings from activity one and two, a cognitive work analysis (CWA) was performed. The aim of the CWA is to help develop an understanding and explicit representation of how a crew attends to a property fire. The complexity of this system is in the problem of resolving the fire with great uncertainty and time constraints, whilst gathering information from numerous sources, liaising with multiple third parties including the casualty and other emergency services, as well as working in a team comprising of personnel, the service control room, IC and SiC, crew and subject matter experts.

4.5.1 Method

CWA has been selected to identify the key features of the work and clarify the constraints. As mentioned in chapter 3, CWA consists of 5 defined phases work domain analysis (WDA), control task analysis (ConTA), strategies analysis (StrA), social organisation and cooperation analysis (SOCA) and worker competencies analysis (WCA). See figure 4.8 which outlines the phases, the types of analysis that can be completed for each phase and the representations (Stanton and Bessell, 2014).

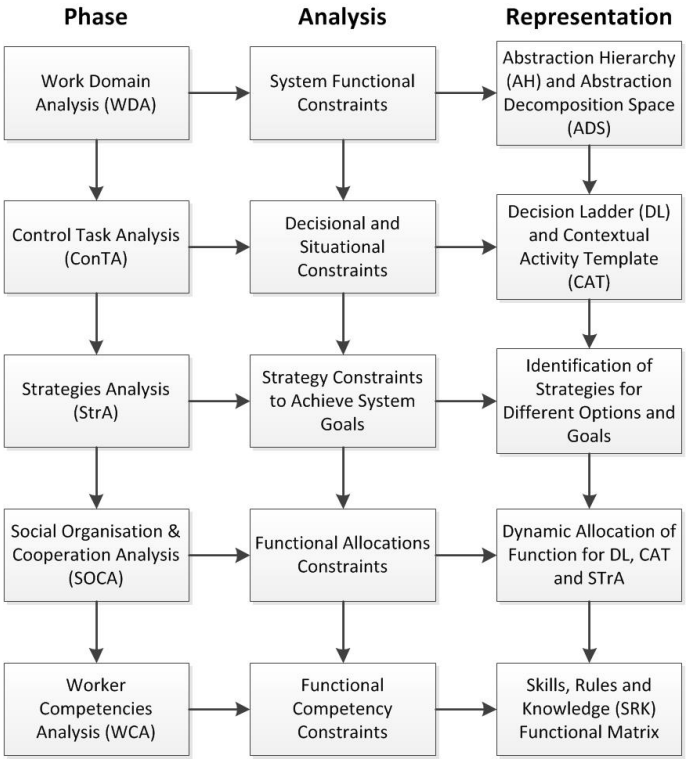


FIGURE 4.8: Overview of the Cognitive Work Analysis Process (Stanton and Bessell, 2014)

4.5.2 Participant

The researcher developed the CWA based on activity one and two findings. The CWA along with a write up of the CWA were sent via email to a F&RS systems manager (interviewed in activity one) for review. The F&RS systems manager checked it for accuracy and returned notes to the researcher for update into the CWA. For example the manager checked in the AH the flow of the elements, identified that no elements were missing. The manager also checked that the correct wording such as "snatch rescue analysis" was used. He also identified elements that were not covered in the interviews. For example, a drone had been purchased recently which they were now using at incidents to get a birds eye view of the incident and exploring the surrounding environment.

4.5.3 Stage 1: Work Domain Analysis

The first phase in CWA is Work Domain Analysis (WDA), which is the foundational phase for all subsequent phases. WDA describes the domain in which the activity takes place independent of any goals or activities. The first stage provides a description of the domain and constructs an abstraction hierarchy (AH) of the domain. WDA organises information in a systematic manner that will support design (Jenkins et al., 2009).

Figure 4.9 outlines the abstraction hierarchy, which describes the system at a number of levels of abstraction. There are five levels of abstraction (Jenkins et al., 2009):

- Functional purpose – the purpose of the work system and the external constraints on its operation.
- Values and priority measures – the criteria that the work system uses for measuring its progress towards the functional purposes.
- Purpose-related functions – the general functions of the work system that are necessary for achieving the functional purpose.
- Object-related purposes – the functional capabilities and limitations of physical objects in the work system that enable the purpose related functions
- Physical objects – the physical objects in the work system that affords the object-related processes.

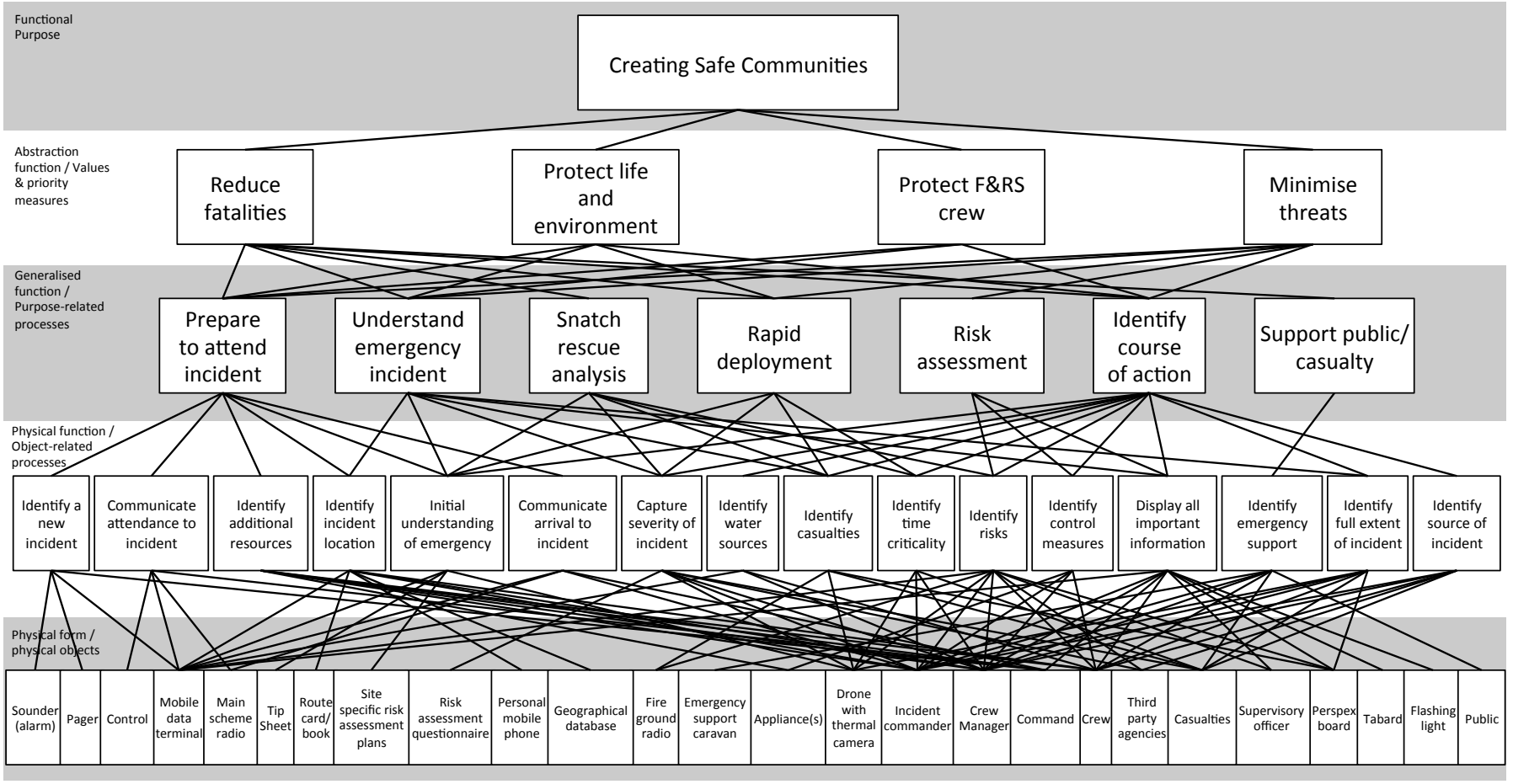


FIGURE 4.9: Abstraction Hierarchy

The AH has been created using a top down and a bottom up fashion (Stanton and Bessell, 2014). The bottom level of the hierarchy, is at the base of figure 4.9 summarising the physical objects within the domain. The bottom level comprises of both equipment and the people involved in the domain. The fourth level outlines the processes that are conducted by the physical objects. This stage investigates what the physical objects in the system actually do and captures the affordances of the physical objects independently of their purpose. For example "identify a new incident" is afforded by the combination of "sounder", "pager", "command" and "data terminal". A comprehensive list of the object-related processes can be found at the level above the base level of figure 4.9, as well as the links that indicate to which object they relate. In many cases, an object may perform a number of functions, similarly a particular function may be afforded by a number of objects.

The purpose-related functions level in the middle of the AH describes the functions that need to be performed in the work system. These functions could be of individuals, teams and departments in the work system. They have the ability to influence one or more of the values and priority measures and link to the object-independent functions. Each of the levels can be linked by means-ends relationships using the why-what-how relationship. For example, taking "Identify a new incident" node in the physical function level, the question of "what" is clearly answered. The node is then linked to nodes in the level directly above to answer the question of "why" identify a new incident, (in this case to prepare to attend to an incident). The node is then linked below to answer "how" can the incident commander identify a new incident, (in this case through an alarm, pager notification and mobilisation of the MDT).

The next level above, presents the values and priority measures, which are the constraints on the functional purposes. The values and priority measures are a method of measuring how the system is achieving the functional purposes. The first level of the AH presents the reason why the system exists. For the fire and rescue domain, firefighters ensure the safety of their communities. This is represented as the top node in figure 4.9.

The AH can be decomposed based on levels of resolution through the system. The system can be decomposed using three categories of resolution: system, subsystem and individual components (see figure 4.10).

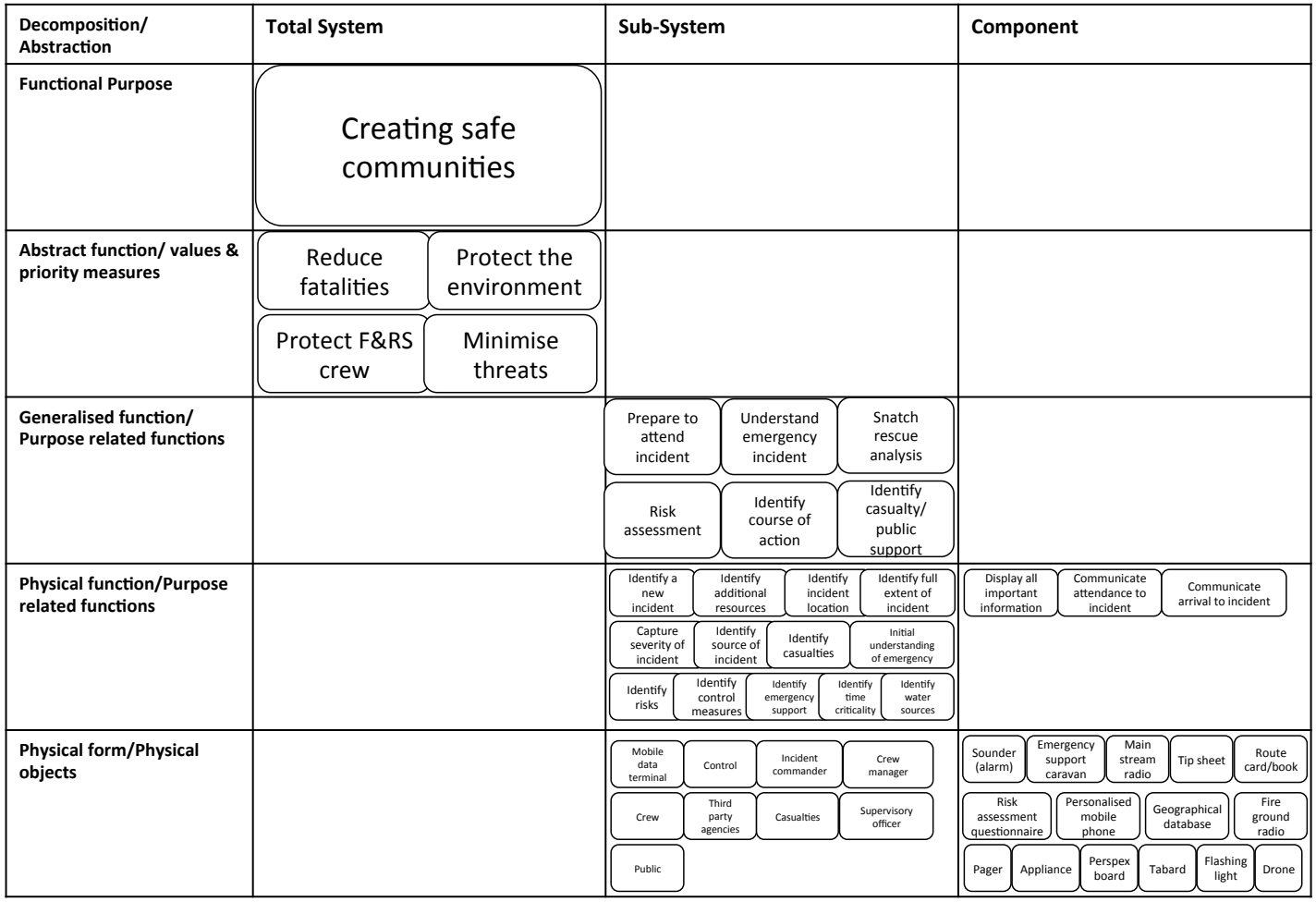


FIGURE 4.10: Abstraction Decomposition Space

4.5.4 Stage 2: Control Task Analysis

The WDA investigates the domain independent of activity and the recurring activities that occur within the domain. The second step of the CWA, Control Task Analysis (ConTA), investigates the activities that occur in the domain. ConTA models one or more of these known recurring tasks, focusing on what has to be achieved independent of how the task is conducted or who undertakes it.

Activity Analysis in Decision-Making Terms

ConTA uses a Decision Ladder (Rasmussen, 1986), see figure 4.11, which has been adapted to capture a linear sequence of information processing steps in the F&RS. There are two types of nodes in the figure: the rectangular boxes represent data-processing activities, and the circles represent states of knowledge resulting from the data-processing. Novice operators typically follow the decision ladder in a linear fashion, however, expert operators tend to take short-cuts. Two types of shortcuts have been identified: "shunts" connect an information-processing activity to a state of knowledge (box to circle) and "leaps" connect two states of knowledge (circle to circle). This shows that one state of knowledge can be directly related to another without any further information processing.

The system is activated when an incident has been identified (shown on the bottom left leg), usually when a member of the public has called the emergency services. Once an incident is identified, information is recorded regarding the location and additional basic information from the caller of the emergency call. Additional information is collected when arriving at the scene visually, from exploring the environment, speaking to the third party emergency services and members of the public. An assessment is then made to calculate the threat of the incident. Depending on the threat, this allows the F&RS to determine how much time they have to resolve the incident and prioritise what needs to be done. The IC is also able to understand the potential risks and what counter measures may need to be put into place. The IC and SiC will determine the CoA and implement them based on best practises and coordinate the crew to implement the CoA.

In order to expedite the process it is possible to bypass some of the steps. Removing some of the decision-making processes allows the transition from the set of observations and gathering of information straight to deciding a CoA (marked 1 in 4.11) or going straight to completing the CoA (marked 2 in 4.11).

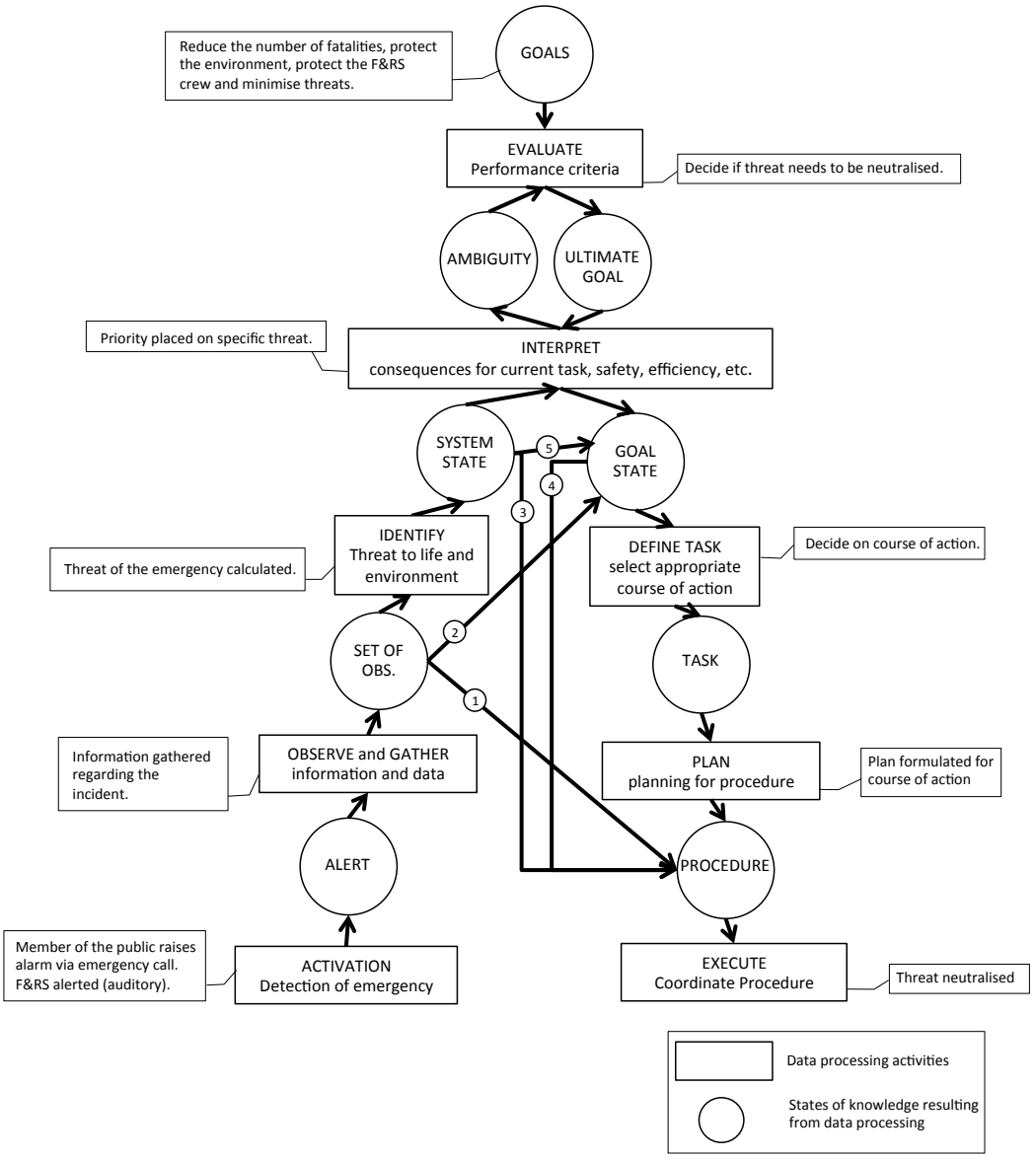


FIGURE 4.11: Decision Ladder (adapted from Rasmussen (1986))

A second decision ladder has been constructed to identify the key questions that are asked at each stage of the decision-making process, see figure 4.12.

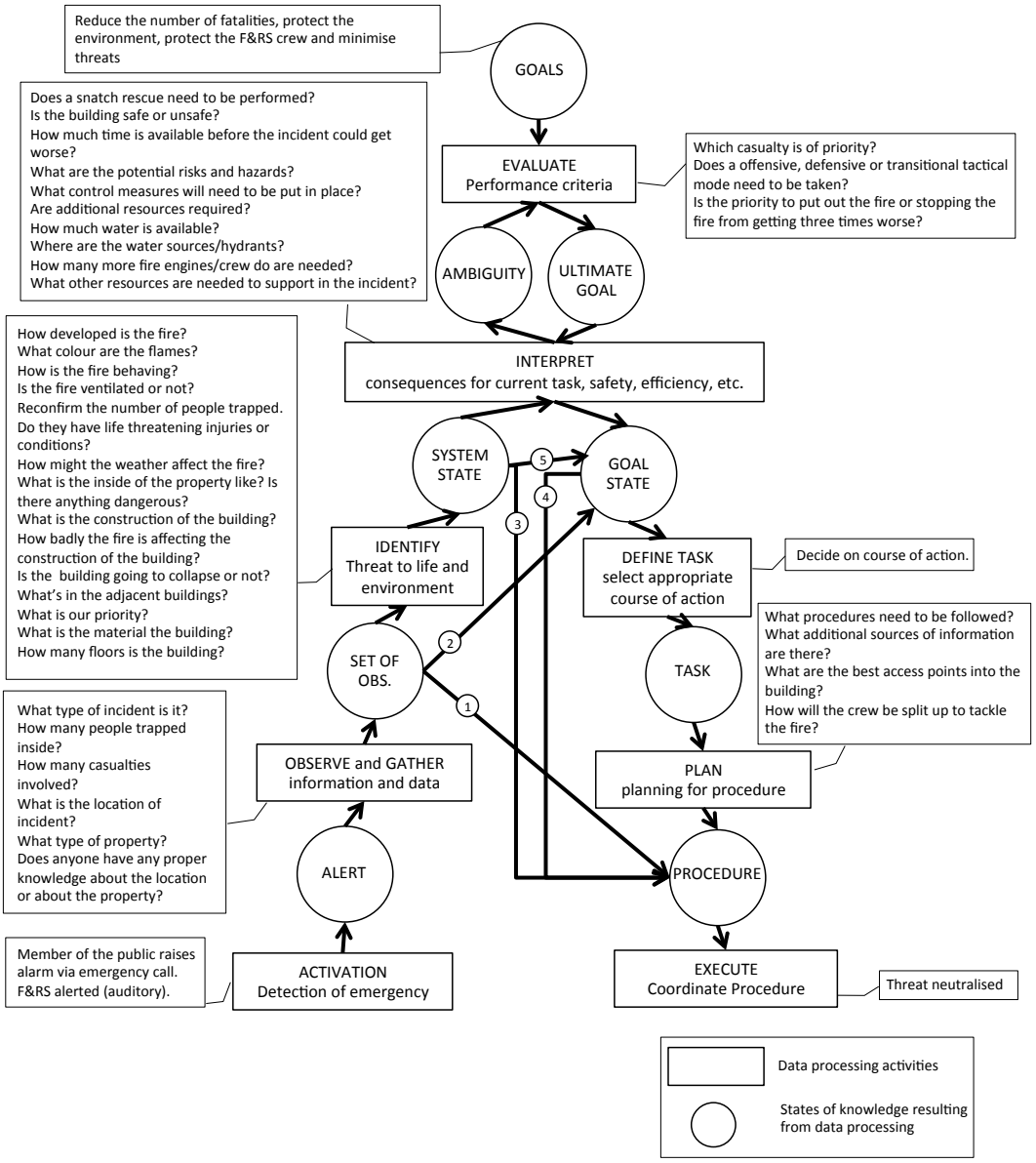


FIGURE 4.12: Decision Ladder showing Questions at Each Stage

Naikar et al. (2005) suggest the use of the context activity template for this phase of the CWA, see figure 4.13. This template highlights activity in the work systems, which are characterised by both work situations and work functions. Naikar et al. (2005) indicates that the work situations (situations decomposed by schedules or location) are presented along the horizontal axis, and the work functions (activities characterised by its content independent of its temporal or spatial characteristics) are shown along the vertical axis of the context activity template. The dashed boxes show in which situations the work functions can appear, and the circles and whiskers reveal where the work functions can usually be present.

The work functions captured in this diagram are typically similar to the purpose related functions in the WDA (figure 4.11). For the F&RS there are four distinctly different situations that have been selected due to the constraints enforced by their geographical variation, which are: in the command centre, at the F&RS, on route to the incident, and the incident location itself. Figure 4.13 shows that the constraints imposed on the system mean that two of the functions are bound by the situations (Timing calculation, risk calculation). The functions of tactical mode calculation, resource allocation, understand critical information for the incident and casualty calculation can take place in any situation. Figure 4.13 illustrates that the function of "tactical mode calculation" can occur in any situation, however it typically occurs at the incident location.

The ConTA considers the known reoccurring activities within the domain and identifies further system constraints by investigating the typical activities against specific situations. In this ConTA, certain activities are bound by geographical location.

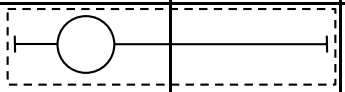
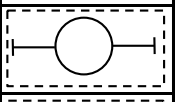
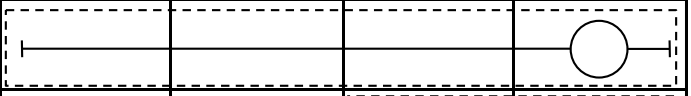
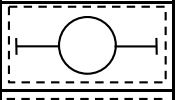
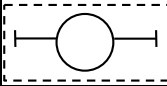
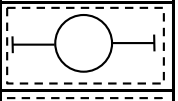
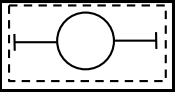
Functions/Situations	Command Centre	At the F&RS	On route to Incident	Incident Location
Route Planning.				
Record information regarding the type of emergency.				
Time calculation.				
Emergency threat calculated.				
Weather calculation.				
Tactical mode calculation.				
Risk calculation.				
Environmental understanding.				
Priority placed on threat.				
Decide if threat needs to be prioritised.				
Resource allocation.				
Water sources and location calculation.				
Decide if the threat is genuine.				
Decide on a course of action.				
Plan course of action.				
Neutralise threat.				

FIGURE 4.13: Context Activity Template

4.5.5 Stage 3: Strategies Analysis

Strategies analysis (StrA) is used to investigate known reoccurring activities in more detail. StrA investigates the tasks analysed in the ConTA stage and presents the strategies that could be used to accomplish them. The strategy performed by an operator at a particular time could vary significantly. In addition, different operators could perform the same task in a number of different ways. There are a number of strategies for achieving the same ends with the system described in the Abstraction Hierarchy. Each of these strategies uses different resources and distributes the workload in different ways. Figure 4.14 shows six typical methods for attending to an incident. The list captures those strategies that are most commonly used, but does not intend to be an exhaustive list.

The analysis plots a strategy moving from a start state of an identified incident, to an end state of the incident being attended to.

StrA identifies the different ways in which an activity can be accomplished (Naikar, 2006). This analysis is concerned with how the activity can be completed. StrA is concerned with identifying general "categories of cognitive procedures", which are idealised, abstract descriptions of particular sequence of operations.

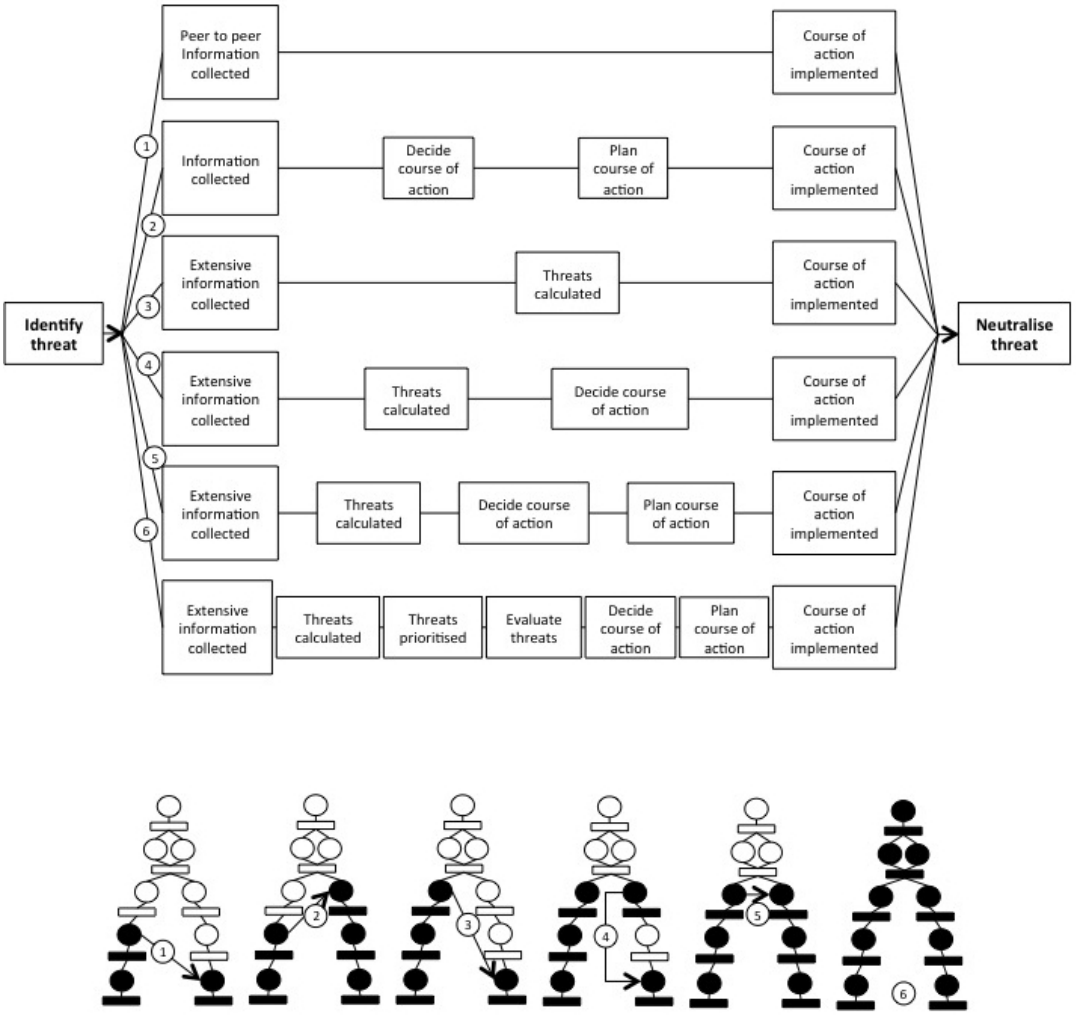


FIGURE 4.14: Strategies Analysis

In this diagram the start state is when an emergency is identified and the end state is that the emergency has been neutralised. The decision ladder illustrated in figure 4.14 outlines that the strategy chosen affects the way in which the task is completed. The first strategy shows that the task is completed at a simplistic level without exploration of all the information. This could be due to the fact that the level of risk has been identified as too great and an action must be completed straight away, this situation requires the identified emergency to be resolved as it is detected. An example of a more complex strategy to resolve an emergency is strategy six, which takes into consideration all the factors and a priority is assigned and the appropriate measures are taken.

4.5.6 Stage 4: Social organisation and cooperation analysis

SOCA analyses how the work is distributed, coordinated and managed. This stage maps each of the actor types on to the existing tools in order to show who has the capability of doing what. Using arbitrary colours it is possible to show where each on the actor groups can conduct tasks, see figure 4.15.



FIGURE 4.15: Key of Actor Type and Colour

Figure 4.16 shows the abstraction-decomposition space (ADS) coloured to show the nodes that can be used by the key actor groups. The total system requirements have been not been included in the colour analysis as they apply to all actors.

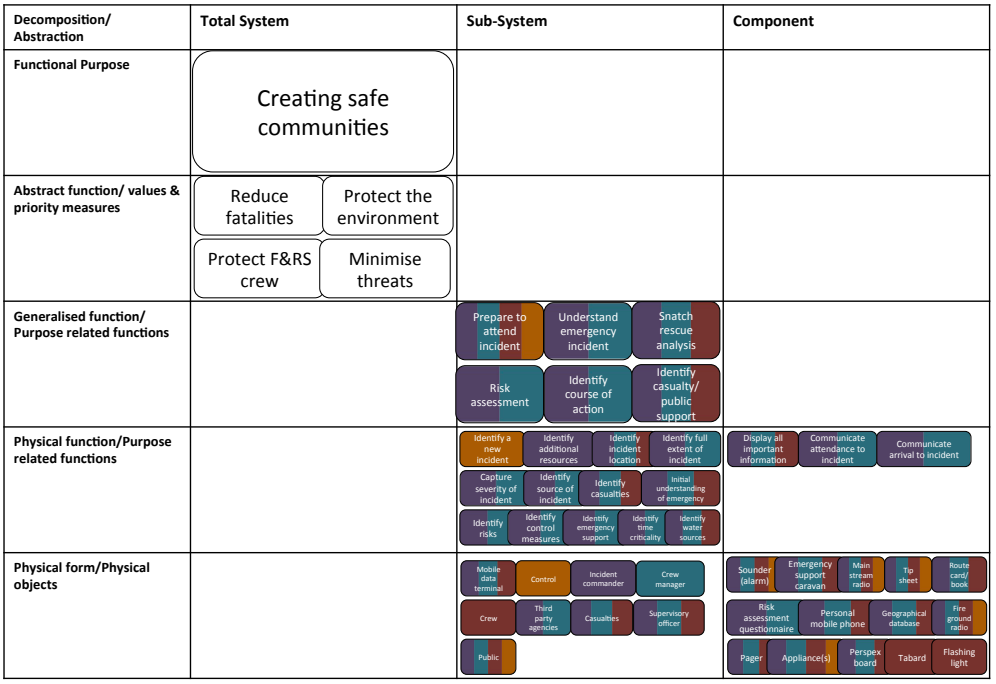


FIGURE 4.16: ADS Showing Nodes Used by Each of the Key Actor Groups

Figure 4.17 shows the decision ladder coloured to show where each of the actor types can conduct tasks. The control room initially take in the call and pass on the details to the IC and crew. The details are then interpreted and further information gathered in order to make a decision about how to resolve the incident.

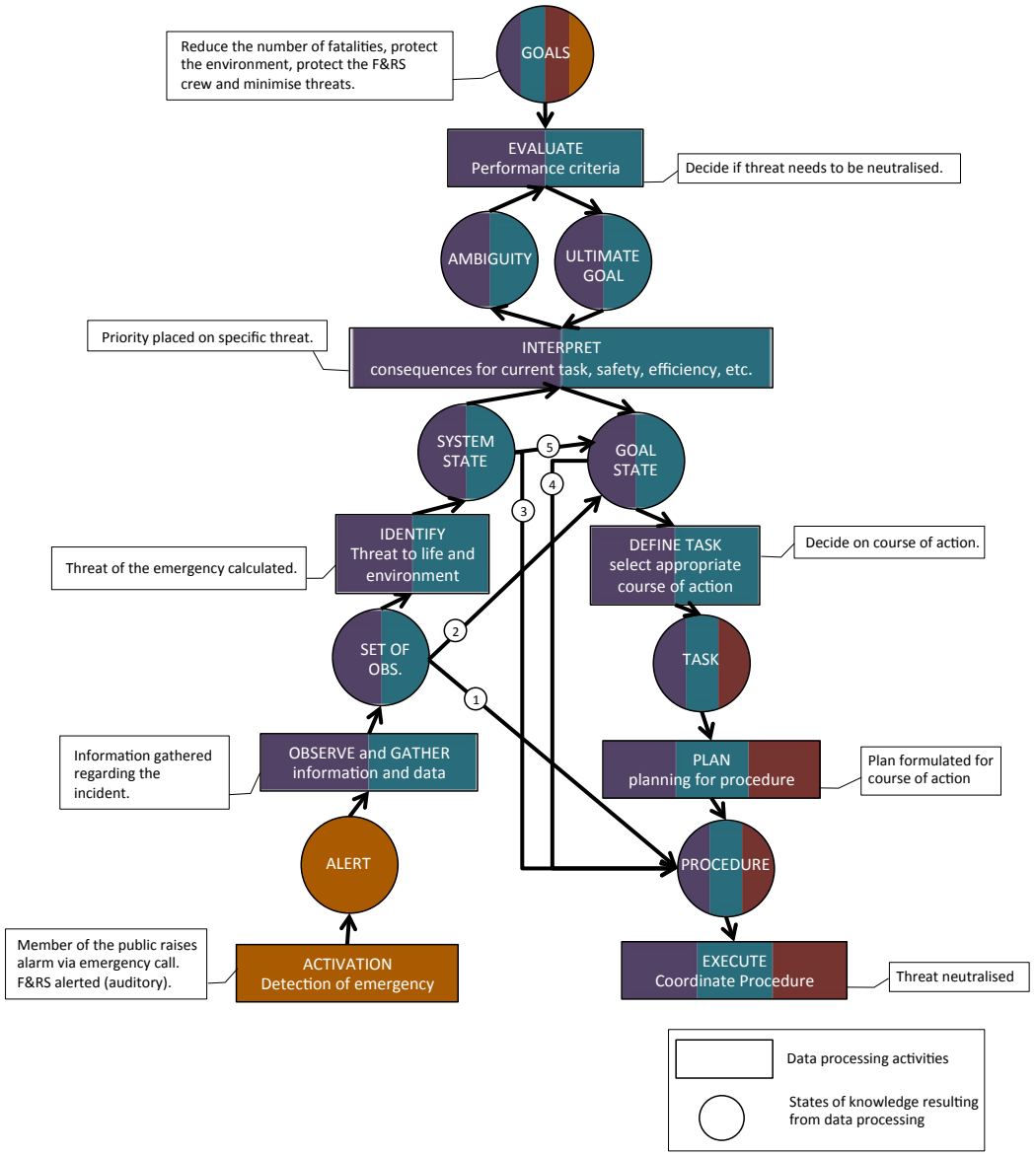


FIGURE 4.17: Decision Ladder Showing Tasks That Can Be Conducted by Actor Types

4.5.7 Stage 5: Worker competencies analysis

Within WCA there are three levels of cognitive control, these are adopted to guide the operator's actions when working in the setting. Skill based behaviour is automated with integrated patterns of actions, performed in real time and linked to the environment in a continuous perception-action loop. Conscious attention is not required for skill based behaviours (Vicente, 1999).

Rule-based behaviours are if-then understandings between perceptual cues in the environment add appropriate actions. Knowledge based behaviour is serial, analytical reasoning based on a symbolic mental representation of the relevant restriction of the environment.

The network structure will also be dependent on the behaviour level expected from the operators. The operators can work at three different behaviour levels dependent on the level of processing required to complete the desired activity. Table 4.2 shows example responsibilities for each of the actors at the three behavioural levels.

	Skill based	**Rule based**	**Knowledge based**
Control	Send the received information to F&RS.	Match the threat of the emergency to the resources required.	Match the threat of the emergency to resources considering the location, environment, type of incident and workload.
Incident commander	Collect information from tip sheet and distribute important information to crew.	Distribute the tasks between the crew based on training.	Based on all information develop a cause of action to neutralise threats.
Crew	Neutralise threat whenever a threat is identified.	Prioritise the the threats.	Neutralise the most dangerous threat without compromising safety.

Table 4.2: SRK Levels for Each of the Actors

4.5.8 Summary of CWA Findings

The CWA analysed the F&RS to get a general understanding of the domain based on how operators make real-world decisions in emergency situations. The CWA was based on activity two which included CDM interviews of real emergencies that had been resolved by the F&RS. The CWA framework describes a domain independent of the goals and activities, investigating how and where decisions are typically made, who completes the activities, the strategies used and the team behaviours.

The CWA framework presents findings in five stages, covering the F&RS domain in several aspects. Stage 1 (WDA) presents an abstraction hierarchy which organises the information from the CDM interviews into a systematic diagram. The diagram presents

the external constraints, values, functions and physical objects that are required for the different types of emergencies in the F&RS. Whilst the task decomposition diagram was referenced through out the CWA process, it was extensively used to develop the AH (items and goals), to identify the context activity template (to show where things took place) and the decision ladder (the main decision points were drawn).

The CDM descriptions of the incidents as well as the task decomposition diagram provided a basis for stage 1: Work Domain Analysis, in particular the abstraction hierarchy. The task decomposition diagram was particularly helpful to identify the bottom two rows of the AH: Physical function/Object-related processes and physical form/physical objects. The CDM descriptions were important to identifying the first three stages. The descriptions provided by the participants identified their goals including their purpose, values and priorities.

Stage 2, ConTA, investigated the linear sequence of information processing steps. Two decision ladders were created. The first identifies shunts and leaps of an experienced decision-maker. The second decision ladder identified the questions that the decision-makers need to ask at the different data processing activities. The findings from decision ladders in figure 4.12 and 4.17 provide value insight into how decisions are made in the F&RS. The questions identified in 4.12 are particularly important in understanding the knowledge required to support naturalistic decision-making. By understanding what information is required and when, we can facilitate the correct presentation of information. These questions are a key finding to support the development of design principles and design of systems. Stage 2 also identifies where the functions from the abstraction hierarchy are completed. This knowledge is important in giving understanding to a system designer of where the information is needed. Also, allowing the system designer to understand what environment the operator will be in when absorbing information and the time constraints that the operator may be under.

Stage 3, StrA identified the different strategies that can be applied to complete an incident. Six strategies are presented; at the simplest, the decision-maker has gathered the main information from peers and then implemented a course of action. A more complex strategy shows that the decision-maker must complete each data processing activity. These strategies are required to understand the different processes the operator undertakes with decision-making. Stage 4, SOCA, identified who in the team completes the tasks using the abstraction-decomposition space and decision ladder, identifying the key individuals involved in the team. The research identifies four main actors; IC, SIC, crew and control room staff. Stage 5, WCA, investigated the behaviours the team based on skill, based and rules.

4.6 Discussion

This exploratory study investigated how operator's make decisions in emergencies. The chapter addresses the second aim of this thesis, to examine NDM and the HF issues in NDM contexts. The CDM interviews provide an account of how each HF issue occurs in a real NDM environment and how they will be used to support the development of guidance to support the design of systems. This was undertaken by carrying out CDM interviews with firefighters, an initial analysis identified the steps typically taken to resolve an emergency; with examples given of how the HF issues manifest. The CDM interviews were then analysed using the CWA framework, which provided the researcher with information on the types of questions the operator ask, highlighting the type of information the operators need. The work also identifies where the information is required, who is involved in the process, the functions and elements that make up the domain.

In addition to the human factors issues identified in figure 4.1, the following key factors were identified to support the development of NDM systems:

Decision-maker and Team

The CWA including the abstraction hierarchy (figure 4.9) ADS showing key actor groups (figure 4.16) and decision ladder showing tasks that can be conducted by actor types shows how the decision makers and the team split the activities and how they interact with the elements in the emergency.

Third Parties

Firefighters may be required to interact with other third parties including other emergency services. The goals of the third party may also need to be considered when investigating how to support the decision maker.

Emergency identification

The trigger to identifying an incident is through an alarm in the control room, any known information is passed to the firefighters via a tipsheet, which allows for an initial identification of what they will be facing. This begins the sequence of events to resolve an incident. The initial information may indicate the urgency of the incident and influence the resources taken/sent to the incident.

Environment

The decision-makers in all three incidents spent considerable time understanding the environment in which the incident was taking place. The firefighters spend time trying to understand the environment whilst travelling to the incident through the use of technology,

they speak to people at the incident and physically investigate the environment to understand what is happening and identify the constraints. The left leg of the decision ladder figure 4.12 illustrates the types of questions the IC needs to answer when investigating the environment.

Time to absorb information

The IC and firefighters absorb information in a number of different places, for example the IC will typically use technology to get information before arriving, however this is typically a short amount of time. When arriving at the incident the IC needs to be prepared to react instantly to stabilise the situation. The context activity template identifies the different functions that are made and shows where they typically take place (Figure 4.13).

Identifying course of action

Once the IC had all the information, they were able to formulate one course of action based on the constraints that had been identified. A system should be designed to identify the constraints which can be used as a basis for the course of action. Figure 4.14 identifies the types of strategies the decision-makers make to formulate a course of action.

Confirm success of the course of action

Once the decision-maker has committed to a course of action, the decision-maker and crew will monitor the situation from a distance and ensure that the correct procedure and result is achieved. The roles of the firefighters are identified in Stage 4, figures 4.16 and 4.17, identifying the responsibilities for the different members in the crew.

Overall, the CWA framework was an effective method to investigate human information behaviour, identifying the complexities in the context, including the types of decisions, strategies, people and technology involved. However, the method has limited output to support the development of systems. Furthermore, whilst CWA attempts to understand decision-making, a deeper analysis of the naturalistic decision-making process is required to get a clearer understanding of how to support system design in emergency contexts.

The CDM interview technique was a good approach to investigate how decision-makers resolve emergencies. During the CDM interview, the task decomposition diagram supported the participant during the interview, acting as a clear visual representation of the steps in the incident that they had attended. The task decomposition diagram provide discussion points and facilitated recall of sub-tasks. However, this exploratory study only presents three CDM interviews, the research would benefit from investigating a larger number of emergency incidents which cover a wider range of emergencies covering all aspects an operator may have to deal with. Further understanding could be gained by exploring in greater

detail the decision points of the decision-making process. Future work would benefit in extending the CDM interviews to include a more systematic method of investigating the decision points.

4.7 Chapter Summary

This chapter described an exploratory study, which investigated NDM in the F&RS. The chapter presents findings to address the second aim of the thesis by investigating the decision-maker's decision-making process, tasks and HF issues that affect them.

The research consisted of three activities; kick-off meeting, CDM interviews and CWA. The kick-off meeting presented an initial introduction to the domain including the decision-maker's tasks, team and technology. The CDM interviews presented case studies of the types of emergencies decision-makers must complete. The interviews provided greater detail regarding the tasks the decision-maker must complete and an insight into the HF issues. The CWA provided further understanding of the domain, the decision-making process, the strategies used, the distribution of activities between the actors and the workers competencies. The findings from this chapter will be used to identify how systems need to be designed to support decision-makers.

Chapter 5

Exploring NDM in the Aviation Domain: Stages 1, 2 and 3 of Decision Centered Design

5.1 Chapter Overview

Chapter 5 investigates decision-making in a second NDM context; the aviation environment. Like chapter 4, chapter 5 contributes to the second aim of the thesis to examine NDM and the human factors issues in real-world environments. Decision centred design (DCD) is used to investigate the aviation setting. DCD is made up of five steps (see Figure 5.1) and focuses on designing to support decision-making during challenging situations. DCD explores the primary cognitive requirements to inform the design process (Crandall et al., 2006, Hutton et al., 2003, Klein, 1993a). This answers how technology can support the operator's difficult decisions and the cognitive demands of an operator's work, resulting in improved task performance.

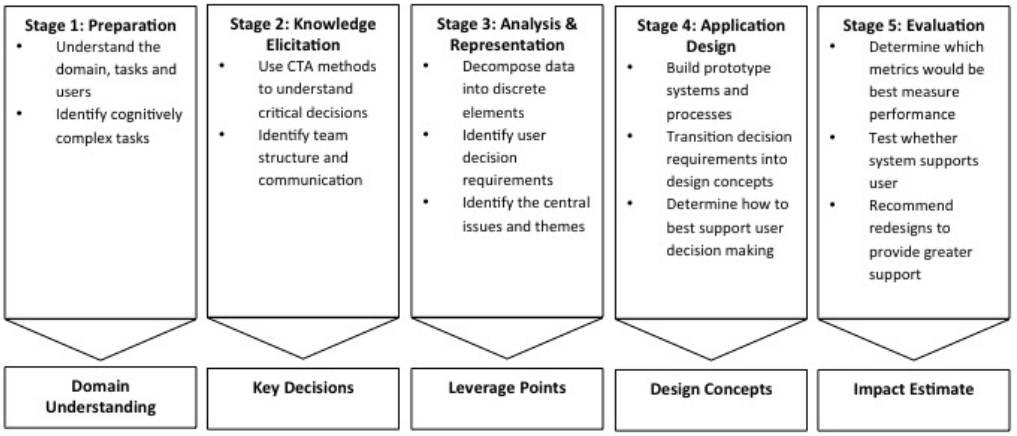


FIGURE 5.1: Decision Centered Design

The DCD stages are presented over two chapters. This chapter presents stages 1-3, which detail the main knowledge elicitation and design ideas sections. Stage 1 presents an initial understanding of the aviation domain. The stage investigates the pilot's tasks, the decision-making points and the human factors issues, which occur during normal operations. It is identified in this stage that pilots experience complex decision-making during non-normal situations, such as emergency situations in the cockpit. Stage 2 investigates these non-normal situations using a retrospective interview technique, which explores emergencies that the pilots have experienced in the cockpit. This allowed a further investigation of the pilot's decision points, human factors issues and decision requirements for design. Stage 3 uses the decision requirements to identify a number of design solutions to support the real-world decision-making in the aviation setting.

Chapter 6 presents stages 4 and 5, which apply chapter 5 findings to the design and evaluation of a real-world decision-making system. An additional section has been included before stages 4 and 5, an introduction to single pilot operations to introduce the domain the new system will be used in.

5.2 Stage 1: Preparation

Stage 1: Preparation gained an overview of the aviation environment and investigated real-world decision-making including the decision-maker's tasks and factors that affect their NDM process during normal operations. The outputs of stage 1 are:

- An introduction to the aviation domain.
- Identification of the flight phases that pilots complete.

- The pilots' tasks during each of the flight phases.
- An overview of the human factors, which occur in the flight phases.
- The cognitively challenging tasks for investigation in stage two: knowledge elicitation.

The stage begins by presenting findings from an ethnographic study of a two pilot jet aircraft flight and interviews conducted post-flight with the aircrew. The tasks conducted in each of the flight phases under normal conditions in civil aviation are described. In this section, the human factors issues in this domain are investigated, using the seven human factors issues identified in chapter 2. Also outlined are the cognitively challenging tasks, which are investigated in the next stage.

5.2.1 Method

Two activities were implemented to understand the environment; an ethnographic study in an aircraft and post-flight interviews with the aircrew. For the first activity observations were undertaken of a ferry flight from Austria to Germany (December 2014) in a Cessna Citation, a small jet aircraft. This identified the flight phases and types of tasks in each phase the pilots must complete for a successful flight. Pilots were highly experienced with both commercial and military pilot licenses. The pilots were observed from the departure airport until arrival at the destination airport.

Post-flight semi-structured interviews with the aircrew were then carried out. In the interview the pilots reviewed the flight phases and tasks performed in a normal flight. The pilots were then instructed to describe how the human factors issues outlined in chapter 2 manifest in each of the flight phases. They also identified where the difficult tasks occurred when aviating.

5.2.2 Participants

Stage 1 used a two pilot aircrew; pilot in command (PIC) and co-pilot (CP). The aircrew share the responsibilities of pilot flying (PF) and pilot monitoring (PM) roles in the flight deck in a normal flight. The PF is typically responsible for controlling the vertical flight path, horizontal flight path and energy management through supervision of the autopilot or by manually flying the aircraft. The PM actively monitors the flight parameters, calling out excessive deviations and assisting the PF. The PM also manages radio communications, supervises system configuration, monitors aircraft status, performs actions called by electronic/paper checklists and coordinates with the PF throughout the whole flight. In

military environments the aircrew can be larger, with an extra crewmember in the cockpit known as a flight engineer. He/she sits in the cockpit and is responsible for the aircraft systems during the flight.

The normal operational environment involves the pilots completing well-rehearsed procedures for different phases of the flight. The procedures are a step-by-step guide of the tasks that need to be completed for each flight phase. They outline the "what-to-do" and "when-to-do". Normal checklists are implemented to confirm that all essential actions in the previous procedures have been performed and maximum situation awareness is maintained. Procedures include inspecting the aircraft, testing the on-board systems, analysing the information (i.e. notice to airmen (NOTAM), weather information, passenger lists, cargo information) and configuring the systems. The procedures aid the crew through the progression of tasks and actions ensuring the tasks at hand are completed in a logical, efficient and error free manner (Degani and Wiener, 1993). They also provide the pilot with a standard way to complete actions, which ensures crew coordination and quality control.

5.2.3 Procedure

The researcher observed the aircrew throughout the flight. As the aviation domain is a highly specialised domain, it was not possible for the researcher to implement a traditional ethnographic study, instead the aircrew took the time to explain the steps that they were completing before, during and after the flight.

The pilots started by explaining the items that they needed to complete before the flight. They then explained the items they need to complete during the pre-flights checks and the walk around of the aircraft. In the cockpit the pilots were observed and the researcher recorded each of the phases and tasks the aircrew completed. The researcher had prepared a task decomposition diagram template on a laptop before attending the flight which she filled in as the pilots completed the activities of the flight. The researcher also identified human factors issues, which were entered into another template and later discussed with the pilots. Post-flight an interview was performed to confirm the flight phases and tasks as well as identifying and extending the human factors issues. Once the work had been written up, it was sent via email for final validation to the pilots to ensure accuracy of the write up.

5.2.4 Ethnographic Study Results

The results are split into flight phases, aircrew tasks and human factors issues observations.

5.2.4.1 Flight Phases

There are six distinct flight phases; flight planning, pre-flight checks, clearances and taxi, take off, climb, cruise and descent, approach and landing (see Figure 5.2). However in the sixth phase in the figure, after landing and post-flight, the procedures are a subset of the pre-flight checks and are therefore not specifically handled in this research.

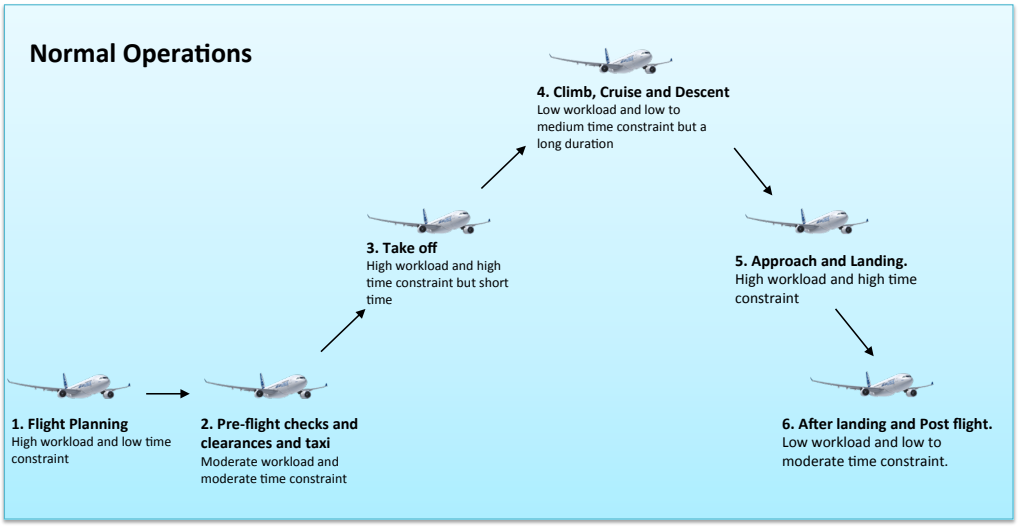


FIGURE 5.2: Flight Phases

5.2.4.2 Aircrew Tasks

Using the outline of the flight phases together with the input from pilot interviews, the tasks were identified for each of the five flight phases. Table 5.1 describes the main tasks for each flight phase. A detailed overview is provided in Appendix B.

Flight Phase	**Task(s)**
Flight Planning	The pilots received and analysed the briefing package, which contains details of the flight. PIC focuses on the flight plan and weather, whilst the CP focuses on the constraints in the Notice to Airman (NOTAMS). NOTAMS are a written notification which outline issues before a flight and any circumstances that relate to the state of flying, this typically advises the pilots regarding potential hazards along a flight route or at a particular location. The pilots come together in a verbal briefing where they discuss the details and decide on the elements of the flight. ATC are then informed of the flight details.
Pre-flight Checks, Clearances and Taxi	Pre-flight checks, clearances and inspections are completed by both pilots. Check technical status of the aircraft refuel to the amount required, programming flight management system with flight plan, performance parameters such as aircraft weight and weather data.
Takeoff	The takeoff procedures are completed. The CP monitors the PIC and both pilots monitor systems for accuracy.
Climb, Cruise and Descent	Climb altitude and monitor systems e.g. engine parameters, cabin pressure, flight path. The pilots monitor the systems and flight path, as well as taking updates from ATC.
Approach and Landing	The pilots program the flight management system with the expected/cleared approach. An approach briefing is completed followed by the procedures for descent, approach and landing.

Table 5.1: Flight Phase and Tasks

Figure 5.3 presents a task decomposition diagram of the tasks in each flight phase, which are completed during normal procedures for a flight.

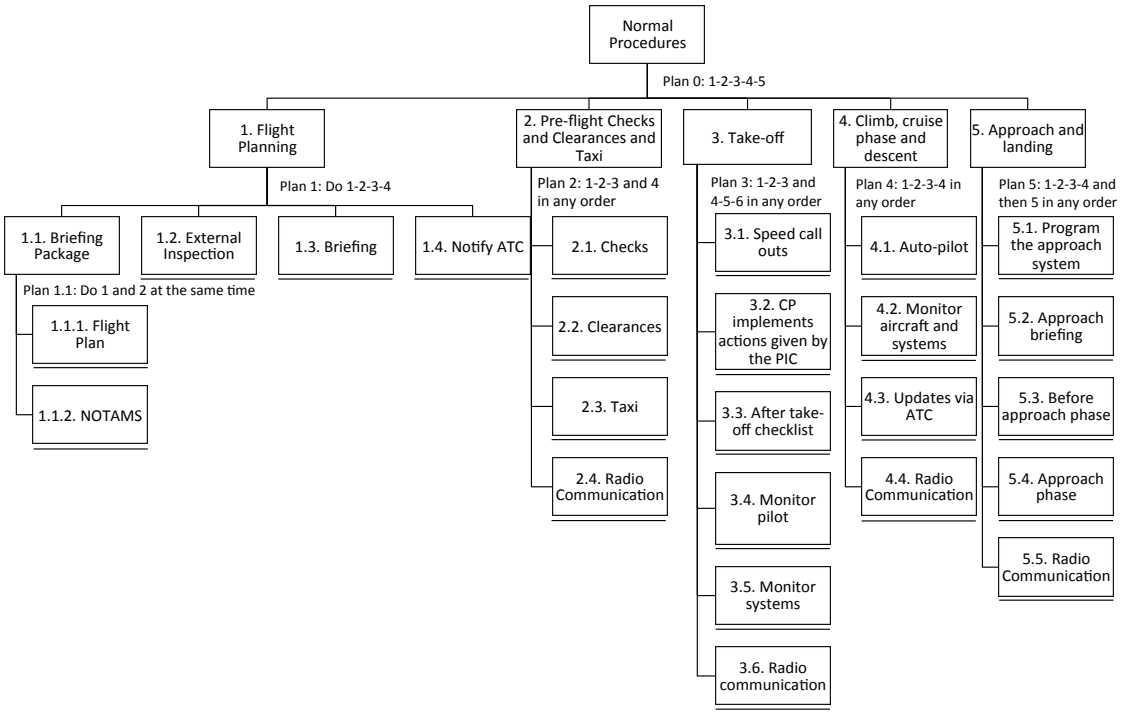


FIGURE 5.3: Task Decomposition Diagram of Normal Procedure Tasks

During the interviews, the pilots stated they experienced the most challenging tasks during non-normal conditions such as emergency and abnormal procedures. The pilots outlined that if an emergency occurred on the ground, the aircrew could abandon the aircraft and usually there were a number of people to support them, however, once in the air experiencing a failure was more difficult to handle.

5.2.4.3 Human Factors Issues Observations

The human factors issues for each phase were developed with the aircrew and a table was constructed (see appendix C). These were based on the tasks highlighted in appendix B. An overview of the observations made for each human factor issues with relevant examples from appendix C are now discussed.

- **Factors referring to cognitive processes**

Decision-Making

Decision-making is a collaborative process between the aircrew, however, the PIC's role is to make the strategic decisions for the flight and is primarily responsible for the flight and passengers on-board. Before the flight, the PIC decides if deviations from the planned

route are needed and any implications of taking a deviation such as the extra journey length and extra fuel requirements.

An hour before the approach, the pilots are required to make decisions regarding how to land. The aircrew prepare and program the flight management system for landing. To make a decision on how to successfully and safely land the aircraft, information about the weather, the remaining amount of fuel, the constraints at the destination airport, etc. are assessed. The pilots share ideas, agree on the exact method of approach and inform each other of what they are doing (see table 5.2). Pilots making decisions in normal procedures are under relatively low workload, as the pilots have time to deliberate and discuss their strategy. The aircrew use checklists to support decision-making, as well as rules and regulations, which can support and/or limit the decisions.

Approach briefing. The controls are handed back to the CP and the PIC carries out the approach briefing.	The PIC checked the aircraft weight at landing, the speeds, which flap settings he would use for landing, talked about the approach, what he planned to do if he could not land. The CP was happy with the PIC's briefing and both pilots were aware of the next sequence of actions.

TABLE 5.2: Example of Decision-Making During the Approach Period

Situation Awareness

The aircrew develops an understanding of the flight through the avionic functionality, cockpit displays, air-ground communication, NOTAMS and the weather forecast. When planning the flight, each pilot develops individual situation awareness, through individual study. During the flight planning phase, the PIC predominantly concentrates on the flight plan, whilst the CP concentrates on analysing the NOTAMS (see table 5.3).

Phase One – Flight Planning:	
Flight Plan. Flight plan contains information such as departure airfield, destination airfield, the route (this consists of way-points and the airway routes), the information about the type of aircraft and the number of people on-board.	The PIC checked the flight plan, to reconfirm the flight details. The pilot's stated that the PIC's role is to make all the strategic decisions of the flight.
NOTAMS. NOTAMS contain short-term information about the airport. Examples include: the closure of parking stands, bad weather (which would require instrument landing system), closure of airways, construction work at an airport, cranes which are inside the safety area, etc.	In the NOTAMS, the CP received hundreds of pieces of information. The CP had to sufficiently analyse and evaluate key information points that might affect the flight. There were only 2 or 3 pieces of information that applied to the flight.

TABLE 5.3: Example of Individual Situation Awareness During the Flight Planning Phase

The pilots identified that the aircrew undertake two monitoring tasks to update and maintain their understanding of the situation:

1. **Monitoring cockpit systems** these include:

   (a) **Identifying anomalies in the system.** The pilots monitor the systems to see if there are anomalies, which could impact the flight. For example, irregular values in the fuel interface could indicate a leak.

   (b) **Difference between the pilot's instrumentation.** The aircrew monitor both sets of instrumentation in the cockpit to identify any differences in each of the pilot's systems. For example, if there is a difference between the two altimeters, the pilots would need to investigate which altimeter is working correctly.

2. **Monitor the environment:** The pilot's monitor the activities that are occurring outside the aircraft, for example, during the cruise phase there might be icy conditions or there might be other aircraft flying dangerously close.

Once the pilots develop their individual understanding of the flight, the aircrew come together to develop a shared situation awareness, this is discussed under the teamwork section.

Mental Models

Pilots' tasks in the cockpit are based on their expertise and intuition, which have an important role in safe flying operations. Their expertise helps formulate a mental model

of the aircraft, the procedures that they need to complete and an understanding of the checklists.

The pilots stated that there are two main parts to pilot training, theoretical study and practical flying, and together these form the basis of their mental models. The theoretical part consists of: aerodynamics, aircraft systems (electric, hydraulic, mechanics), propulsion systems, navigation (radio navigation, based on installed radio transmitters, GPS navigation, inertial navigation systems), meteorology (how weather develops, the dangers of different met phenomena like thunderstorm, super cooled water in clouds, fog, wind shear, etc.), human performance (limitations due to lack of oxygen in low density air, dehydration, long working hours etc.) and air law.

The practical flying includes basic flying on single pilot small aircraft, then multi crew, multi engine, IFR (about 120 flight hours are necessary). After this, a type rating is undertaken for e.g. A320/B737, which takes 4-5 weeks with 2 weeks of theoretical training (systems introduction/aircraft specialities) and a further 2 weeks of simulator flying and 5 landings in real aircraft, which can take 2 years to complete.

This training gives them knowledge of the procedures that must be completed in the aircraft and an understanding of how the aircraft should behave.

- **Factors resulting from interactions between individual and environment**

Workload

As previously stated, aircrews are trained to support human performance. As part of this training they are trained to manage workload. The CP takes a key role in support the PIC and it is his/her job to ensure that the PIC does not become overloaded, completes activities in a timely manner, in the correct order, and that no activities are incomplete. To further manage workload, the aircrew use procedures and checklists to complete actions in the cockpit, which provide the aircrew with a memory aid. Usually the CP will read the items and the PIC carries out the action in the cockpit, see table 5.4. Pilots are also trained to monitor each other to identify "target fixation", where the mind focuses on a single element, which can result in the pilot missing other key information and problems.

Workload can increase if a time slot to take off is missed. This could put the aircrew into a more stressful situation, where they are rushed through a system to meet the take off time. The pilots stated that workload increased if an emergency was detected in the cockpit as this would trigger additional procedures and actions.

Monitor pilot. The CP is a constant monitor of the PIC ensuring the correct aircraft operation.	Throughout the flight, especially taking off and landing (this is a high priority task and deemed a high workload task) the CP must monitor the PIC on all parameters. Things that the CP looked for included if the PIC might was focusing on the speed or the altitude, which results in the PIC missing the glide path.

TABLE 5.4: Example of Workload

Human Error

The aircrew monitor each other's actions in the cockpit. The pilots stated that the CP is an extra *"head, pair of ears and eyes in the cockpit, monitoring the aircraft and the environment but also the PIC"*. The CP monitor's the PIC in the following ways:

1. **PIC enters the correct parameters:** The CP undertakes a crosschecking activity, which ensures that the items programmed into the systems by the PIC are correct. The CP monitors the values in his/her set of instrumentation as he knows the target values (e.g. altitude during cruise or at distinct points during approach, briefed speeds for approach and landing or limit speeds for flaps and gear) and will cross check the PIC's values with his/her instrumentation. When an inaccuracy is found the CP will verbalise his concerns to the PIC.

2. **PIC completes the correct procedures:** The CP monitors the PIC to ensure the correct procedures are completed at the correct time, during the different phases of the flight. For example, if the aircraft has been cleared to fly at an altitude of 32,000ft and the pilot levels off at 32,200ft according to the CP's altimeter, the CP will say, "check altitude!" If the PF accidentally levelled off too high he will answer (e.g.) "Copied! Correcting"

3. **Incapacitation:** The CP monitors the PIC to ensure he is not incapacitated at any time during the flight, this is particularly important during take off. In the event the PIC becomes incapacitated, the CP takes over control of the aircraft and seeks help immediately.

Uncertainty

The aircrew is presented with constraints in the NOTAMS; these constraints result in uncertainties, which could impact the flight plan. For example, the pilots spent substantial time analysing the NOTAMS and understanding what impact the bad weather had on the flight. Having bad weather presents a lot of uncertainty to the aircrews as they do not know what they could face during the flight.

- **Factors resulting from team environment**

Teamwork

The team is made up of on-board and on-ground actors. The on-board actors are the aircrew and cabin crew. The pilots' goals in two pilot aircrews are to ensure the safety of the aircraft and the passengers on-board. The two pilot aircrew work as a team and each pilot knows the exact tasks they must complete, see table 5.5 for the main responsibilities for each crew member. The cabin crew are responsible for the safety of the passengers, cabin preparation before take-off and during emergency operations.

Pilot in command	**Co-pilot**
Analysis of flight plan. Main decision-maker. Primary responsibility of the aircraft and passengers on-board. Predominately flying tasks. Monitoring the cockpit systems and environment.	Analysis of NOTAMS. Support decision-making. Predominately non-flying tasks including monitoring the PIC's performance. Monitoring the cockpit systems and environment. Main communicator with ATC

Table 5.5: Responsibilities for Each Crewmember

On-ground actors include technical/logistical personnel and air traffic control (ATC). The aircrew is supported by technical/logistical personnel to support technical inspection of the aircraft. The flight operation office provide supporting flight information such as NOTAMS, weather briefing, passenger/cargo lists or details. ATC, also communicate with the aircrew to provide guidance and clearances for air navigation procedures for the flight including, start up of the engine, taxi and takeoff clearance and take off.

In order to support the team, shared situation awareness and mental models are discussed:

- **Shared Situation Awareness** During the pre-flight preparation and once the pilots have analysed their individual resources, the aircrew communicate their findings to each other during the briefing period. This briefing allows the pilots to discuss their findings, explore any constraints that could affect the flight (e.g. bad weather, which could cause a delay or possible re-routing) and formulate the final flight plan. This process allows both the pilots to develop shared situational awareness; thus both pilots have a similar understanding of the overall flight. Pilots can then pre-empt what may go wrong and consequently plan ahead to avoid errors.

- **Shared Mental models** The pilots share similar mental models of the aircraft operations and what the cockpit systems should display are based on the aircrews individual mental models from similar training programs and hours in the simulator. Using their shared situation awareness they update their mental models of the aircraft and flight plan.

Communication

The pilots highlighted that two pilot aircrews spend a considerable amount of time communicating with each other to discuss the flight plan, exchange ideas and problem solve (Helmreich et al., 1999). During the post-flight interview, three types of communication were identified:

- **One-to-one communication.** The communication is between the pilots, particularly for decision-making but also on a social level.
- **Communication with third parties.** This included communication with the cabin crew, passengers, as well as, ATC.
- **Verbalisation.** As part of the communication training, the pilots are encouraged to verbalise their actions. This allows both pilots to know what the other is doing and to understand what impact that has on the aircraft and/or flight plan. The process also allows both pilots to validate what the other is doing, ensuring that manual errors in the flight deck are caught. The pilots outlined that the CP also verbalises each checklist item and then the PIC carries out the item.

Pilots complete substantial training to enhance the communication and use exact phraseology to avoid miscommunication and misunderstanding. This training is called crew resource management, which was developed to enhance communication and verbalisation between the PIC and CP. The pilot is trained to be aware of their own capabilities whilst realising that everyone could fail, even those with a lot of experience.

Table 5.6 summarises the human factors findings.

Flight Phase	Decision-Making	Situation Awareness (SA)	Mental Model	Workload	Human Error	Uncertainty	Teamwork	Communication
Flight Planning	Decisions made about the flight and route based on the constraints.	Initially the pilots build individual SA and then during the briefing the pilots develop shared SA.	Mental model of a successful flight plan.	Workload is shared between the aircrew; each pilot has his/her individual responsibilities.	Briefing allows the pilots to highlight any errors that could of occurred in each of the pilot's SA.	Uncertainties in the NOTAMS.	Shared SA is developed during the briefing and shared mental model from training.	One-to-one pilot communication to brief and discuss the flight details as well as communication with ATC.
Pre-flight Checks & Clearances & Taxi	If a takeoff should be aborted.	Maintain SA through monitoring of systems and environment for anomalies.	Pilots use their training, procedure knowledge and checklists to complete the tasks.	The pilots have a number of tasks to complete and it is considered to be medium workload.	Both pilots monitor each other; CP in particular monitors PIC.	Question the data which is displayed and check for reasonability.	Shared SA maintained via communication and shared MM from training.	CP verbalises checklist steps to the PIC, general communication between pilots and between pilots and ATC.
Takeoff	If a takeoff should be aborted.	Maintain SA through monitoring of systems and environment for anomalies.	Mental model of a successful takeoff	Shared, the workload here will increase as there are many tasks to complete.	Both pilots monitor each other.	Question the data which is displayed and check for reasonability.	Shared SA maintained via communication and shared MM from training.	Communication between pilots and between pilot and ATC.
Climb, cruise and descent	If a deviation from the planned flight needs to be made.	Maintain SA through monitoring of systems and environment for anomalies.	Normal flight parameters	Considered low workload, as the aircraft will usually be in autopilot.	Both pilots monitor each other.	Question the data which is displayed and check for reasonability.	Shared SA maintained via communication and shared MM from training.	Communication between pilots and between pilot and ATC i.e. if a new action needs to be completed.
Approach and Landing	Decision regarding the approach.	The aircrew will actively update their SA with new information such as receiving updates from ATC and weather updates to base their decisions on, whilst monitoring the systems.	Approach and Landing mental model	Workload increases as there are several tasks to be completed for this phase.	Both pilots monitor each other.	Question the data which is displayed and check for reasonability.	Shared SA maintained via communication and shared MM from training.	CP verbalises checklist steps to the PIC, general communication between pilots and between pilots and ATC.

TABLE 5.6: Human factors in Each Flight Phase

5.2.5 Summary of Stage 1 Findings

Stage 1 gave an initial understanding of the aviation environment, providing a baseline of tasks for a safe flight. Identified were the challenging situations in a cockpit, these occur during non-normal situations such as emergency procedures.

The stage outlines the main tasks two pilot aircrews must complete for a successful flight, as well as outlining the main decisions and the associated human factors that are needed to support effective decision-making. The observations found that there are five main flight phases, for each of these phases example tasks were identified.

The aircrew identified how the human factors issues manifested to support their tasks in the cockpit. The findings showed that decision-making is a collaborative process between the aircrew, decision-making can be found during tasks for flight plan and approach briefing. Pilots develop individual situation awareness during the flight planning and then come together to develop shared situation awareness. Pilots monitor the systems to keep their situation awareness up-to-date and identify any changes in parameters. Mental models developed during training, both in theoretical study and practical flying are used as a basis to their tasks. This gives them the knowledge of the procedures in the aircraft and an understanding of how the aircraft should behave. The aircrew monitor each other's actions to manage workload and error. The CP monitors the PIC's workload and ensures that the PIC completes tasks in a timely manner, in the correct order and that no activities are incomplete. The findings show that the CP monitors the PIC and his/her actions for errors. Teamwork identified that the pilots have their own individual tasks whilst working together. Communication showed that they communicate with each other, third parties and verbalise information within the aircrew.

5.3 Stage 2: Knowledge Elicitation

Knowledge Elicitation investigates the decision-making process that pilots need to make during non-normal conditions such as failures in the cockpit. The stage provides:

- An overview of a variety of emergencies that aircrews have previously experienced.
- The main tasks that a pilot must complete to resolve a non-normal situation.
- Understanding of the decision-making processing by investigating the types of decisions the aircrew must complete. This includes the pilot's goals, cues, information, knowledge and strategies.

There are two types of emergencies that can occur in the cockpit; abnormal failures, which require the pilots' immediate attention and emergency failures, which require both the pilots' immediate attention and action. Emergency procedures require a set of "off by heart" actions which are memorised actions that are carried out immediately.

5.3.1 Method

Knowledge Elicitation analyses and represents the information about key decisions and cognitively complex tasks in order to inform the design and to support the design team (Crandall et al., 2006). To investigate NDM in the aviation environment, it was not possible to implement observations of emergency situation, as it is difficult to predict when emergency and abnormal incidents occur. Therefore, a retrospective cognitive task analysis technique called Critical Decision Method (CDM) was applied to recall an incident that the participant had previously attended (Klein et al., 1989). The interviews were open-ended and exploratory, but aimed to address the specific actions taken to resolve the incident and the associated information used to support these actions and decisions. The interviews also provided an understanding of the goals, critical cues, assessments and strategies. The participants were asked to complete a task decomposition diagram of the steps, which provided a time line of events. Based on the task analysis, the researcher in agreement with the participant, identified the key decision points. These decision points were then systematically investigated using O'Hare et al. (1998) CDM probes. A larger sample size was collected in comparison to the F&RS interviews; in total ten CDM interviews. The larger sample size allowed naturalistic decision-making to be covered in a greater range of emergencies. The output of stage presents the decision requirements to resolve the situation and investigates the associated NDM process.

5.3.2 Participants

The CDM study was conducted with ten subject matter experts that included both military and test pilots who all held current military and commercial pilot licenses. The pilots were European and recruited because of their experience of dealing with non-normal situations in the cockpit.

5.3.3 Procedure

Initially participants read the information sheet and completed a consent form. They were briefed regarding the aim of the research and the CDM process. The pilots then identified

incidents where they had experienced non-normal situations and had to make decisions. In the event the participant identified multiple incidents, the researcher and participant jointly decided which incident would be discussed.

Once a scenario was identified, the participant gave an initial description of the incident. This gained an initial understanding, then the participant discussed in detail each of the steps they completed from the start of the incident until it was resolved. The steps were put into a task decomposition diagram template, which had been prepared before the interview.

Once all tasks and subtasks were identified in the task decomposition diagram and decision points were identified. The researcher asked the participant to review the task decomposition diagram and identify the main points in the emergency where they made decisions. These main decision points were then taken and put into a blank decision point template (see appendix D) which was adapted from CDM prompts (O'Hare et al., 1998). For each decision point, the researcher systematically went through each piece of information with the participant and entered the details the participant identified.

Each interview took between 1.5 hours up to 4 hours and audio was recorded. After the interview, the audio recording was analysed by the researcher and written up. The interviews were then sent back to each of the participants for review to ensure accuracy of the details. Corrections included correcting and extending the incident description, as well as, updating details in the task decomposition diagram.

5.3.4 CDM Interview Results

Ten CDM interviews were carried out with pilots. The CDM write up has been illustrated in appendix E. Overall, the decisions fall into the recognition primed model where pilots do not compare options, instead the process involves recognition matching which highlights the most likely course of action based on the given constraints. The CDM interviews show that there are common decision requirements that the pilots need to complete in order to solve an emergency.

The qualitative data shows five distinct steps; identify an emergency, stabilise situation, determine and analyse the problem, identify and perform course of action to address emergency and confirmation of success of course action and monitor aircraft. Each step has been described below, a comprehensive table with examples of how they manifest in each of the CDM interviews can be found in appendix F. It should be noted that the order of the steps; stabilise situation and determine and analyse the problem, may be interchanged. The five steps include:

- **Identify an emergency:** here the pilots are either alerted to a problem in the cockpit or the pilot identifies an issue by monitoring the aircraft and the system. Table F.1 shows every point in the CDM interviews where identification takes place.
- **Stabilise situation:** at this point the pilot needs to stabilise the aircraft, which ensures the safety of the aircrew and allows the pilot to have more time. The time might be required to get further understanding of the situation, to make a decision and/or implement the required steps. Table F.2 presents stabilising the situation in the CDM interviews.
- **Determine and analyse the problem:** here the pilots are identifying what the problem is, often trying to understand the root cause, the severity and the criticality of the problem. This allows the pilot to understand and determine what needs to be done immediately. Table F.3 evidences determine and analyse the problem, in the CDM interviews.
- **Identify and perform course of action to address emergency:** the pilot carried out the steps that are required to solve the problem. These could be actions that the pilot decides on, based on checklists including memory items that they have rehearsed during training. As part of addressing the emergency, the pilot may need to identify a suitable landing. A number of factors are considered including the severity of the emergency, the available fuel, the closest airfield, the available resources at the airfield, etc. Table F.4 shows identify and perform course of action in each of the CDM interviews.
- **Confirmation of success of the course of action and monitor aircraft:** Here the pilot spends time monitoring the systems to ensure the course of action has been successful and the emergency has been controlled. Table F.5 presents evidence of confirmation of success in the CDM interviews.

5.3.4.1 Human Factors Issues Identification

Human Factor	Description	Required Design Support
Decision-Making	Decision-makers attend a number of different types of emergencies, which may require them to make a number of different decisions at the incident. At each incident, the decision-maker needs to make a number of decisions which first centre on stabilising the situation and then once it is safe, the operator will then make a decision on how to resolve the emergency. It order to identify how to resolve the incident, the decision-maker analyses the constraints and elements that make up the emergency. There are number of things the operator tries to identify for example, what is the cause, what are the anomalies in the situation, is the situation typical or novel. This understanding impacts on the decisions that the operator will make in order to resolve the situation.	Identify the different types of emergencies that the decision-maker may have to attend to. This could indicate the types of decisions they may have to make and indicate what support and resources the operator may need. Identify the typical decision points for the emergency and design information according to the decision points that the operator needs to make. Consider the steps the operator may take to stabilise the situation before resolving the emergency. Identify the constraints and elements the operator needs to investigate when making a decision. Support the identification of the cause of the incident, the anomalies and if the emergency is typical or novel. If the situation is typical, can checklists, procedures or information on past similar situations be provided to the operator.

Situation Awareness	The pilots scan and monitor the systems to identify the anomalies in the system to determine what emergency is occurring. The pilots use their senses (auditory, visual, smell) to identify the different aspects of the incident occurring. The pilots investigate the individual elements in the emergency by investigating the systems and environment around them. The pilots identify the values in the system that do not fit in with their expectancies of the aircraft performance. For example, a rapid decrease in fuel indicates that there is an anomaly in the aircraft. The pilots then bring meaning to the individual elements to get an understanding of what is occurring in the emergency. Here the pilots may identify the cause of why the emergency is occurring. Using this information the pilots then identify what could happen according to the identified elements. For example, projecting an immediate landing as the remaining fuel on board the aircraft is not enough to get to the destination.	Identify the strategies the operators use to highlight anomalies in the system and environment around them. Consider the senses they will be using. For example, is information collected through visually scanning of a system, does the operator react to a smell in their environment or react to a vibration in the system? In addition, identify the cues the operator is looking for to identify the type of emergency. Support bringing together the key elements, constraints and anomalies of the emergency to give the operator an understanding of what is occurring in the emergency. Furthermore, support the projection of future events and how the intricacies of the incident could impact the operator and their safety.
Mental Model	Pilots have extensive knowledge of the aircraft and it should perform. Using this understanding in an emergency they might test a system to see how the system reacts and how it changes. Depending on the output they can then determine what is occurring and perhaps identify the cause of the problem.	Identify the training the operator is given for both normal and emergency situations. Understanding the operator's training will identify what the operator may base their decision's on. This could also identify the key information that they need.

Workload	In the aviation domain the aircrew work as a team. In an emergency the aircrew have clear roles to split the workload. For example, the pilot in command predominately takes the flying role whilst the co-pilot identifies the procedures that need to be completed. Both pilots are responsible to ensure that the other pilot does not become incapacitated or fixated on a target which could result in them missing information. Furthermore, whilst the pilot in command is overall responsible for the aircraft, both pilots work together, sharing information and opinions to formulate a course of action to resolve the incident.	Identify the roles and responsibilities in the team, and consider the information needs for each operator according to their role. Identify the points where the workload is high and where additional tasks could impact the operator's performance. By identifying when workload is high, consider how the operator could be supported in their tasks.
Human Error	The aircrew work together to ensure that no errors are made, regarding diagnosing the emergency, identifying the course of action and resolving the incident. For example when making a decision of how to resolve the incident, the aircrew work together to identify that no information has been missed and that the correct decision according to the available information and constraints is made. The co-pilot in particular ensures that the correct information has been entered and the procedures are completed correctly by the pilot in command. Three types of strategies are implemented in the cockpit to prevent and identify errors: 1. Correct parameters have been entered into the system. 2. Correct procedures are completed. 3. Identify incapacitation.	Identify the types of errors the operators could make. For example, identify if the operator has to enter parameters or complete procedures. Identify if errors could be made and implement counter measures to prevent possible errors.

Uncertainty	Pilots experience uncertainty in a number of ways. This could include uncertainty in the information that they have, as it could incomplete, or in correct. Also, the aircrew considers if the recognised failure is a false alarm. Is it a single failure or multiple failures? What is the cause of the failure? As well as identifying the severity of the emergency. Pilots need to identify how long they have to handle the aircraft safely, which indicates the amount of time they have to resolve the situation and determine where a suitable landing can be performed.	Identify where the operator may experience uncertainty. For example, is there uncertainty about the emergency itself, the information they have, can the operator be sure that it is a real emergency and not a false alarm. Also, identify if there could ambiguity to the cause of emergency, the severity and what course of action should be implemented to resolve the incident.
Teamwork	The aircrew work as a team alongside air traffic control. Pilots share a similar mental model of the aircraft and environment to each other, as in an aircraft they are geographically in the same location. However, air traffic control may have a different understanding which may include additional information that may unfold on the ground. The aircrew liaise with air traffic control to get real-time updates once an emergency is identified. This additional information will be considered when formulating how to resolve the incident at hand.	Identify during an emergency how the different parties support each other to formulate a course of action. For example will the core team utilise additional information from third parties to formulate a course of action.

Communication	Communication occurs throughout the emergency to develop situation awareness of what is occurring, help make decisions, identify errors, obtain more information, etc. Communication occurs between pilot to pilot, and pilots to air traffic control. Strict phraseology is used to avoid miscommunication and misunderstanding. This may be particularly important in the event of an emergency as noise may be a factor. Verbalisation of the procedures between the pilots is completed to ensure that the steps in the procedure are completed correctly.	Consider the actors who communicate with each other and then identify what information is communicated to the team. Identify the processes that a verbalised to ensure that items are completed correctly in the procedure.

TABLE 5.7: Human Factors in the Aviation Domain

5.3.5 Summary of Stage 2 Findings

Knowledge Elicitation gave the researcher an in-depth understanding of the tasks and NDM that pilots make during challenging tasks in the aviation environment. The findings show that the pilots deal with a number of different types of non-normal situations, for example, incidents that are a result of human error, bad weather, birds, real and false aircraft failures.

Stage 2 identifies five distinct steps to resolve an emergency, identifying the types of tasks that occur for each step. It should be noted that the three recognition primed decision points; situation recognition, serial option evaluation and mental simulation, can be identified in these steps. Situation recognition appears in determining and analysing the problem, whilst serial option evaluation and mental simulation are present during identifying and performing a course of action. Figure 2.6 presents four steps to resolve an emergency, however the results show that there is an additional step, stabilise situation, where the pilot makes initial decisions to prevent the emergency from getting worse. This is an important step where the pilots stabilise the situation in order to have time to collect as much information as possible and then formulate a course of action. Another important step for the pilots is once the course of action has been performed and implemented, they then monitor the systems to ensure that the course of action has been successful, in the event it has not, the pilots would restart the process by re-identifying the emergency. The results also confirm the occurrence of the seven factors that need to be supported for effective decision-making. Table 5.7 reports the seven human factors and establishes the support for the design of systems. The identified support will contribute to the development of the design principles.

This section provides a new insight into how decision-makers need to be supported during emergencies. It not only looks at the decision-making process but also the additional factors that need to be support the decision-making process. For the development of the principles, the analysis of the CDM interviews will be used as a basis to provide examples of how each principle manifests in the real-world. The design support, identified in table 5.7 will be used to support the elements that the designer needs to consider when designing to support the human factors issues.

The decision requirements and design leverage points will be used in stage 3, Analysis and Representation, to extract decision requirements, challenges and aspects of expertise to be supported.

5.4 Stage 3: Analyse and Representation

Analyse and Representation identifies difficulties, critical cues, expert strategies and design ideas for each of the design requirements. The aim of this section is to understand how to integrate the decision requirements into the design of the cockpit. A decision requirements table is used for extracting decision requirements (Lee and Kirlik, 2013), see table 5.8.

5.4.1 Method

Analyse and Representation investigates the decision requirements and the design leverage points. This stage presents a decision requirements table, which identifies difficult decision points, cues, strategies and hypothesises design ideas to address the decision points. The decision requirement table was developed with the support of the PIC from the observed ferry flight in stage 1: Preparation. A design ideas meeting was set up with the pilot. The researcher created a template based on the decision centred design approach (Hutton et al., 2003). She completed the table using the information identified in stage 2, entering preliminary information in columns "Decision Requirements", "Why Difficult/Potential Errors" and "Critical Cues".

On the day of the interview, the participant was asked to review these columns to ensure that he agreed with the contents that had been identified by the researcher. Then he was asked to provide input for "Expert Strategies" that are used to address each of the "Decision Requirements". The main task of the interview was for the participant to then detail possible "Design Ideas" for each of the difficulties using information identified in "Critical Cues" and "Expert Strategies".

Once the table was completed, the researcher reviewed the table for initial proof-reading. Once the proof-reading had been completed this was then sent to the participant via email to review for accuracy. The participant reviewed the table and identified minor corrections of details, which the researcher integrated into the final version of the table.

5.4.2 Participants

The table was created with the support of a pilot; this pilot was the PIC from Stage 1.

5.4.3 Procedure

The table was based on an overview of resolving a situation, the steps were used as the decision requirements for the table. An interview was performed with the PIC to get an understanding of the difficult decision points, cues, strategies and hypothesise design ideas to address the decision points.

5.4.4 Decision Requirements Table

Table 5.8 outlines the decision requirements and design ideas.

Decision Requirements	**Why Difficult / Potential Errors**	**Critical Cues**	**Expert Strategies**	**Design Ideas**
Recognising an Emergency	Two methods: **1. Pilot detected emergency:** • Pilots monitor the systems and identify a problem in the system. The pilots are detecting anomalies in the data. This can be difficult as the pilots have to evaluate a large amount of information from a number of sources. • Several subtle pieces of information could result in an incident. **2. System detected emergency:** • The system identifies that there is a problem and an alarm goes off. Often the alarm is unexpected and the pilot may not have all the information regarding why the alarm has gone off. Recognising an emergency can be difficult due to attention, screen clutter, memory, loss of understanding and knowledge of common false positives in the aircraft.	From rigorous training and experience the pilot has a picture (mental model) of how the aircraft should behave. To recognise an emergency the following cues are used: **1. Pilot detected emergency.** • Values in the system do not match the pilot's expectancy (e.g. missing values or values that do not change as expected). • A failure in the system (e.g. display turning black or no/partial radio communication received). • Any unusual noise, smell, movement, vibrations in the aircraft (e.g. sudden movement of the aircraft caused by an engine failure, then the asymmetric thrust causes a yaw moment). • Information from the environment; in and outside the cockpit. **2. System detected emergency.** • Visual cautions/warning (amber/red warnings) in the systems, usually in the crew alerting system. • Audio warnings (sound/verbalised automatic warnings). • The pilot must determine if the alarm is a false alarm (e.g. software bugs or known faults).	The pilots are working to the philosophy *"expect the unexpected"*. The aircrew scan and monitor the systems to see what does not fit into their expected picture. The aircrew are given extensive training on *"scan pattern"* of the instruments. They have experience in the variations from *"normal"* expected parameters of the aircraft.	**1. Pilot detected emergency:** • Systems could highlight slight anomalies in the system before they become critical (e.g. if there is a slight fuel imbalance the system could point this out). • Merge related information together from related interfaces. • Support the pilot's mental model of the aircraft state and identify anomalies. **2. System detected emergency:** • Use of 3D visual and audio warnings at the cause of the information point. (e.g. if the information is in the overhead panel then an alarm could go off above the pilot vs. if the information is in front of him then the alarm is directly in front of him). • Using other senses (e.g. vibrating the seat to *"wake up"*, there is something out of place. • Detection of change of noise level in the flight deck. • Automatic failure correction, but PF and CP must stay informed and in the loop.

Stabilising Situation	The pilot needs to quickly stabilise the situation to avoid escalation of the situation as it can become life-threatening. The difficulty is ensuring that the pilot has the control and the right procedures are implemented from memory for stabilisation.	Cues include monitoring the changes and ensuring generally that the aircraft is under control. If the pilot identifies that a landing needs to be made the pilot must assess the vectors to the closest airfield, airfield specification, weather and information from NOTAMS and the severity of the emergency.	The PIC needs to ensure that he has the aircraft under control, ensuring that the aircraft it still flying (usually checking the aircraft is in autopilot and auto thrust is still engaged). Procedures are completed from memory and then emergency checklists are carried out to stabilise the situation. Whilst 99% of the time the flight path "straight ahead" is clear and safe, there is the possibility that if the terrain is a factor then a smooth turn (or climb) especially when an engine has to be shut down and the aircraft has to descend over mountainous terrain to a safe area is required. Knowing this is part of the situation awareness they build up during the briefing.	• The aircraft can provide information regarding the status of the stabilisation of the aircraft. • Support correct procedures are completed from memory, through checklists. The aircraft could detect each action the pilot completes from the checklist.

Determining and Analysing the Problem	The pilot has to assimilate ambiguous data from several sources to identify the problem and also investigate what the cause may be. There is a lot of uncertainty that usually surrounds determining the problem. The aircrew must consider a number of things: • If the recognised failure is a false alarm. • If it is a single failure or multiple failures. • What is the cause of the failure? • Assess the severity of the emergency. The pilot needs to know how long he/she can handle the aircraft safely. • Identify the time the pilot has to resolve the situation. • Where to make a suitable landing? The pilot does not want to worsen the situation and or not to do any actions too quickly.	When determining the problem, the aircrew will investigate parameters associated to the identified emergency to get an understanding of what is exactly going on. Here the aircrew spend time discussing the emergency and the cause. The pilots will not only use the systems, but also visual cues i.e. checking the engine out of the window to identify a fire. Identifying a false alarm could be based on the aircrew's past experience.	The aircrew tests the system to identify the problem. The pilot will do this by testing the identified problem against the normal behaviour they expect. The pilot will try the following strategies: • Provoke a reaction from the system to see if it reacts correctly i.e. decreasing power so rpm should decrease, thrust, the propeller rpm will decrease, etc. • Identify how the system changes in a given period of time. • Test for smells in the flight deck. A process of elimination is used to determine where the problem could be in the system. Aircrews use checklists to identify the problem. Newer cockpits identify and present the checklists and procedures that need to be completed but currently this is not standard across the majority of aircraft. The pilot will also predict future calculations for example how much fuel there is and calculate how long they can fly for. The pilots take a stop watch to see how much fuel drops – if there is a difference then the fuel is going somewhere else.	The system should provide detailed information about the failure. Current systems provide what the emergency is i.e. the system states that it is a left engine fire but does not identify the impact on the aircraft nor the root of the problem. This will allow the pilot to get a rapid understanding and decrease the time it takes to update their situation awareness and understanding of what is occurring. The system should merge related data together into a single interface, bringing together information and give greater meaning to the data. The system should support the pilot's mental model of the aircraft state and identify anomalies.

Identify a CoA	Many hypothesises may be developed by the aircrew, which means that a number of solutions may be formulated. The pilot might find himself with no good solution but some bad solutions. The pilot needs to weigh up which is the best solution out of the bad solutions.	The aircrew need to also decide what has to be done (fight the fire, divert to an alternate field, inform ATC, prepare for crash landing/bail out/ditching, etc.). Once CoAs are outlined, the aircrew: • Identifies CoA's with critical consequences. • Predicts what could happen. Pilots ensure that the associated switches have been switched off, fuel balances are resolved, and scanning for further abnormalities. Use of abnormal checklists; selecting the correct checklist.	When a "real" failure has been identified, it is relatively straight forward and are trained and published emergency procedures are good for the situation. Whilst the pilot will treat the emergency as real, the pilot will still be looking to see if it is a false alarm. It can be more tricky to deal with false alarms, which could occur due one or more sensors is faulty (could be a crack in a connector, in a wire, or a leak in a hot bleed air which blows on a temperature sensor which then indicates "engine hot/on fire").	The system should suggest the best CoA, taking into consideration all the information, where the aircrew could then select the CoA they want to implement. The design of the system should detect erroneous actions to minimise and prevent mistakes. The sensors should be coupled together in a way that individual sensor failures are detected and discriminated.
Implement selected CoA	When performing the selected CoA, the aircrew will usually need to complete many steps in a procedures.	Some tasks are completed by memory, by instinct or using checklists.	Based on training and set procedures.	The system should automate actions in the procedures that need to be completed, in particular those actions which are non-critical.
Confirm CoA and monitor	It's not always clear if the CoA has correctly resolved the situation.	The pilots monitor the systems and aircraft behaviour.	Pilots use scan patterns, comparing parameters to what they expect including the information from the emergency.	The system could monitor the parameters and advise on the success of the CoA.

TABLE 5.8: Decision Requirements Table

5.4.5 Summary of Stage 3 Findings

The stage, Analyse and Representation, presented findings for difficulties, critical cues, expert strategies and design ideas for each of the design requirements. There are a number of design ideas for each of the decision requirements; this will be narrowed down when applied to the scope of the new system design. These decision requirements will be used as a basis for the design of a system to support NDM in the aviation environment.

The final two stages of the DCD approach application design and evaluation, are investigated in chapter 6, they are applied to the design of a system for single pilot operation.

5.5 Chapter Summary

This chapter presents an investigation of naturalistic decision-making in the aviation setting using decision centered design. The findings for the first three stages of this approach are presented. The first stage, provided an initial understanding of the aviation environment, highlighting the tasks for each of the flight phases in normal operations, as well as how the human factors issues manifest themselves in normal operations. Stage two, investigated decision-making in non-normal situations using a retrospective interview procedure. The stage used critical decision method and allowed investigation of the decision points. The main decision points were further explored with the support of the pilots to identify cues, strategies, information, knowledge, difficulties they face and design solutions. Stage three, used the decision requirements to identify design solutions to support the pilot's naturalistic decision-making process.

The findings from the stages 1-3 will be used to design a system for the aviation domain, the system focuses on supporting real-world decision-making. The next chapter outlines the final 2 stages of decision centered design; application design and evaluation.

Chapter 6

Moving Towards Single Pilot Operations: Stages 4 and 5 of Decision Centered Design

6.1 Chapter Overview

Chapter 6 presents stages 4 and 5 of Decision Centered Design (DCD). The chapter contributes to aim three, develop guidance to support NDM system designers. This chapter was motivated by Airbus Group's need to design interfaces for single pilot operations which support the pilot's decision-making process and to understand the impact on the remaining pilot when reducing the aircrew. It was identified in collaboration with Airbus Defence and Space that the findings from the previous chapters would be used to design a novel single pilot jet aircraft as part of a technology research project.

Three activities have been completed in this chapter; Moving to single pilot operations, stage 4: application design and stage 5: evaluation. Figure 6.1 presents an overview of the chapter.

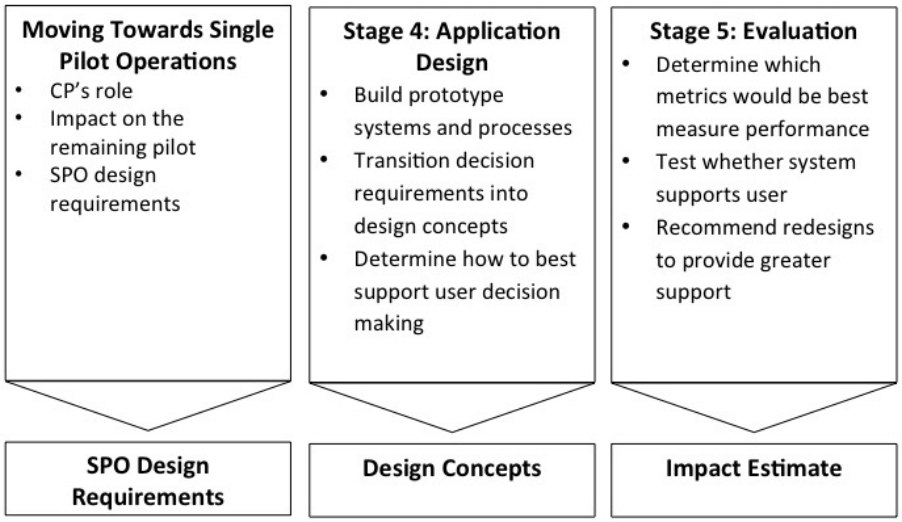


FIGURE 6.1: Overview of Chapter 6

The DCD process is adapted by adding an additional section, which investigates single pilot operations (SPO) including background literature and identifying the impact on the remaining pilot based on findings from chapter 5. As the single pilot will no longer have the support of the CP, the section investigates the CP's role and identifies the human factors issues that impact the pilot in command (PIC) when removing the co-pilot (CP) from the cockpit. This identifies the design requirements for the SPO system.

Stage 4 of the DCD framework used the findings from the design requirements to design a NDM system for SPO. With the support of Airbus, it was identified that a fuel system would be developed and evaluated for this study. A senior test pilot advised throughout the design and evaluation process.

Stage 5 evaluated the design of the NDM system, to identify the impact on the pilot when in the cockpit. This stage outlines the method of evaluating the system including the procedure and human factors methods. With the support of Airbus, four measures were identified for evaluation; decision-making, situation awareness and workload as well as usability. The NDM system was compared to a system that was based on the traditional cockpit, which had been adapted for SPO. Results show that the pilots were able to use the new system with limited training, as well as the classic system which they had extensive training and experience with.

6.2 Introduction

Concomitant with developments in computational intelligence and unmanned aerial vehicles, there is a movement within the aviation industry to change traditional pilot-co-pilot manning of the flight deck to a situation of single pilot operation (Johnson et al., 2012). Moving to single pilot operations could be seen as the next natural step in the aviation transport industry as over the past 50 years the aircrew has been decreased from five members to two members (Graham et al. (2014); Lachter et al. (2014)). Advances in automation and technological developments have changed piloting, as pilots have become system monitors and managers. SPO may require only one pilot to carry out all flying and non-flying procedures within a civil aircraft flight deck, whilst the second pilot/co-pilot could be stationed on the ground. From the ground, the co-pilot will monitor and advise several flights at once, only intervening if the pilot in the cockpit requires support. In the event the co-pilot must operate the aircraft, the aircraft will be controlled in the same way as an unmanned aerial vehicle (Lachter et al., 2014). An alternative could be that the PIC is supported by a flight dispatcher (Croft, 2015) who receives extra training, and there is always the possibility that the pilot on-board the aircraft may no longer be supported by a CP.

The benefits of moving towards SPO include reducing the workforce, reducing the complexity of scheduling and positioning crew, saving space in the cockpit, removing redundant instrumentation from the flight deck and ultimately decreasing the weight of the aircraft (Schutte et al., 2007). These factors have a cost benefit for commercial airlines, which in turn could benefit the consumers. However, SPO could be seen as a controversial step with resistance from key stakeholders for example, aviation agencies such as Federal Aviation Administration, the customer base such as the passengers on-board the flight, the aviation workforce such as the pilots and the unions supporting the flight (Graham et al., 2014). While some of these reservations lie outside the scope of scientific investigation to address, we can identity here a requirement for study of the viability of SPO whilst maintaining aircraft safety. Extant programmes conducting research into SPO feasibility include Advanced Cockpit for Reduction Of Stress and Workload (ACROSS) program in Europe and NASA's Airspace Systems Program in the USA (Bayram et al., 2013). Research into SPO explores aircraft configuration (Deutsch and Pew, 2005), SPO flight deck design (Harris, 2007), development of ground stations (Lachter et al., 2014) simulating the cost analysis vs. the impact on workload (Graham et al., 2014) and non-verbal communication (Lachter et al., 2014).

Past research has investigated, single pilot operations configuration (Deutsch and Pew, 2005), shift of non-flying pilot duties to either on-board automation and/or ground based

systems (Harris, 2007, Johnson et al., 2012), cost analysis of moving towards single pilot operations (Graham et al., 2014), development of scenarios for testing future concepts and technologies (Connor et al., 2013). Research also investigates display panel design which takes a multi-criteria decision-making approach (Senol et al., 2009).

(Stanton et al., 2016) state that in order for SPO aircraft to be safe and usable in a wide range of normal and non-normal operations one needs to consider the design of the user interfaces and develop new concepts of operations. We believe in order to design the user interface and new concepts for SPO that we need to understand the processes that need to be supported for decision-making in the design of the system. This is particularly important during peak workload, for example, during approach in normal operations and emergency situations in non-normal operations.

In the SPO vision, a co-pilot's role still may exist albeit it radically changes and is enacted remotely from the ground. It poses considerable challenges for flight deck developers to design new SPO commercial flight decks to support the remaining pilot. Flight deck procedures and the pilot's cognitive processes will be impacted. This is echoed by Harris (2007), who states that the Human Factors requirements need to be considered in the design of SPO aircraft. Flight deck developers need to understand the cognitive impact of the change and understand how the design of the systems can support these cognitive processes.

Based on the findings from the previous chapter, this chapter investigates how systems should be designed to support the remaining pilot on-board a commercial single pilot aircraft. The chapter consists of three main sections; the first section identifies the impact of moving to SPO based on the findings from the first three stages of DCD. The next two sections describe the last two stages of the DCD approach. Section two presents stage 4 of DCD which designs a SPO system based on previous findings and section three presents stage 5 of DCD, which evaluates the system using the set of human factors methods.

6.3 Moving Towards Single Pilot Operations

There are three main options moving forward with SPO: the PIC working alone, the PIC working with a dispatcher and the PIC working with a co-pilot on the ground. We discuss the main implications of each possibility.

Option one, the PIC carries out all responsibilities including the non-flying procedures, with the aid of new systems and training. This could enhance the safety in the aircraft, as the system has the capabilities of predicting and highlighting a failure more accurately

than a pilot. For example, the PIC would need to carry out the pre-flight activities, including plan the flight, check for the weather forecast and review NOTAM. Whilst this would allow the pilot to have perhaps a better situation awareness as he/she must go through all the information and time could be saved as the PIC does not need to go through a briefing period, there will be an increase in workload, however the pre-flight phase will take much longer as the pilot will have more tasks/activities to complete. As the PIC has more activities to complete, this might cause the pilot to make a plan that is not quite as comprehensive (in comparison to the co-pilot sharing the tasks) which may result in the PIC not exploring as many different types of plans in order to find the final solution. Overall the PIC would have more responsibility and workload on-board, which could contribute to the pilot's stress. On-board there will be less/no cross checking of the pre-flight planning which would result in no one additional to identify errors or key things that might be missed in the system. This could be overcome by having more automated cockpits, which can check the calculations, speed and fuel. There would be no verbalisation of the tasks, which means the PIC will have no one to talk through the flight plan. There might be a training issue where CPs are less experienced than PICs. How will the CPs receive training to become a PIC? Does it require them to spend more time in the simulator?

Option two would use a dispatcher for the pre-flight phase, known as a "super dispatcher" (Croft, 2015). In the current two pilot configuration, the dispatcher monitors the progress of flights, issues necessary information for the safety of the flight and prepares flight control releases. It is envisioned that with extra training the dispatcher could step in for the pre-flight phase aiding the pilot to develop an understanding of the flight and route. The capabilities are already in place as dispatchers frequently advise for some commercial flights. Whilst this allows support for the pilot, the dispatchers will require further training to support pilots in this role and it is envisioned that they will only support the pilot until the briefing period.

Option three, a more novel concept, could see the PIC being supported by a co-pilot on the ground (CPG) who is monitoring the aircraft and the on-board systems. The CPG could attend the pre-flight phase in person; this would help support both the PIC and CPG to develop similar situation awareness about the flight. This will allow the CPG to monitor several flights at once and only intervene when the PIC requires dedicated co-pilot support. The co-pilot would have a copy of the inflight interfaces, allowing the co-pilot to see the same information as the pilot and allowing the CPG to support the PIC through the decision-making process in an emergency.

However, whilst there are great advantages of the CPG being on the ground, we may need to consider issues such as the CPG not having an inside view of the cockpit which consequently may result in he/she not being able to appreciate the complexity or urgency of a situation. We also need to consider the maximum number of flights the CPG can monitor at any one time, the procedures of the PIC handing over controls to the CPG, the procedure of handing over flights to other CPGs in the event one flight required individual co-pilot attention, how we can ensure that the CPG can maintain adequate situation awareness for several flights, how the CPG can rapidly build their situation awareness in the event of an emergency, the consequence of the co-pilot no longer being in the cockpit and so on.

To make SPO possible, secure and reliable data and communication links are paramount between the ground and the aircraft so that the CPG has up-to-date real time data. We also need to consider how the co-pilots role from being in the aircraft to being on the ground will change and consequently consider how to change procedures and training to support this scenario. With the new SPO flight deck concept there is the possibility of merging monitoring and system interaction in a single location, changeable and dynamic interfaces, decrease in development and qualification costs for custom-made control panels. If the co-pilot on the ground scenario is implemented, this pilot will need up-to-date information from the systems in the flight, which will require strong data links between the ground and the aircraft.

The next section investigates the impact of removing the CP from the cockpit on the remaining pilots based on findings from 5.

6.3.1 Method

As two pilot aircrews have well-established roles, it is anticipated that the change in aircrew will impact the remaining pilot's human factors, particularly the naturalistic decision-making in emergency situations, which in turn affects performance and safety of the aircraft. For all three options of moving towards SPO one of the key questions for system developers will be *"how should the pilot's human factors be supported in the cockpit?"*

Two additional activities have been completed in the decision-centred design framework to get an understanding of how to support the pilot's human factors in the cockpit. First, the researcher identified the CP's key tasks in each flight phase based on the task decomposition diagram in figure 5.3, chapter 5. Figure 6.2 depicts the main tasks. These key tasks were then used with the understanding from appendix B and appendix C as a basis

to identify the HF impact of removing the CP from the cockpit. The researcher used the HF understanding from to hypothesise the impact of removing the CP from the cockpit, see figure 6.1.

6.3.2 Activity One: Co-Pilot's Role

Activity one identified the CP's key tasks in each flight phase based on the task decomposition diagram in figure 5.3 and appendix B, 5.

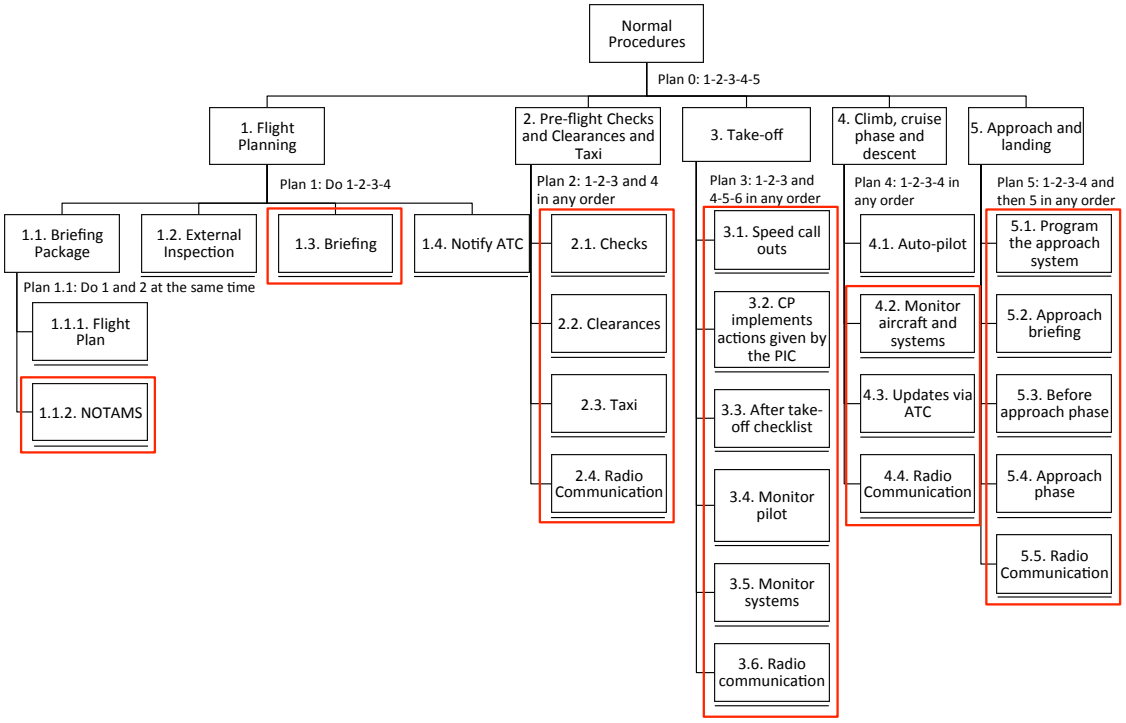


FIGURE 6.2: Task Decomposition Diagram of CP's Roles Highlighted During Normal Procedures

It should be noted that radio communication is relevant throughout the flight and ground operations.

The diagram shows that the CP contributes to each of the flight phase; in particularly in phase two (pre-flight checks, clearances and taxi), three (take-off) and phase five (landing). These are the phases where the aircrew are required to make decisions. The next activity uses the identified tasks in the decomposition diagram to investigate the HF impact on the remaining pilot if the CP is removed from the aircrew.

6.3.3 Activity Two: Human Factors Impact on Single Pilot

Using the understanding from activity one and appendix C, the researcher identified the possible HF impact of removing the CP from the cockpit, see figure 6.1.

Task	**CP's Role**	**Human factors impact of removing CP**
Flight Planning	Reviews NOTAMS. Identifies and briefs the PIC regarding the constraints in the NOTAMS. Discusses and supports decision-making of the flight plan.	Decision-making: the PIC will not have support when making decisions. Situation awareness: the PIC will not have support when building an understanding of the flight plan. The pilot will have an increase of sources to examine in order to get the same level of understanding. Workload: The PIC's workload may increase, as he/she will have to do more tasks such as review the NOTAMS. Human error: The PIC may miss information as he/she has more workload. Uncertainty: Uncertainties are outlined in the NOTAMS. The pilot needs to read and understand all relevant NOTAMS which are of interest for the flight. Communication: The PIC will not have the CP to discuss and develop ideas and identify any constraints. Lack of communication could impact the performance of procedures.

Pre-flight Checks & Clearances & Taxi	Supports the setup and crosscheck of the FMS programming. Finds and reads the checklists. Supports the decision-making when a take off should be aborted. Monitors the systems and environment for anomalies. Monitors the CP. Crosschecks the values in the PIC's systems with the CP's systems. Supports communication between the aircraft and ATC.	Decision-making: The PIC will have less support to identify when to abort a takeoff. Situation awareness: Less support of monitoring the PIC, the systems and the environment. Workload: Increase in activities for example the PIC may need to now crosscheck the values he inputs, work harder to scan the systems for anomalies, finding and implementing the checklists. Human Error: Anomalies and errors might not be identified due to wrong attention/target fixation. Communication: ATC communication has to be done by the PIC.
Take-off	Initial speed call outs. Monitors the PIC - CP takes over in the event of a problem or emergency. Monitors both sets of instrumentation. Implement actions given by the PIC. CP finds checklist, verbalises the items and ensures they are completed correctly. Carries out radio communication with ATC.	Decision-making: Less support identifying if a take off should be aborted. Situation awareness: Less support to monitor the aircraft and environment for anomalies. CP acts as a "waking up" mechanism to get the PIC out of his "target fixation". Workload: PIC can not give the controls to anyone or ask for support for work. It's one less pair of eyes and hands in the cockpit. This flight phase consists of a lot of tasks, which will mean that the PIC will have more workload. Human error: No one monitoring the PIC. No crosschecking of both sets of instrumentation especially the primary flight instruments (speed, altitude, heading/track, etc.). Communication: The pilot will need to complete the checklists on his/her own and will also need to complete ATC communication.

Climb, cruise phase and descent	Carries out communication with ATC.	Decision-making: Less support identifying if a decision needs to be taken, especially important if an emergency occurs. Situation awareness: Less support to monitor the aircraft and environment for anomalies. CP acts as a "waking up" mechanism to get the PIC out of his "target fixation". Human error: No one monitoring the PIC. No crosschecking of both sets of instrumentation especially the primary flight instruments (speed, altitude, heading/track, etc.) Communication: Lack of social interaction could result in the PIC becoming bored in the cockpit and lack attentiveness. ATC communication to be also completed by the PIC.

Approach and landing	The CP takes over the controls in the case of a deviation. CP checks the programming of the FMS. The PIC briefs the CP regarding the details of the approach. The CP identifies mistakes and clarifies any doubts, ensuring accuracy. CP requests descent from ATC. CP put on passengers seat sign. The CP checks if the speeds, flaps, deviations are correct. CP finds checklist, verbalises the items and ensures they are completed correctly. Monitors the PIC - CP takes over in the event of a problem or emergency. Monitors both sets of instrumentation. Implement actions given by the PIC.	Decision-making: the PIC will not have support when making decisions. Workload: The PIC's workload may increase as he/she will have to do more tasks such as communication with ATC, check if the speeds, flaps and deviations are correct. Human error: No one monitoring the PIC. No crosschecking of both sets of instrumentation especially the primary flight instruments (speed, altitude, heading/track, etc.) Communication: The PIC will not have the CP to discuss and develop the approach. Also, ATC communication will need to be completed by the PIC.

TABLE 6.1: Tasks Impacted When Moving to SPO

The findings from the table above will be used to support the design of a fuel format, presented in Stage 4: Application Design.

6.4 Stage 4: Application Design

The focus of this stage is to integrate the findings from previous stages of DCD into the design of a NDM system; SPO commercial jet aircraft. The novel SPO jet aircraft is a passenger aircraft that is expected to carry between 4-6 passengers on short haul flights. It is expected that only the PIC will fly the aircraft with the support of existing personnel (and not with CPG or super dispatcher). It is expected that using NDM requirements to develop a system, which supports the pilot's real-world decision-making in their environment, will have similar decision-making, situation awareness, workload and usability to a system that pilots have been using for many years. This stage presents the design of two prototypes; one using the NDM requirements for SPO and one based on an existing two pilot aircrew. For completeness of the study, Airbus Defence and Space mocked up a complete single pilot cockpit but only the fuel system was evaluated.

6.4.1 Method

This study was part of a large project within Airbus Defence and Space (Germany). The researcher was asked to develop the fuel system for a new single pilot aircraft. Using the findings from the previous stages, the researcher created an interface of the fuel format to support naturalistic decision-making for a single pilot aircraft. The researcher first identified how the existing system did not support the design ideas from table 5.8 in Stage 3 and then identified how the new NDM system supported the pilot for single pilot operations. The NDM system was developed by the researcher based on the NDM requirements and was reviewed by a senior Airbus test pilot in an iterative process. A paper design of the system was created based on the identified requirements, the senior pilot reviewed the designs and selected the design which best supported the pilot's tasks. The selected design was then developed into a a working system which could be tested with operators.

Airbus' role in the project was to provide the remit of the project, senior test pilot, as well as, providing the classical system based on the design of an existing two pilot system. The classical system was developed by Airbus and was adapted from the Airbus 330 cockpit philosophy.

6.4.2 Participants

A senior Airbus test pilot was allocated to the project to support the development of the fuel system prototype.

6.4.3 Procedure

The researcher first identified how the existing system did not support the design ideas and then identified how the new NDM system supported the pilot for single pilot operations. The researcher then developed a paper prototype of the NDM system using the NDM requirements, this was reviewed by the senior test pilot. Once the details of the system were finalised, the researcher programmed a working prototype using avionics display development software called Vaps XT. The senior test pilot then reviewed the working prototype several times until a final design was reached. The test pilot reviewed the design of the system to ensure that the design prototype could logically work in the cockpit for both normal and emergency procedures.

In parallel, Airbus Defence and Space developed the SPO prototype based on the A330 fuel system. They took a similar iterative approach to develop the prototype by first developing a paper prototype and then a working prototype using Vaps XT. Each of which were reviewed by the same senior test pilot.

Due to the non-disclosure agreement from Airbus, images and in-depth descriptions of the fuel system cannot be disclosed.

The two fuel systems are described below.

6.4.4 Classic Fuel System Design

The classic system was developed by adapting the existing two pilot fuel system philosophy, figure 6.3. The system consists of two separate interface displays (fuel and engine) in the cockpit systems and the majority of physical switches in the overhead panel.

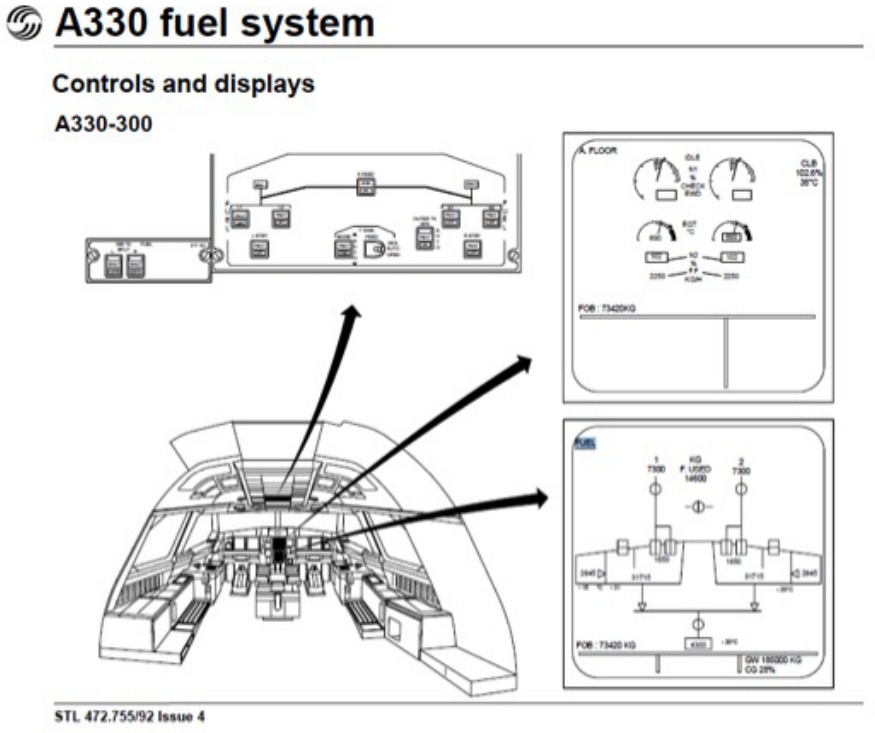


FIGURE 6.3: Overview of A330 Fuel System

6.4.5 NDM Fuel System Prototype Design

The researcher presented two designs based on the NDM requirements for SPO to the senior test pilot. During the iterative paper design process, the following points were identified:

- **Colour and symbol philosophy:** Clearly highlighted the significance of each colour and symbol used in the interface to avoid confusion. This was particularly important when representing the system state vs. a representation of movement in the system. For example, the colour green in the fuel flow lines represent that there is fuel flowing in the lines oppose to the fuel lines are working.
- **Design to highlight inactive actions:** Actions that cannot be carried out in the interface must be clearly indicated in a change of representation (i.e. by greying out the buttons) and the system must be "unlocked" between the two modes.
- **Feedback and confirmation:** This is instrumental for the pilot's safety. The system has safe guards and confirmations in order to ensure that the software buttons are not pressed accidentally. The number of confirmations is dependent on the consequence of the actions of the software button.

- **Integration of switches into the display:** The pilot requires four pieces of information when using the software buttons in the interface:
  - Switching Feedback – the pilot needs to know did he switch the button? In a traditional aircraft this would be the physical action of turning a switch.
  - Switch/Selection Feedback – the pilot needs to know whether the switch carried out the action after switching its state.
  - System Feedback – did the system complete the desired action that the pilot wanted the switch to do after switching it on or off?
  - Failure Feedback – It is important for the pilot to understand when a failure occurs, in what status it occurs (i.e. Auto On, Man On or Off) and why it failed.
- **Autopilot or manual mode:** The system identified autopilot or manual mode. The SME indicated that the interface should have three states; Auto On, Manual On (Hereinafter Man On) and Off. In addition to this, the interaction showed the state the pumps and valves are in, for example if they are in auto or manual and whether they are on and off.

The final design of the system was based on the following design, see figure 6.4.

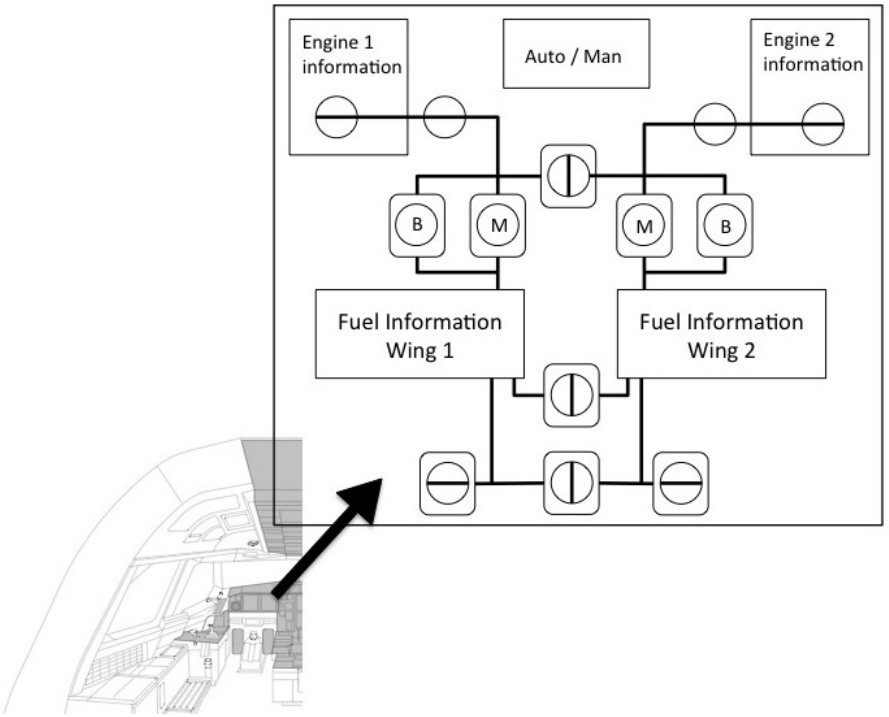


FIGURE 6.4: Design of NDM Fuel System

6.4.6 Development of SPO Fuel System Prototype

The development of the SPO fuel system was based on the requirements and design ideas identified in chapter 5. Table 6.2 identifies how the design of the new NDM system meets the pilot's requirements and, in addition, how the classic system does not.

Decision Requirements	**Design Ideas from Table 5.8**	**A330 Fuel System**	**NDM Requirements & Design**
Identify an Emergency	**1. Pilot detected emergency:** • Systems should highlight slight anomalies in the system before they become critical (e.g. if there is a slight fuel imbalance the system could point this out). **2. System detected emergency:** • System could use 3D visual and audio warnings at the cause of the information point. (e.g. if the information is in the overhead panel then an alarm could go off above the pilot vs. if the information is in front of him then the alarm is directly in front of him). • System could use other senses (e.g. vibrating the seat to *"wake up"*, when there is something out of place. In addition, the system should detect change of noise level in the flight deck.	• Currently in the A330 the information which is outside the normal values is highlighted orange (without auditory signal) and when the values become critical the value turns red (with an auditory signal). If there are critical emergencies identified in the cockpit, the system will give a master warning and a message in the crew alerting system will be given, indicating what emergency has been detected. However, there is limited support to direct the pilots attention to the key information. Furthermore, if there are multiple emergencies detected, there is limited prioritisation of which emergency to complete first.	• System was designed to highlight anomalies (auditory and visually) and provides detail regarding the location and impact on other systems. For example, if there is a left fuel leak, then the associated tanks highlight, as well as, which engine and pumps are affected.

Stabilise Situation	• The system should provide information regarding the status of the stabilisation of the aircraft. • The system should identify that correct procedures are completed from memory, through automatic and integrated checklists in the system. The aircraft should detect each action the pilot completes from the checklist.	• The A330 does not provide support to stabilise the aircraft, this is a task that the aircrew must complete themselves. • The procedure to stabilise the aircraft is usually done from the pilot's memory. Paper checklists onboard the aircraft contain the steps that need to be completed during this stage.	• The system integrates checklists into the system presented in a separate interface on the screens, the associated checklist was triggered depending on the identified emergency. • The system automatically detects the items completed from the memory checklist to ensure the correct procedure is completed in the right order.
Determine and Analyse the Problem	• The system should provide detailed information about the failure. Current systems provide what the emergency is i.e. the system states that it is a left engine fire but does not identify the impact on the aircraft nor the root of the problem. This will allow the pilot to get a rapid understanding and decrease the time it takes to update their situation awareness and understanding of what is occurring. • The system should merge related data together into a single interface, bringing together information and give greater meaning to the data. • The system should support the pilot's mental model of the aircraft state and identify anomalies.	• The A330 has many interfaces and gauges spread out across the cockpit, which results in the pilots having to check different places to bring the data together, with the possibility to miss data or misinterpret it. • Information is presented in the screens in front of the pilot, however the associated switches are above their heads in the overhead panel.	• A more visual representation of the information was created to support the pilot's mental model. The information was designed to be absorbed in a single glance by merging information from the fuel, engine and air flow information into a single interface. The system provides clear representation of fuel flow through the presentation of fuel lines as well as proving information about the tanks in the aircraft. • The data should be fused to bring greater meaning and reduce the amount of calculations a pilot must make.

Identify and Perform Course of Action to Address Emergency	• The system should suggest the best CoA, taking into consideration all available information. The aircrew could then select the CoA they want to implement. • The design of the system should detect erroneous actions to minimise and prevent mistakes. • The sensors should be coupled together in a way that individual sensor failures are detected and discriminated. • The system should automate actions in the procedures that need to be completed, in particular those actions which are non-critical.	• Currently there is limited support for identification of the best CoA, the pilots will identify the correct procedure to implement by identifying the procedure in the emergency procedures checklist in paper form. They then go through each action and manually complete it in the cockpit. In addition, there is limited support to identify if the pilots complete the checklist incorrectly.	• Electronic checklist were implemented into the system, which prioritise the associated procedures and checklists to complete. The system also prioritises the failures to complete first. • Integrated procedures and checklists, where the system detected the flight phase and presented the relevant checklists and also detected the completion of the checklist item. • The system detects and prohibits actions that have a detrimental impact on the flight. • Switches from the overhead panel were integrated into a touchscreen interface integrated into the visual representation. This reducing workload and splitting of attention between the display and overhead panel.

Table 6.2: NDM Requirements for SPO

6.4.7 Summary of Stage 4 Findings

Stage 4: Application Design presents two fuel systems; the first, classic system is based on the traditional A330 cockpit philosophy and adapted for SPO use and the second, is developed on the NDM requirements identified at the beginning of this chapter. The design focuses on supporting the PIC through the decision-making tasks in the cockpit without the support of the CP.

6.5 Stage 5: Evaluation

This section presents the final stage of the DCD approach, evaluation. Stage 5 presents the evaluation of the two systems created for SPO to identify the impact of the new fuel system on the remaining pilot.

6.5.1 Method

The method outlines the population, part-task simulator, independent variables, procedure and evaluation method. The senior test pilot advised regarding the scenarios and evaluation methods.

6.5.1.1 Population

Fourteen experienced Airbus test pilots were recruited for this study. The participant sample consisted of 11 active pilots and 3 retired pilots, within this sample 2 weapons officers were used. All participants had both commercial and military licenses. The participant sample included all European male and had an average of 2277 flying hours in various commercial and military aircraft.

6.5.1.2 Part-task Simulator

A part-task simulator of a SPO jet aircraft was used, which included a high-resolution screen for the flight scenario, flight deck including multiple screens, trackball, throttle board (with engine master, flaps, etc.), overhead panel and joystick.

6.5.1.3 Independent Variables

The independent variables are the type of system and type of scenario. Two types of fuel system were used. Firstly, the classic system, which uses a traditional fuel interface, similar to that of an Airbus large passenger aircraft, with traditional instrumentation and input interaction. The second system, NDM system, consisted of a fuel interface designed to support single pilot cognitive demands, with direct interaction with the interfaces. Three types of scenario were used; low, medium and high demand.

A between subjects study design was carried out with seven participants evaluating each of the flight decks. The study was designed to balance the pilots, according to active and retired duty, for each experimental group. Each group contained one weapons officer.

6.5.1.4 Evaluation Method

Airbus Defence and Space indicated that the evaluation needed to investigate performance, situation awareness, workload and usability. The following methods were selected to evaluate the SPO system:

Decision-Making

In order to investigate decision-making, two measures were investigated. First, if the pilots were able to successfully resolve the incident and secondly, the time taken to complete the failure was investigated. The time taken was identified by pilots as important factor because as pilots are trained to resolve a failure as quickly as possible.

Situation Awareness

Subjective and objective measures of situation awareness were taken to get a rounded view, formally known as triangulation (Wilson and Sharples, 2015). Situation present assessment method (SPAM) were used to get an objective view of situation awareness and workload. SPAM used real-time probes to measure participant situation awareness, without simulation freezes (Stanton et al., 2004). SPAM probed the pilot for situation awareness using task related situation awareness queries, based on key information in the environment. SPAM evaluated the time for a participant to retrieve and answer the situation awareness question after acknowledging that they can take a question. Appendix G describes the process and questions asked.

3D situation awareness rating technique (SART) questionnaire was used after each scenario to get a subjective view of the pilot's own perception of their situation awareness. 3D-SART is multidimensional scaling technique and is a simplification of the 10 dimensional

version, which assesses three dimensions of situation awareness; demands on attentional resources (complexity, variability, and instability of the situation), supply of attentional resources (division of attention, arousal, concentration, and spare mental capacity) and understanding (information quantity, and information quality) (Strybel et al., 2007). This questionnaire was used, as it was quick and short to implement.

Workload

To evaluate workload, both objective and subjective measures were taken. As part of the SPAM method the pilot was asked if he was ready to take a question. The amount of time taken to take the situation awareness question indicated the workload. NASA Task Load Index (TLX) with weightings were used to get a subjective view; this like the 3D SART questionnaire was implemented after every scenario. NASA TLX is a multi dimension rating procedure which consists of six dimensions; mental demand, physical demand, temporal demand, performance, effort and frustration. The questionnaire uses a twenty-step scale to obtain ratings for each dimension and produces a result in a score between 0 to 100. The six dimensions are then combined to give an overall workload scale, again a score between 0 to 100. A weighting of each of the dimensions which allowed the pilots to compare the dimensions pairwise based on their perceived importance.

Usability

At the request of Airbus, an additional usability questionnaire, system usability scale (SUS) were used to see if the usability of the flight deck impacted the pilot. This was important, as the system created had significantly changed in regards to the available controls and displays. SUS is a 10 question survey, which measures how well users can interact with the system.

6.5.1.5 Fuel Leak Task Decomposition

Figure E.4 was used to identify the tasks for an engine fire and a second task decomposition diagram of events was developed with the support of the senior test pilot, figures 6.5 and, was developed to identify each step that the participant needs to complete in order to successfully resolve a fuel leak and engine fire emergencies.

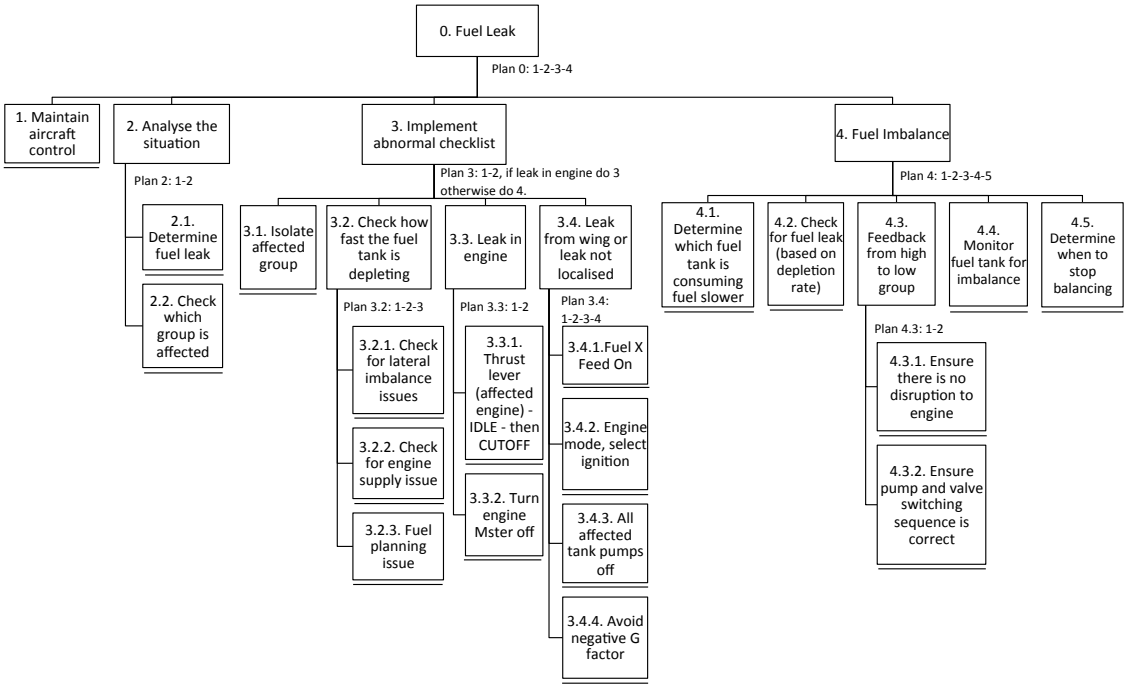


FIGURE 6.5: Fuel Leak Task Decomposition Diagram

6.5.1.6 Scenarios

Three scenarios were developed with the test pilot to evaluate the SPO systems. Scenario One, figure 6.6, was designed to put the pilot under low demand. This was implemented by starting the scenario on track of the route and there were no deviations from the flight plan. In addition, there was minimum ATC communication. The failure implemented in this scenario was a fuel leak.

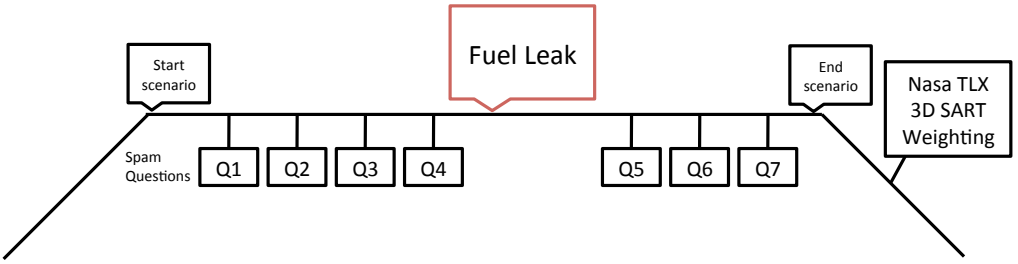


FIGURE 6.6: Overview of Scenario One: Low Demand

Scenario Two, figure 6.7, was designed to put the pilot under medium demand. This was implemented by asking the participant to intercept the flight path, additional ATC instructions were given to change the course of the flight. The failure implemented in this scenario was an engine fire.

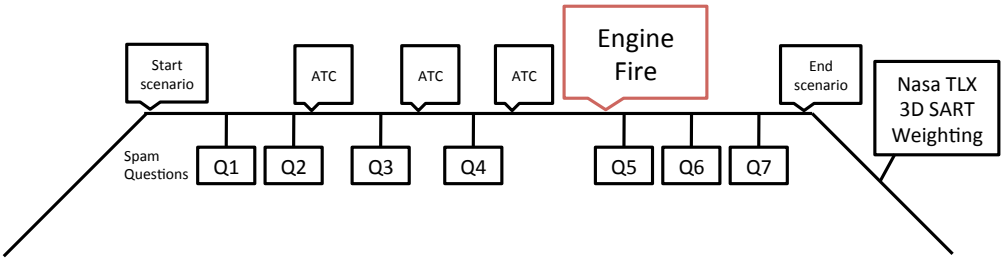


FIGURE 6.7: Overview of Scenario Two: Medium Demand

Scenario 3, figure 6.8, was designed to give the pilot high demand. This was implemented by asking the participant to intercept the path, additional ATC instructions were given to change the course of the flight. The failures implemented in this scenario were both the engine fire and the fuel leak. The multi-failure environment requires the pilot to make simultaneous decisions whilst prioritising which failure to attend to first.

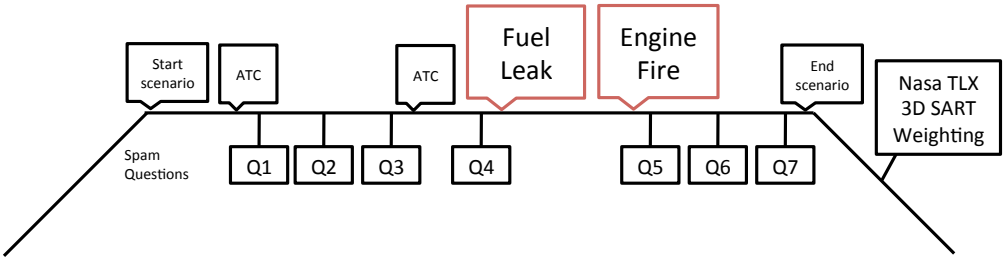


FIGURE 6.8: Overview of Scenario Three: High Demand

6.5.1.7 Procedure

On the day of the evaluation, the participant was given information about the evaluation and asked to sign a consent form. The researcher explained the evaluation process and introduced the evaluation methods including the SPAM method during the scenario, as well as the post-scenario questionnaires. It was explained to the participant that initially they would be asked if they were ready to take the situation awareness question. In the event they were not, they were asked to state *"Standby"*, similar to the ATC communication. It was explained that they could then ask to take the question when they were ready and if they did not state they were ready, they would be asked every 30 seconds until they stated *"yes"*. The participant was then asked to complete the NASA TLX weighting questionnaire as part of the workload measure. It was explained to the participant that they would be requested to communicate with air traffic control (ATC) as normal.

The researcher then introduced the cockpit philosophy to the participant and an explanation was given for each of the systems. The participant was then provided with training

by the simulator technician to familiarise them with the simulator and cockpit philosophy. Once the training was complete, the participant was given time to further familiarise themselves with the system.

The participants completed three flight scenario from Manching to Kassel, northern Germany, whilst flying manually. All three scenarios began mid-flight during normal flying procedures. During the scenario the participant experienced an aircraft failure (engine fire, fuel leak or a combination of the two), which required the pilot to deviate from normal flying operations. The scenario order was randomised for each participant to account for learnability effect.

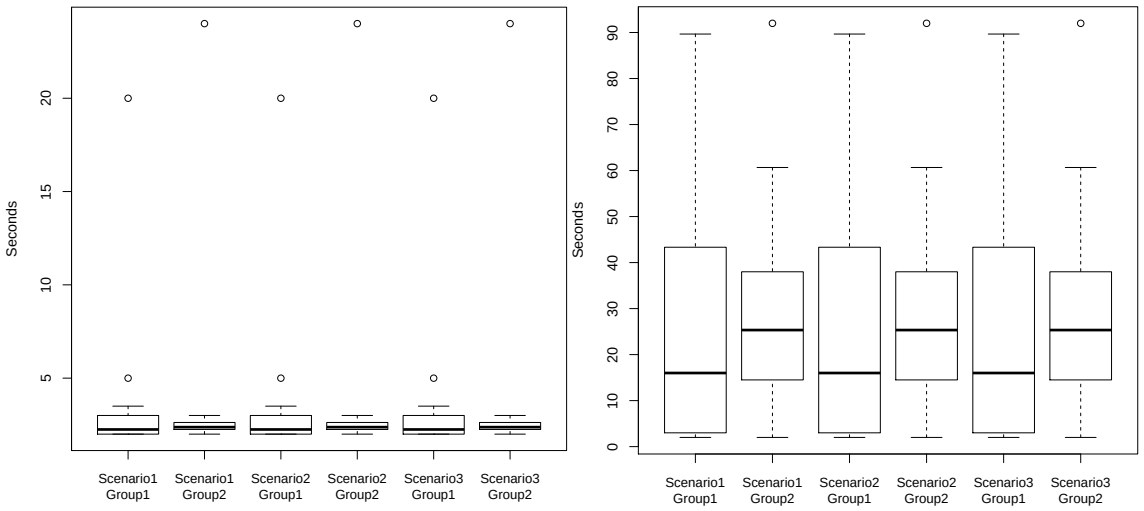
The researcher implemented the evaluation methods; SPAM questions were delivered during the scenario. The questions were pre-recorded so that the delivery was the same for each participant. NASA TLX and 3D SART questionnaires were implemented after each of the scenarios and the SUS questionniare was implemented once all three scenarios were completed. The simulator technician set up each scenario in the simulator and also acted as air traffic control during each scenario. The participants were videotaped.

6.5.2 Results and Analysis

The following section presents the results from the evaluation. Numbers presented are means unless otherwise stated. Group 1 performed the evaluation using the classic system, where as, group 2 used the NDM system.

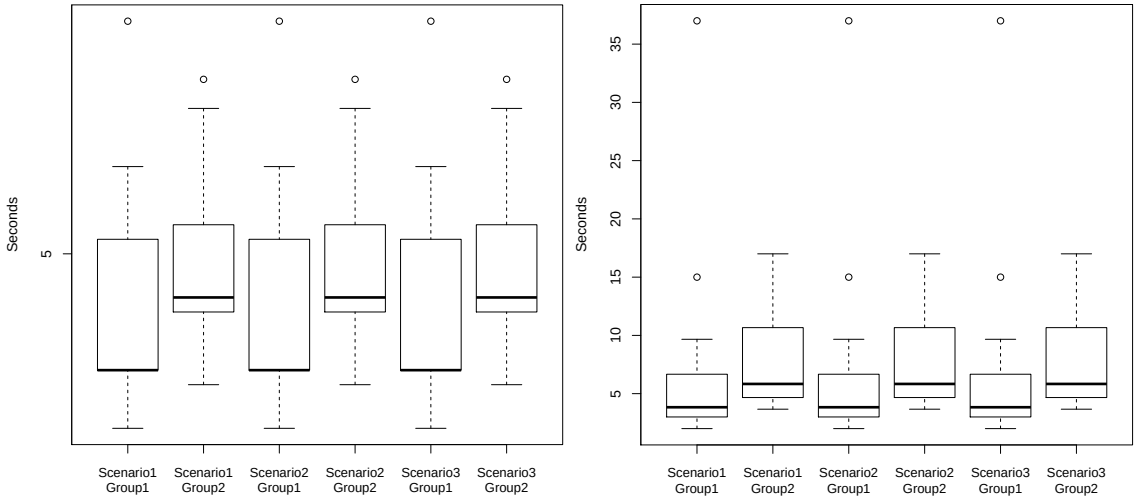
SPAM Results

To analyse the SPAM, response latencies of time to take the question (workload) and the time taken to respond to perception, comprehension and projection queries (situation awareness) are assessed. Seven situation awareness questions were asked, questions 1 - 4 in each scenario investigated level 1 (perception) and questions 5 - 7 investigated levels 2 (comprehension) and 3 (projection). The results are presented in box plot form in figure 6.9. As expected the median workload values for level 2 & 3 are much higher than that of level 1 highlighting the extra workload placed on the user. For all levels the median workload value is consistently higher for the second group. The same is true for situation awareness, however for situation awareness level 2 & 3 there appears to be more outliers (circles in the boxplot) for group 1.



(A) Workload Level 1 Questions (B) Workload Level 2 & 3 Questions

FIGURE 6.9: SPAM Workload Boxplots



(A) SA Level 1 Questions (B) SA Level 2 & 3 Questions

FIGURE 6.10: SPAM Situation Awareness Boxplots

	Level 1 Questions		Level 2 & 3 Questions	
	F-Value	P-Value	F-Value	P-Value
Group	1.97	0.17	0.48	0.49
Scenario	0.43	0.52	3.78	0.06
Group:Scenario	0.05	0.83	0.66	0.42

TABLE 6.3: SPAM Situation Awareness P-Values, $*p < 0.05$

	Level 1 Questions		Level 2 & 3 Questions	
	F-Value	P-Value	F-Value	P-Value
Group	0.0	0.99	0.18	0.68
Scenario	0.0	0.99	1.50	0.23
Group:Scenario	2.46	0.12	0.04	0.85

TABLE 6.4: SPAM Workload P-Values, $*p < 0.05$

A 2x3 (2 cockpit systems x 3 scenarios) between-subjects ANOVA was undertaken for each SPAM value (objective situation awareness: time taken to respond to query and workload: time taken to take question). The situation awareness results show the absence of main effects of cockpit system (F=1.97, p=0.17) and scenario (F=0.43, p=0.52), table 6.3. The workload results show the absence of main effects of cockpit system (F=0.00, p=0.99) and scenario (F=0.00, p=0.99), table 6.4. This shows that in this study using the NDM requirements for SPO designs pilots were able to perform to a similar level to that of the classic system. These results are promising for the use of the NDM requirements in the design principles as the pilots have used extensively trained in the classic system for many years.

SART Results

A participant's overall subjective situation awareness was identified through the use of a 7 point scale, investigating three main factors; demand on attentional resources, supply of attentional resources and understanding of situation. The midpoint for each scale was 3.5, with a minimum of 1 and a maximum of 7. Using the values from the SART questionnaire, an overall SART score was calculated using the following equation: (Understanding – (Demand – Supply). Boxplots of the SART scores are presented in Table 6.11, which are similar between the the two groups, in scenarios 1 and 3 the median scores are higher for the NDM system and in scenario 1 specifically the spread of results is compressed towards a single value.

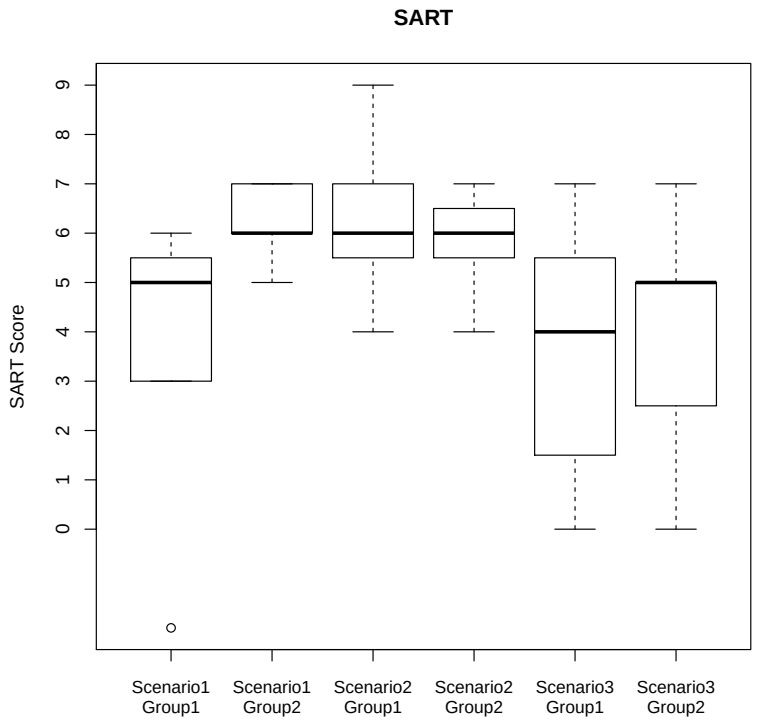


FIGURE 6.11: Boxplot of SART Results

A 2x3 (2 cockpit systems x 3 scenarios) between-subjects ANOVA was undertaken for the SART scores. The SART results show the absence of main effects of cockpit system (F=1.25, p=0.27), table 6.5. Significance between the scenarios (F=4.50, p=0.02) were expected, the experimental design required different demands be placed on the pilots for each scenario, this is now confirmed and will not be further investigated.

	F-Value	P-Value
Group	1.25	0.27
Scenario	4.50	0.02 *
Group:Scenario	1.734	0.19

TABLE 6.5: ANOVA of SART Scores

NASA TLX Results

NASA TLX scores were calculated using the weighting results. Figure 6.12 presents a boxplot of the median values, and interquartile ranges for overall workload for each scenario. The results show that the median NASA TLX score for the NDM system was consistently higher and in the case of scenario 2 & 3 the ranges were consistently greater. The greater ranges may show the inconsistencies in the abilities of the pilots to perform on the new

system, some pilots have much better results than others. With training it maybe possible to reduce the median values towards the lower NASA TLX scores that some pilots achieve.

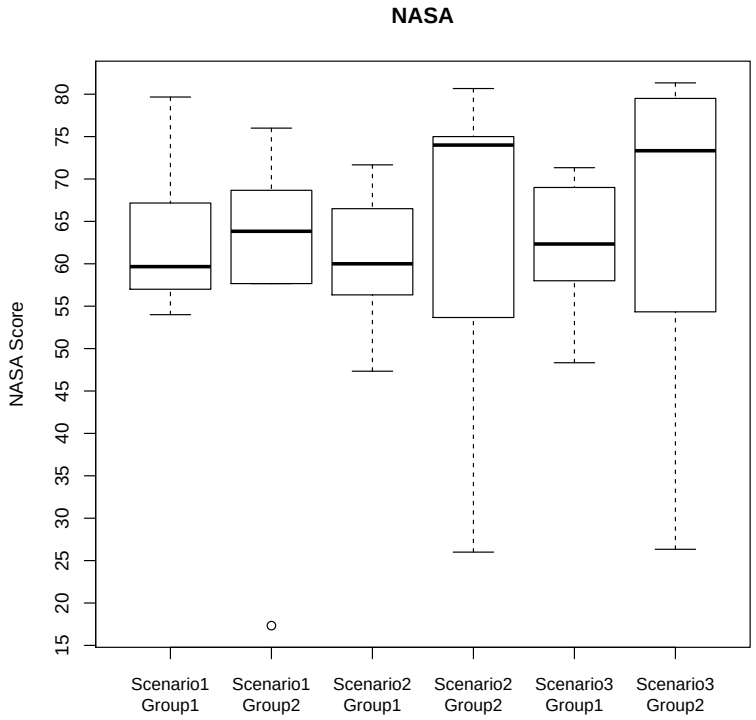


FIGURE 6.12: Boxplot of NASA TLX Results

A 2x3 (2 cockpit systems x 3 scenarios) between-subjects ANOVA was undertaken for the NASA TLX results. The NASA TLX results show the absence of main effects of cockpit system (F=0.00, p=0.95) and scenarios (F=0.09, p=0.92), table 6.6. Thus, at this sample since the differences are not significant in support or against the new system.

	F-Value	P-Value
Group	0.0	0.95
Scenario	0.09	0.92
Group:Scenario	0.22	0.81

TABLE 6.6: ANOVA of NASA TLX

Decision-making Results

The performance results, time to complete emergency scores were taken from the start of the scenario to the end, see figure 6.13. In scenarios 1 and 2 the time to complete the

scenarios are very similar, however in scenario 3 the NDM designed interface has a reduced median value.

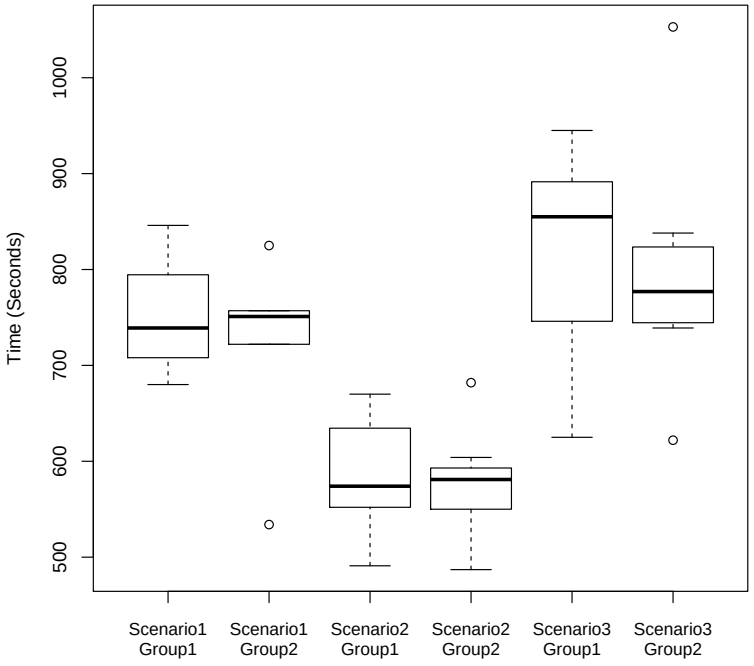


FIGURE 6.13: Time to Complete Scenario

	F-Value	P-Value
Group	0.45	0.51
Scenario	20.82	1.11 e-06
Group:Scenario	0.04	0.96

TABLE 6.7: ANOVA of Time to Complete Emergency

A 2x3 (2 cockpit systems x 3 scenarios) between-subjects ANOVA was undertaken for the performance results. The performance results show the absence of main effects of cockpit system (F=0.45, P=0.51), table 6.7. The results showed there was an effect of scenarios (F=20.82, P=1.11 e-06) but this was expected. All participants expect one were able to successfully complete each of the scenarios. It should be noted that participant 1 in Group one for scenario one shut down the wrong engine which resulted in the aircraft crashing and causing the scenario to abruptly end and was not able to complete the full scenario. As the pilot incorrectly turned off the engine, this suggests that the classic system did not give the pilot the understanding that he required to resolve the emergency.

SUS Results

Overall SUS scores were calculated, for odd items, one was subtracted from the user response and for even-numbered items, 5 was subtracted from the user responses. Using the overall usability scores a 2 by 3 ANOVA was performed, see table 6.8.

	Mean		SD	
	Group 1	Group 2	Group 1	Group 2
Overall Usability	78.93	85.83	16.13	13.66
Usability	62.50	67.50	12.50	12.04
Learnability	16.43	18.33	4.05	2.04

TABLE 6.8: SUS Mean and Standard Deviation

Usability was measured through a SUS questionnaire administered to the pilots once all three scenarios where complete. The results were therefore compared through a t-test. The t-test showed that for overall usability there was no significant difference between the groups (t = -0.83566, p-value = 0.4211). Showing that for this experiment there was no significant difference in the mean results for usability for the two systems.

6.5.3 Summary of Stage 5 Findings

Results show that the NDM design had similar performance to that of a system based on the current design methodology, in spite of the fact the pilots had little experience with the system. The statistical analysis shows that the NDM system had similar scores for performance, situation awareness, workload and usability in comparison to the classic system. Whilst similar scores were seen and no effects identified between the types of fuel system, descriptive analysis indicated that group two performed slightly better for a number of situation awareness and workload results in SPAM. For example, for scenario three, which was designed to have high demand, for both workload and situation awareness factors of SPAM, there is an indication that group two performed better than group one. It was also noted that for scenario three, SART and NASA TLX scores indicated that group two performed better. In addition, for performance, group two performed faster for all scenarios and indicated slightly better usability using the NDM system. These results could indicate with further statistical power that the NDM system could better support the operator when decision-making in high demand situations than the classic system.

Every effort was made to use experienced pilots who would be the typical end users of the system, which would provide realistic results. However, there was a restriction placed

on the types of pilots used, due to the confidentiality of the project, the researcher was only able to study Airbus pilots, which resulted in a limited number of pilots being able to evaluate the systems. It is hypothesised that the small sample size used in the study has resulted in no statistical power and therefore no effect was found between the systems. Future work could investigate repeating the study with a larger sample size, for example using at least 20 participants per condition, with Airbus pilots from other countries (dependent on available resources) this could give greater insight and more statistical power.

The pilots were provided with training for the NDM system, however, the training did not cover all the normal and emergency procedures. This limitation was due to time restrictions in pilot hours caused by project costs. After the experiment was performed some pilots stated that more training time was needed to become fully accustomed to the new philosophy of the NDM cockpit. Pilots have trained for many years on the classic system. Comments such as "I'm used to this [old] way", "I'm not used to the cockpit yet" and "I would need more training [for the NDM system]" were made during the evaluations. Future studies could provide the participants with greater training over a number of weeks and provide the pilots with self study material, allowing familiarisation with new cockpit philosophy.

The study also presents a combination of evaluation methods to evaluate the impact on the pilot whilst attending to an incident. Although the focus of the study was not to justify the method of evaluating systems for real-world decision-making, we identify that there is a gap in the literature when supporting the evaluation of these types of systems.

6.6 Discussion

Chapter 5 and 6 present DCD framework findings in the aviation domain. Stage 1: preparation, presents an ethnographic study of the tasks pilots complete during normal situations and confirms the seven factors for decision-making in normal situations. Stage 2: knowledge elicitation, presents ten case studies using the CDM interview technique, identifying the key decision points and the associated elements that support the decision-making process. Using understanding from stage 1 and 2, stage 3: analyse and representation presents design ideas to support the decision-making process. Stage 4: application design, presents the integration of the design ideas into the design of a single pilot aircraft system. Finally, stage 5, evaluates the system which shows that the design had similar performance to that of a system based on the current design methodology, in spite of the fact the pilots had little experience with the system. Based on the DCD findings, figure 2.6 from chapter

2 has been updated to include the additional steps in the decision-making process, see figure 6.14.

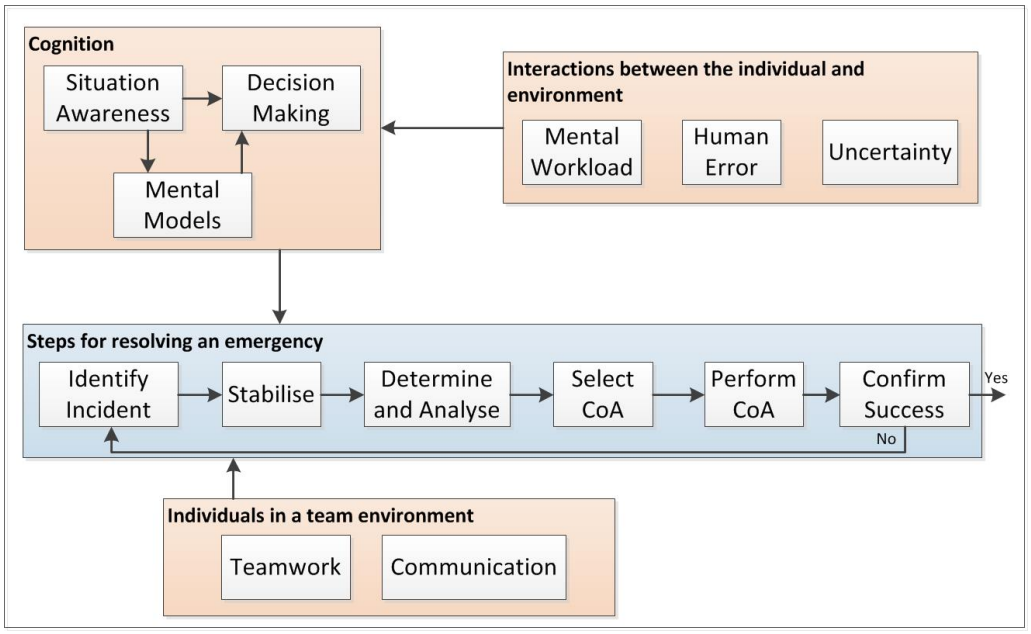


FIGURE 6.14: Overview of Cognition Informed System Design

There are a number of valuable contributions from the DCD approach for the development of the design principles first, the knowledge from the ethnographic study and CDM interviews provide a basis for case studies and examples for each of the design principles, which give the principles real-world validation. The findings also detail the practical application of the human factors influences of a real system and what should be considered when designing naturalistic decision-making systems.

The DCD approach is an excellent method to investigate naturalistic decision-making where there is a limited understanding of domain. The method guides the researcher in getting an understanding of the domain through to designing a system which supports the decision-maker. However, there is limited support to investigate the seven human factors, which impacts the decision-maker's performance. The model could be further developed to incorporate the investigation of the HF issues, especially in knowledge elicitation and analyse and representation stages. By taking into consideration this understanding this will have a positive effective on the operator's decision-making performance in emergency situations.

Moving to SPO for commercial aircraft is presently a controversial topic in the aviation industry, yet immensely topical. Whilst technological advancements have made SPO possible, there has been limited research, which investigates the feasibility of commercial SPO. Presently, there are single pilot concepts (especially in military (Eurofighter) and civil

non-commercial domains) and these pilots undertake all the tasks that are required for a safe flight. This is proof that SPO can effectively work, however, we need to undertake further research as the level of safety, which is required when transporting passengers is far greater.

Whilst we have the technological feasibility we need to consider the cognitive feasibility of moving to SPO. For this reason we propose that the designers of SPO aircraft consider the decision-making process and the human factors issues that affect this process and accordingly design the flight deck to support the single pilot. By considering this, systems, training and procedures can be designed, which better support the pilot's NDM process during a safe flight. This research is the first steps that need to be taken to get an in-depth understanding of what is required for SPO.

When designing for SPO the following should be considered:

The Human Factor

People are predictive, intuitive, flexible and adaptable to deal with any situation. A system is not as adaptable as a person. The systems are designed by humans and are only able to do what they have been programmed to do and only able to predict within the parameters of the software. Automation, regardless of how sophisticated it is, is reactive. It takes past information, and calculates probabilities from that information. It cannot imagine, envision circumstances, or take contextual information and project it forward into emergent conditions to see a possibility to reduce risk. However, the pilots are able ensure the safest possible outcome for the plane and all the passengers on-board. Pilots use expertise, intuition and highly developed mental models, which have a great role in safe flight operations.

Detachment from the Flight

In the scenario consisting of the co-pilot is supporting the PIC from outside the flight deck, that the CPG may not experience the same sense of commitment to completing the flight. As the co-pilot is on the ground he/she may not feel the intense risk of life in an emergency. The pilot on-board can feel, smell and hear many indications of an impending problem and begin to formulate a course of action before even sophisticated sensors and indicators provide positive indications of trouble. Whereas, the CPG will only be able to see the information that is in front of him/her. One of the questions that needs to be asked is "will the CPG be able to put himself truly into the pilot's shoes if something goes wrong?" Another question should be considered "will the CPG be able to perform equally as well as an on-board co-pilot?"

Degradation of Pilot Skills

We need to be aware that the pilot's skills may be compromised by technology, an example of this can be seen at the Asiana Airlines 777 crash at SFO. Pilots' skills are diminishing due to creeping automation on the flight deck and some would say they become "button pushers", where they focus on managing and monitoring the systems, which is severely impacting the quality of manual flying. We need to consider how we should train the SPO aircrews and find the balance between flying manually and in autopilot. This ensuring the quality of manual flying is maintained.

Training for Single Pilot Operations

Currently, co-pilots learn how to be professional captains while working alongside the pilot in command. The co-pilot develops valuable experience from on-the-job learning, especially when handling emergencies. The co-pilot is required to accumulate a number of flying hours in order to be able to progress to a pilot in command. Moving towards single pilot operations will present a fundamental problem of how the pilot can accumulate the number of required flying hours. A possible solution could be to increase the number of hours the co-pilots spend in the simulator, however, this will not provide them with the real experience of flying in the aircraft.

The interaction between the pilot on board and the pilot on the ground should be investigated. Trust issues, cues and information that might be needed to support the pilots needs to be investigated (Stanton et al., 2016). In addition, the change in aircrew could also impact their communication as the pilots will no longer have the non-verbal cues that they presently have in two pilot aircrews.

Acceptance from Passengers, Pilots and Ground Crew

Even though it is expected that the move towards single pilot aircraft will be over a significant period of time, social barriers may be faced from passengers, pilots and potentially the ground crew. Passengers may not accept the SPO concept, especially considering events on Germanwings Flight 9525 where it was suspected that the co-pilot intentionally crashed the flight (BBC News, 2016). Passengers put their trust in the quality of the pilots and their crew. It is much harder to place this trust in a more automated system with fewer pilots. We need to clearly develop the passengers understanding regarding on-board safety, security (from attacks such as cyber-hijacking) and general trust in the technology.

Barriers of acceptance of SPO by pilots may be experienced, as currently the certification authorities for commercial flights indicate the aircraft should fly with a minimum of two pilots. Whilst pilots are capable of flying the aircraft without a second pilot their may be resistance especially for long-haul flights. Furthermore, as the ground crew may play

a larger role during the flight, the aircrew needs to accept them as another crewmember.

6.7 Chapter Summary

This chapter presents three activities moving towards single pilot operations and the final two steps of the DCD approach; application design and evaluation. Based on the findings from the first three steps of DCD from chapter 5. This activity identified the impact on the remaining pilot by investigating the existing role and identifying the human factors issues that could impact the remaining pilot as a result of moving towards SPO. In addition, the activity identifies the design requirements for the system. Stage 4 of the DCD framework presented the design a fuel system for a novel SPO jet aircraft using the design requirements. Stage 5 of DCD evaluated the NDM system against a classic system to investigate the impact on performance, situation awareness, workload and usability.

Chapter 7

Synthesis and Evaluation of Design Principles

7.1 Chapter Overview

This chapter contributes to aim three, develop guidance to support NDM system designers. This chapter consists of two sections; first, to develop an initial set of design principles based on previous findings and secondly, evaluate the initial set of design principles and further develop them into a final set that are presented in chapter 8.

The presented design principles are based on a synthesis of the findings from previous chapters. An initial set of sixteen design principles are presented in three main sections; decision-making, situation awareness and workload. Each principle contains an explanation, illustrative examples and questions to consider when designing. Three questions were identified for further investigation; Are the principles usable and understandable to design real-world decision-making systems? Are the principles complete in supporting the designer through the design process? Are the principles applicable to other domains? To address these questions two workshops were carried out to evaluate the initial 16 design principles.

The workshops consisted of 10 HF experts, who were instructed to design and evaluate a system using the design principles. Four activities were performed in the workshops to evaluate the principles. In the first activity, each group worked as a design team and used the principles to create a system to support the F&RS incident commander's (IC) decision-making process during an emergency incident. In the second activity, the group indicated which design principles had been used to inform their prototype. The third activity required the group to order the principles according to how useful they were to

design of the prototype. The fourth activity obtained the participants' views regarding their use of the design principles through a semi-structured focus group.

7.2 Section One: Initial Design Principles

This section presents an overview of the design principles and identifies areas for further investigation.

7.2.1 Overview of the Initial Design Principles

A brief overview of the initial sixteen design principles is provided in the following sections. In addition, evidence is provided to show the research which each principle is based on. These initial principles are given in full in appendix H, including descriptions, examples and points to consider when designing for a NDM system. In section 7.3 these initial principles are evaluated and developed into a final validated set of principles that are given in chapter 8.

Principle 1: Organise Information around the NDM decision points

The Recognition Primed Decision (RPD) model investigates how individuals effectively make decisions in complex situations (Klein, 1993a, 1999). RPD involves non-optimising and non-compensatory strategies, which require minimal conscious deliberation. RPDs do not compare options, but instead involve recognition matching, where the the most likely action is highlighted (Klein and Klinger, 1991). In a naturalistic environment a decision-maker develops a potential course of action, considers the constraints imposed by the situation and selects the first course of action which is not rejected (Klein et al., 1989).

Table 7.1 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Section 2.2
Chapter 4: Section 4.4
Chapter 5: Section 5.3.4
Appendix E.

Table 7.1: Research Evidence: Principle 1

Principle 2: Design for Emergency Identification

When an emergency occurs, the decision-maker will either be alerted to a problem by using scan patterns to identify an anomaly, or alternatively they may be alerted by a system or person. Support should be provided to the decision-maker's information needs, providing understanding into what the emergency is and why it is occurring. If for example, the system is alerting the decision-maker, consider providing information regarding the anomalies in the system, what impact they might have on the system and any time constraints.

Table 7.2 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Figure 2.2
Chapter 4: Section 4.4.7 and Figure 4.8
Chapter 5: Section 5.3.4, table 5.8
Appendix E

TABLE 7.2: Research Evidence: Principle 2

Principle 3: Design to Determine and Analyse the Emergency

The operator will need to determine and analyse the emergency by developing an understanding of what is happening at the incident. The decision-maker may try to understand the root of the problem, the severity and criticality of the problem. Identifying the root of the problem and may support the identification of the course of action. The system should allow the decision-maker to determine if the situation they are attending is typical or novel (Klein, 1999). The operator may then need support for the novel situations, which they have not come across before as the situation may be challenging and unfamiliar (Klein, 1999).

Table 7.3 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Figure 2.2
Chapter 4: Section 4.4.7, Figure 4.8 and Figure 4.12
Chapter 5: Section 5.3.4, table 5.8
Appendix E

TABLE 7.3: Research Evidence: Principle 3

Principle 4: Single or Multiple Decision-Maker(s)

Consider who are the decision-makers. For example, is there one decision-maker with the support of a team, or are there several decision-makers who have to work collaboratively? By identifying who the decision-makers are, the designer can focus the design of the system to help the decision maker needs.

Table 7.4 shows the evidence of where the principle was derived from.

Evidence
Chapter 4: Sections 4.3.3.2 and 4.5.6
Chapter 5: Section 5.2.2

TABLE 7.4: Research Evidence: Principle 4

Principle 5: Operator's Environment

Due to the challenging nature of NDM contexts the design of the system should consider the operator's environment. NDM contexts can have ill-structured problems, uncertain, dynamic environments, shifting, ill-defined or competing goals, multiple event-feedback loops, time constraints, high stakes, multiple players, and finally organisational norms and goals (Orasanu and Connolly, 1993a). The designer should consider the environment to understand how the system will be used and any constraints that the decision-maker may face. By understanding the characteristics and problem areas the designer can support the decision-maker in these areas.

Table 7.5 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Section 2.2
Chapter 4: Sections 4.3.3.1 and 4.4
Chapter 5: Table 5.8 Appendix E

TABLE 7.5: Research Evidence: Principle 5

Principle 6: Time to Absorb Information

During an emergency the decision-maker has limited time to search for information in often unstable environments with the possibility of fatalities. The decision-maker will want to understand as much information as possible as quickly as possible. The design of the system should support the information retrieval for the operator and present it in a way that is easy to comprehend for the operator. By supporting and understanding when

the decision-maker can absorb information this can better support the decision-maker's situation awareness and consequently determining and analysing the situation.

Table 7.6 shows the evidence of where the principle was derived from.

Evidence
Chapter 4: Sections 4.6
Chapter 5: Table 5.8

TABLE 7.6: Research Evidence: Principle 6

Principle 7: Support the identification of a course of action

The recognition primed decision model identifies that the decision-maker develops a single course of action based on the constraints in the environment. Randel et al. (1996) find that experts base their decisions on the nature of the situation using their expertise; they have a large repertoire of past experiences on which to base the current situation. The decision-maker spends little effort in deciding how to react to a situation, once they have understood the situation; the reaction is often obvious. The decision-maker wants "workable," "timely" and "cost effective" actions (Klein and Klinger, 1991).

Table 7.7 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Figure 2.2
Chapter 4: Section 4.4.7, Figure 4.8 and Figure 4.12
Chapter 5: Section 5.3.4, table 5.8
Appendix E

TABLE 7.7: Research Evidence: Principle 7

Principle 8: Mental Simulation

Mental simulation in the RPD model evaluates if an action is satisfactory. When simulating, the decision-maker performs the course of action in his or her imagination; plays out the steps, the potential outcomes, the problems that might occur and how these problems may be handled. The decision-maker either implements the action, or modifies it, or rejects it and goes on to the next action (Klein, 1999). Mental simulation appears in at least three places when decision-making; diagnosing to form situation awareness, generating expectancies to help generate situation awareness, and evaluating a course of action (Klein, 1999).

Table 7.8 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Figure 2.2
Chapter 4: Section 4.4.7, Figure 4.8 and Figure 4.12
Chapter 5: Section 5.3.4, table 5.8
Appendix E

TABLE 7.8: Research Evidence: Principle 8

Principle 9: Confirm success of the course of action

Once the course of action is performed, the decision-maker will need to identify the success of completing the course of action and identify if further actions are required. Outcomes of performing the course of action include: correct with no errors, correct with errors and incorrect.

Table 7.9 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Figure 2.2
Chapter 4: Section 4.4.7, Figure 4.8 and Figure 4.12
Chapter 5: Section 5.3.4, table 5.8
Appendix E

TABLE 7.9: Research Evidence: Principle 9

Principle 10: Support for Individual Situation Awareness

Situation awareness is the foundation for decision-making and performance (Salas and Klein, 2001). SA is developed through the situation assessment process in the RPD model. Endsley (1988) defines SA as *"the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future"* or simply put *"knowing what is going on."* SA is dynamic in nature and the repetition of the process continuously updates the decision-maker's understanding of the environment (Parasuraman et al., 2008).

Table 7.10 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Section 2.3.1.1
Chapter 4: Table 4.1
Chapter 5: Section 5.2.4.3 and Table 5.7

TABLE 7.10: Research Evidence: Principle 10

Principle 11: Team Situation Awareness

Team situation awareness refers to a shared or distributed awareness or mental representation of the environment between team members. Lipshitz et al. (2001) outlines that team situation awareness is essential for effective decision-making, especially since obtaining and maintaining SA in teams is far more complex than in individuals. Team SA can be acquired when members of the team collect and exchange information and when the members engage in closed-loop communication (Orasanu, 1990). Endsley and Jones (1997) state for a team to successfully function, all team members must possess a high level of the same SA on shared requirements.

Table 7.11 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Section 2.3.3.1
Chapter 4: Table 4.1
Chapter 5: Section 5.2.4.3

TABLE 7.11: Research Evidence: Principle 11

Principle 12: Communication

Communication can be considered as the way one mind can affect another, it can be either verbal or non-verbal, intentional or unintentional (Eccles and Gershon, 2004). Hogg and Vaughan (2002) define communication as the "transfer of meaningful information from one person to another", which involves the production and the reception of messages. Isaac and Ruitenberg (1999) indicates that communication starts when a sender encodes an idea or message and sends it through one or more channels that can be either verbal or non-verbal. The receiver then decodes this message using long term memory to bring meaning to the message. The receiver may have different characteristics which include experience, culture and expectations which may affect decoding.

Table 7.12 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Section 2.3.3.2
Chapter 4: Table 4.1
Chapter 5: Section 5.2.4.3 and Table 5.6

TABLE 7.12: Research Evidence: Principle 12

Principle 13: Verbalisation

Verbalisation is when actions and tasks are verbally communicated. Consider which actions might need to be verbalised to the other operators in the team. For example, in two pilot aircrews the co-pilot will read out the procedures on a checklist and the pilot in command will complete the procedure and acknowledge the items are complete. This allows both pilots to know what the other is doing and to understand the potential impact on the aircraft and/or flight plan. Verbalisation is needed to consolidate the information the pilot has acquired and gathered to further extend their understanding of the situation. It can be considered as a process to help the pilot to slow down his/her thinking process.

Table 7.13 shows the evidence of where the principle was derived from.

Evidence
Chapter 5: Section 5.2.4.3
Appendix E

TABLE 7.13: Research Evidence: Principle 13

Principle 14: Workload

Workload is defined as *"the relation between the function relating the mental resources demanded by a task and those resources available to be supplied by the human operator"* Parasuraman et al. (2008). An increased workload reduces the ability of the user to undertake efficient decision-making, thus the decision-maker needs to be supported when completing his/her tasks. These tasks include gathering information and identifying problems; reviewing causal factors with other team members; considering and sharing risks of alternative courses of action. The NDM environment is a multi-task environment, where the decision-maker uses several different resources for information processing (Wickens, 1984). Two forms of technological intervention are therefore possible; technology that reduces workload by automating tasks that would otherwise consume mental effort (also known as "offloading") or technology that supports the process of decision-making itself (Rogers and Scaife, 1998).

Table 7.14 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Section 2.3.2.1
Chapter 4: Section 4.1
Chapter 5: Tables 5.6 and 5.7

TABLE 7.14: Research Evidence: Principle 14

Principle 15: Automation

Automation is a method to support operators with workload that they may experience. Automation can differ in type and complexity from simply organising the information sources; to integrating them into a summary format, to suggesting decision options that best match the incoming information, or even carry out the necessary action. Automation can provide decision support, alleviate the heavy demand and augment system performance to reduce errors. Good automation reduces workload whilst maintaining the operator's situation awareness. The system designer can introduce different levels of automation into systems, Kaber and Endsley (1998) present the levels of taxonomy, which present different levels of automation for monitoring, generating, selecting and implementing tasks.

Table 7.15 shows the evidence of where the principle was derived from.

Evidence
Chapter 4: Section 4.4 and Table 4.1
Chapter 5: Tables 5.6 and 5.8 and Section 5.3.4

Table 7.15: Research Evidence: Principle 15

Principle 16: Monitoring and Crosschecking

Consider the monitoring and crosschecking activities that the operator(s) may require to ensure that errors do not occur.

Table 7.16 shows the evidence of where the principle was derived from.

Evidence
Chapter 4: Section 4.4 and Table 4.1
Chapter 5: Tables 5.6 and 5.8 and Section 5.3.4

Table 7.16: Research Evidence: Principle 16

7.2.2 Further Development

There should be certainty regarding whether the format of the principles were usable and understandable by system designers. Construct validity needed to be evaluated to examine the extent to which a measure represents the concepts that it should and particularly that it does not represent those that it should not (Wilson and Sharples, 2015). Uncertainty regarding the completeness of the principles needs to be addressed to ensure that the guidance can support the designer through the design process. Content validity needs to be investigated to measure the completeness of the principles and to measure all the

relevant parts of the concept it claims to measure (Wilson and Sharples, 2015). Finally, external validity needed to be investigated to outline the generalisability of the design principles to other situations, times and contexts (Wilson and Sharples, 2015).

Therefore the following three questions for further investigation were identified by the researcher:

- Are the principles usable and understandable to design real-world decision-making systems?
- Are the principles complete in supporting the designer through the design process?
- Are the principles applicable for other domains?

These three questions are addressed in the next section.

7.3 Section Two: Evaluation of Design Principles

Section two evaluates the initial design principles by investigating the three questions identified in section 7.2.2 of this chapter.

7.3.1 Method

- **Are the principles usable and understandable to design real-world decision-making systems?** The first activity to investigate construct validity asked designers to apply the principles to a real context to create a prototype system. A second activity highlighted where the principles were applied within the designed prototype system. The study verifies applicability: are the design principles usable and convenient for the intended purpose? The study also verifies clarity: are the design principles understandable and comprehensible?
- **Are the principles complete in supporting the designer through the design process?** Two activities were designed to investigate content validity; the participants ordered the principles according to how useful they felt they were for designing the system and then critiqued the design principles.
- **Are the principles applicable for other domains?** To investigate external validity, the participants stated the other domains the guidance could be applied to.

7.3.2 Population

A total of 10 human factors (HF) experts with experience in emergency services, health care, automotive industries and architecture were used to evaluate the principles during a design workshop. The participants were split into two groups of five participants and grouped according to their experience. Group One consisted of early career human factors experts with an mean age of 29 years old and an average of 3 years in industry. Group Two consisted of senior human factors experts with an average age 42.8 years and an average of 10.4 years working in human factors. Each group contained 3 females and 2 males.

7.3.3 Procedure

The participants were first given information sheets, consent forms and were shown a presentation to introduce the F&RS domain. The presentation covered the role of the incident commander and the variety of emergencies, which occur in the F&RS. The participants were then given information regarding the four activities they would be completing during the workshop. The four activities are explained below:

Activity one required each group to work as a design team and use the principles to create a system to support the IC's decision-making process during an emergency incident. The group spent 2 hours creating a paper prototype system and to present the concept at the end of the allocated time slot. Activity one required the participants to apply and use the design principles to a real use case.

The participants were briefed about the IC's role, the scenario and the information that is available to the IC. The scenario presented to the HF experts outlined that the IC has to attend an incident at 2.00am in the morning. The only detail the IC has is from the emergency call, which has provided only limited information. The caller explained that a teenager has crashed a BMW (possibly stolen) into a residential house, which has caught fire. The participants were advised that the IC has information about the location, information about the building and the number of possible casualties. The participants were also briefed regarding the IC's requirements, the steps an IC has to complete during an incident (a task analysis was provided), the key decisions that need to be made and the informational resources available within the F&RS. The principles were presented in booklet form consisting of descriptions, examples, and prompts for the designer to think about. The participants were given some time to first read through each of the principles and were given the opportunity to ask any questions. The participants were then asked to start designing the prototype using the design principles as they needed and to review the "points to consider" to support idea generation.

Activity two The groups indicated on the paper prototype where the principles had been applied to identify which principles had influenced the design of the prototype.

Activity three asked the group to order the principles according to how useful they were to design of the prototype. This was to determine which principles had been deemed the most useful when designing the system. The participants ordered the design principles into themes. This identified alternative groupings and possible themes in which to present the design principles.

Activity four was a semi-structured focus group to get feedback from the participants regarding their views of using the design principles. The following questions were used as a guide for the focus group: What information is missing from the design principles? What would be required for you to be confident in using the design principles? What other contexts do you feel these principles could be applied to? Are there any parts of the guidance (formal or informal) that are already used? For example, are any of the principles redundant against other principles already used in industry? The researcher asked each question and responses were recorded using a video camera. The data was transcribed and the researcher identified the key themes discussed during the interviews.

7.3.4 Results and Analysis

7.3.4.1 Activity One: Prototyping

This section outlines each group's paper prototype system and the principles used to influence the design of the system.

Group One: Early Career Researchers

Figure 7.1 presents the paper prototype designed by group one.

The group began by discussing the hardware and capabilities of the system; they first discussed voice recognition on a mobile device such as a tablet. P4 was the first principle discussed the participants, reviewing who the decision-maker was. The participants went on to using P5 to debate whether voice recognition technologies such as Siri would be appropriate for a *"noisy fire engine with sirens"*. The participants also discussed the operator's personal protective equipment and felt that the voice recognition facility would be inappropriate with the crew's breathing apparatus, rendering voice recognition technologies as *"unreliable"* and inappropriate for emergencies. The participants also discussed concerns about how the IC would interact with a touch screen. As the IC's gloves could interfere with the touchscreen, the participants discussed the use of buttons on the sides

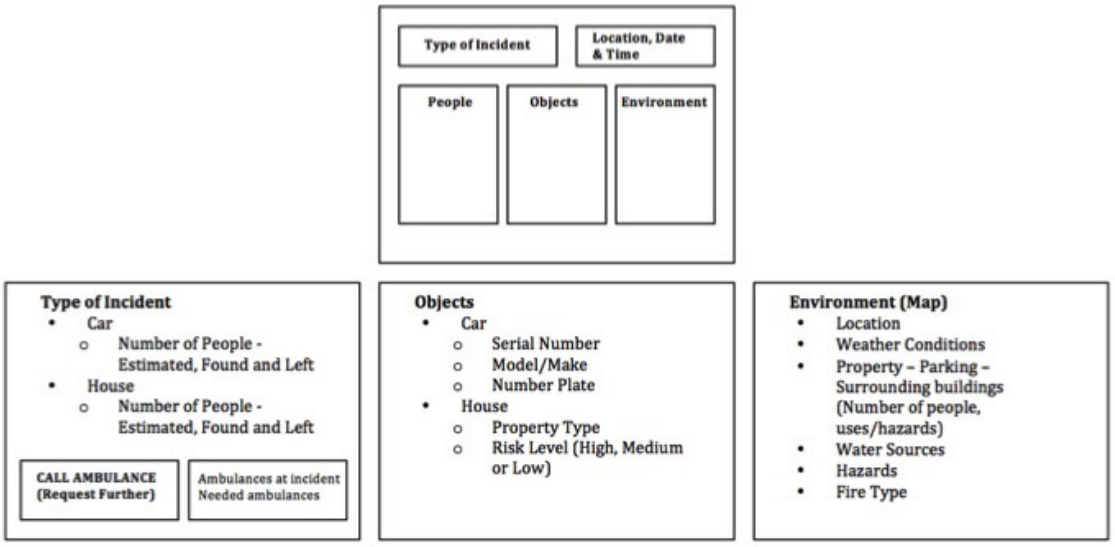


FIGURE 7.1: Group One's Paper Prototype

of a display, however, this suggestion was also deemed not useful as it would reduce the screen size.

Participants moved on to discuss the use of a tablet for the IC, but concerns were raised regarding the large amount of information that needs to be displayed and that the size of the tablet may not be adequate. A participant stated *"not to have too much information on the screen as you have limited size"*. The participants discussed that the IC should not be presented with numerous options on a menu as it would be difficult for them to search in the limited time that they have available [P6]. A participant stated that the IC needs *"to have all the information on one screen, as you don't want to have to go through different menus and try to find different information on different screens."* The participants were concerned not to overload the IC with a large amount of information [P14] as this could have a negative effect.

Based on P10, the participants decided that it was difficult to develop the hardware without knowing what information needed to be presented to the IC. The group abandoned the design of the hardware and using P1 and P10 made a list of information that needed to be presented on the device. Participants stated that this would inform *"How much information we want to present at one time and then we can decide on what the device would look like."* Using the scenario, the participants wrote a list on the whiteboard of the information needed to support decision-making, this included:

- Car information – blueprints of the car.
- Fire information.

- Weather conditions, which could affect the fire.
- Environment.
- Information about the person in the car.
- Residents in the environment.
- Information about the property.

Using P2 and P3 the participants outlined the kinds of questions the IC would ask at the incident. Questions included: What are the hazards? Where are the electricity lines? Where are the water sources? Where should the fire engines be parked? Does the IC need to evacuate the area? Is the property high risk? What is the property made of?

Using the information and questions that the IC would ask, informed the designers that the IC needed different information before arriving at the emergency and at the emergency. The participants stated that whilst travelling to the incident, the IC would have limited time, requiring the information to be simple so that it can be absorbed quickly [P6]. Using P1 the participants stated that the IC's goal is to *"rescue the people, to know the objects and the environment"* and that the system they were creating was not to guide the participant through the emergency, but the goal was to allow the IC to access the information effectively.

The participants emphasised that *"there needs to be a point where it [information] is drawn together"* from the different sources. At the incident the participants discussed that the IC has to go *"deeper, and deeper, and deeper... leaving information behind as you [IC] are getting more detail"* [P10 & P15]. Here the participants not only discussed what information the IC needs, but also how the information should behave in the system. To support this idea, participants designed different levels of information; the levels are discussed in detail later in this section.

The participants wanted to support the IC in recognising the cues associated to the type of incident [P3]. The participants then focused on the information that the IC needs to see and stated *"What do they [operators] need to see first".* The group highlighted that the estimated number of people involved in the emergency, the location of the emergency and the type of car involved in the incident, would be the key information that the IC would require first. The participants stated that they needed to *"Chunk the information into smaller components".* The first interface displayed this information in three categories; People, Location and Environment. The group mentioned it was a *"triangle"* as the three are linked to each other. The participants considered how at different incidents the three categories would have different importance. The participants indicated that a summary

of the information would be presented, highlighting the important information for that particular incident. The summary of information would present all the information which *"you need from the first glance"* [P6]. The group further developed that each of the three categories and the summaries would be presented to the IC in the form of a large press-able button. Once a category is selected, the IC would be presented with more information about that section, presenting a *"second level of information".*

Once the group had the initial information for the system, the participants discussed how automation [P15] could be used to identify the type of incident and consequently the system could identify the important information that the IC needs. The group decided that the raw information from the call would be summarised and classified into a consistent representation that the IC would become accustomed to. The type of incident would be displayed above the three categories and would initially be automated from the emergency call, but the IC would have the functionality to change it when more information becomes available. The information would be *"ranked according to the type of incident"*. The participants indicated that if the type of incident changed, then the key information in the category box relevant to that type of incident would be made more prominent.

The participants revisited interacting with the interface [P5], participants stated that *"The way he [IC] puts the information into the system needs to be as easy as possible. This is me thinking about interface design, forget about everything else, this is an emergency situation, he needs to be able to put the information in in a second."* The participants highlighted the urgency that the IC would experience of accessing all the information. A number of input devices were considered including keyboard (touchscreen and physical), voice and pen. The group settled for a physical keyboard, which would attach to a tablet and would have touch screen functionality. The participants felt that the physical keyboard would allow the IC to easily search for information on the device [P15] and fit in to the IC's current process of using a flipchart when attending an emergency.

The group discussed how the other firemen could support the IC [P11] by considering the use of the firefighter's personal mobile phones as a method of taking pictures and reporting back to the IC [P12]. The participants stated that the firefighters could have an application on their phone, which connects to the system. For example, a firefighter could take a picture of the number plate and use image recognition to bring up the blueprints of the car. However, participants were keen not to over-complicate the process by introducing too much technology. Participants stated *"when you take on technology so much, it over complicates things. If there is an existing system already a walk-talkie and it's going to take you two seconds to say BMW, rather than take a picture, go to the app and send it*

and then find out that the Bluetooth or the Wi-Fi isn't working" this concept refers to P15, complexity creep.

The participants then investigated in detail the information needed for the interfaces, figure 7.1. For the "People" button, the first level of the system would display estimated number of people in the area, the number found and the system would also identify the number of people that need to be found. The level would provide details regarding the number of available ambulances using GPS data from each ambulance. The IC would also have the functionality to see how many ambulances are available at the site, their capacity, etc. Once clicking this button the second level will present detailed information regarding the number of people involved in the incident, whether they are trapped in the car or in the house.

If the IC clicks on the "Objects" button, the second level would contain information about the objects involved in the incident, for example, the car(s), the properties, and any other physical item. When clicking through to the objects second level, this would allow the IC to search the database using the vehicle's serial number, model/make or number plate, which would then present a blueprint of that car and details regarding how to safely dismantle the car (third level). The IC will also be able to search for further property details through a search functionality. Information about the objects will also include the risks involved and information from past assessments on the property.

When clicking on the "Environment" button, this would show a more holistic view of the incident environment on a map. The IC would be able to see the property in question and also the surrounding properties. The detail would highlight hazards surrounding the property, the water sources including the quantity available and potential space for parking the appliances. This interface would also display current weather conditions (i.e. wind speed), the type of fire, the way the fire is moving and the colour of the fire. Participants used principle 2 and 8 to project how the first could spread and progress with type.

Group Two: Expert Researchers

Figure 7.2 presents group two's paper prototype.

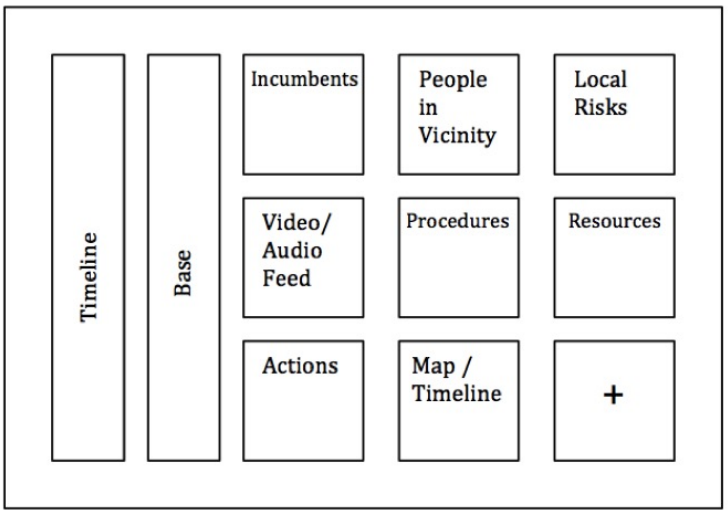


FIGURE 7.2: Group Two's Paper Prototype

Like group one, group two began the task by discussing the hardware of the system. The participants explored the use of two devices, a large display mounted on the side of the fire engine replacing the current flipchart and a personal tablet for the IC. The *"bumpy"* environment in the fire engine led the group to discuss fixing the device in the engine, which then could be demobilised at the emergency [P5]. The participants outlined that the IC would be able carry out the actions [P10] on his own tablet as he would be the main decision-maker with the support of the second in command [P12]. It was also stated that the system is *"for an expert"* [P4]. The IC would share information on the large display with the other firemen [P11 & P12] whilst the firemen would relay information at the emergency back to the IC, which would then be used to inform decision-making.

A participant stated that *"if time is of essence then you're not going to have time to set up the main display and have everyone gather around"* [P6] which made their first hardware option impractical. The second hardware solution discussed was a head mounted display but this too was deemed impractical and the participants felt it would be better for sending information [P4]. Another idea that was also rejected was the use of the fire engine's windscreen as a projector, similar to a head up display, which projects all the information. However, the participants felt this would not be compatible with all weather conditions. The participants decided to use a tablet and stated that it needed to be at least A4 size as *"it [device] needs to be big enough to work with one or more people at the same time, it needs to be visible in all circumstances."*

The group then explored how the IC would prepare himself when travelling to the incident in the fire engine by analysing the IC's tasks and priorities [P1]. The participants used the

task analysis and identified that the first source of information would be the emergency call information. This led to the group identifying that the IC needs to make two decisions; what to do when arriving at the incident and how to stabilise the incident so that he has time to make more decisions [P1 & P3]. The group identified that the IC would investigate the local risks of the emergency and would have a number of questions that needed answering to support the decision-making process: *"Where they need to park? Where are the closest hydrants? Are there any local resource issues? What are the operating procedures to cut in to the vehicle? Where are the casualties? What injuries do they have?"*

This led the group to think about what the IC needs to know *"is this a typical or novel fire and then what are the risks?"* [P2]. The group outlined that if the fire was typical and known then they would present the typical risks and information [P7]. However, this point was debated as some participants felt that as designers they had to be careful of the *"decision tree"* that they sent the IC down. If the group sent the IC down a particular path, this could lead the IC to not explore other information and consequently miss important information [P10 & P15]. A participant stated *"so it's not a case of having two paths, there's got to be roads that cross over."* Therefore the design should allow the IC to cross back to novel situations even if a typical situation was first identified. The participants discussed how the IC would interact with the information, a participant mentioned *"for him [IC] to be, instead of going down a path, he's the centre of it, he's drawing information in to him rather than him going down these hypothetical paths... so we need a screen where he can pull information into him."*

A participant highlighted that the current scenario overlapped with medical emergency care *"where they have decision aids which currently tend to be branched, yes/no type decision aids"*. The participant went on to explain that the medical emergency domain requires *"rapid response... and actually at first you get sketchy information, then you get more information, and then you get the patient coming in on the bed and then you do a load more. So actually that incremental information builds up and that's exactly what we have got here"*. *"You source information and the picture gets bigger and bigger and bigger and at each stage you have to work with what you have got, you can't just wait..."* The participant felt that their system was especially linked to typical and novel situations [P2] as the medical domain uses decision trees.

The participants analysed the quantity of information the IC would receive and the associated uncertainty of the information itself. The participants stated that *"it's not just about understanding what you know, it's also about understanding what you don't know"*. The participants highlighted that the IC would get a *"trickle"* of information. Another participant stated that when in the fire engine *"it [information] gets wider and wider, kind*

of narrows when he gets more concrete stuff when he gets there, so there is more certainty and there's more uncertainty if he is talking to witnesses in the area, so that goes out again so it's about narrowing it down. So at each point you are confirming things that may be probable but not certain and then going through to make the decisions". The participants were trying to develop an understanding of the amount of information required, but also the timing of the different aspects of information. The participants discussed the initial process, step by step from when the IC first hears the bell ring in the fire station, to the moment the IC gets into the fire engine, in order to understand the length of time the IC has and what is needed to be done in the short time before getting into the fire engine. This highlighted that the IC needs to make some decisions even before getting into the fire engine based on the call and local environment regarding the extra resources that they may need such as extra pumps and other equipment.

Understanding the IC's priorities, tasks and flow of information, allowed the group to identify the information that needs to be displayed on the interface and at what point in the emergency. A participant stated *"Could you have a load of boxes on the screen and each of them has a category? For example, local risks. So the structure of what he needs is already on the screen and what he's doing is dropping things in as the information becomes available"*. The participants are supporting the IC's situation awareness, diagnosing the situation and thinking about how the IC is interacting with the system [P1 and P5]. The group stated that the layout needed to fit all types of incidents [P1], be consistent and allow the IC to go anywhere in the system from the desktop.

Based on the requirement that the IC needs to easily identify the missing information that he does not have regarding the emergency, the participants wanted to support his situation awareness [P10] by highlighting the missing information and the confidence the IC would have in the information. When designing the interface, a participant stated *"so he is not only gathering information but you can see what information he's got and what he hasn't got."* [P3]. This led participants to develop a colour coding for the category boxes to identify the information that the IC has and where the emergency falls in terms of its criticality [P3]. Empty boxes were distinguished by the colour red, boxes with incomplete information were amber and complete information were green boxes. A participant stated *"that there might be boxes that need to prompt him [IC] to check if there is new information"*. A participant referred back to his experience with ATC and mentioned that *"when something becomes a risk, everything goes red and starts flashing"* which takes your attention to the item. The participants stated that their system would do the same if there was a change in the system and the IC needed to be made aware of it.

The participants used their understanding of the IC's environment [P5] flow of information to design different interfaces for different stages of the emergency. One participant said *"there might be slightly different interfaces for on the way there to when you get there. So on the way there he's only going to have limited resources and he's going to be chucked around, so he wants big icons which are easy, he doesn't want tiny precise finger movements."* The participant went onto say *"When he gets there, there's going to be more bits of information that he couldn't have gotten until he got there, so there are going to be new boxes appear and hopefully he's going to have more precise ways of manipulating that information because he won't be bouncing around in the back of the vehicle."* The participants also stated *"There's going to be information that he can readily get that's available. There might be another interface which is to ask for more information from command or HQ. So the IC can ask for information about specific uncertainties."* Thus allowing the IC to further understand the uncertainties he has [P3].

Similar to classifying emergencies as typical or novel, participants felt there was a risk regarding automatically generating information to support the IC's situation awareness (SA) and diagnosis of the situation. Several comments were made *"I think there's a risk, you have to feed the information to him, you can't have it automatically populating to him because he might not necessarily be aware of it"*, *"he needs to build up his situation awareness he can't just have it on the computer that he hasn't processed it."* *"Photocopying isn't learning."* The participants wanted to actively support the IC to build up his situation awareness rather than just presenting the information to the IC as it was felt that the IC may not understand what is being presented to them.

Group two considered the possibility of making suggestions for the procedures and courses of actions [P7]. A participant said *"he's [IC] the one who ultimately makes the final decision but the computer could recommend taking into consideration all the factors."* A participant stated that the system should recommend *"... with all the evidence gathered, this is all the evidence that you've put in and this may be the suggestion"* [P7]. Participants made the distinction that *"We are trying to help him [IC] make a decision rather than the computer make the decision"* [P1]. The participants discussed the example of Amazon making suggestions to customers and considered whether the IC's system could to do the same for particular procedures in their system [P7]. Referring to the Amazon example, a participant stated that the user would review the suggestions to see if they were relevant. The participants decided that the system would suggest the information that should be explored, but the IC would determine whether he wants to view the information.

However, the participants stated that this too could lead the IC down *"specific paths"* and would *"switch his brain off"* [P15]. A participant drew on his experience of incident

command, where solving an emergency incorrectly was usually attributed to the operator assuming the kind of incident, resulting in the operator not investigating other information. The participant stated that the systems need to provide feedback to the IC, *"we need to ensure that he [IC] is actively processing information before he gets any suggestions."* [P10]. The participants decided that sending the IC down a specific path would be acceptable for *"cut and dry decisions"* [P10]. But *"the system needs to tell him [IC] why it has made that decision, it can't hide that information from him."*

Participants stated that the IC needs a system that he can fall back on if the system does not work correctly. The participants suggested that spare tablets and flipcharts should be kept in the fire engine. A participant stated that *"if the system has to degrade, it needs to degrade gracefully"*. Therefore the IC can continue his activities in the same way, but by using the backup systems. Another example given was if the instructions that go into a helmet display do not work correctly, then the IC can use the radio to send instructions. The participants stated that the system needs to inform the IC if something goes wrong in the system.

A participant stated that the IC *"needs all the information at hand if he needs it, but does not want to see it all in one go as it would be overload"* [P14]. Based on this notion the participants designed the overall interface to display category boxes, which display a summary of information in the form of a button, see figure 2. The IC can click this button for more information about the category. Nine categories were identified; incumbents, people in vicinity, local risks, video & audio feed, procedures, resources, actions, map/timeline and other (indicated by a plus sign). The IC will be given the current status of the content, its reliability and completeness. The group identified that the first three sections (incumbents, people in vicinity and local risks) would be more prominent before attending the incident as this was deemed as the key information the IC needed to gain an understanding of. Incumbents are the individuals involved in the incident. People in the vicinity are the other individuals that could be impacted by the emergency and the local risks are the risks in the environment.

The other six would become more prominent upon arriving at the incident. The Video & Audio feed section would allow other firefighters to send videos, images and audio back to the IC. The IC would receive informational updates such as images from the other firefighters to update the IC's situation awareness.

The Procedures section would be an information bank of information about key objects such as the procedures to safely handle chemicals and dismantle cars.

The Actions section would allow the IC to allocate specific actions to each member of the team. This theme was designed to allow the IC to delegate out tasks to the rest of

the team. The Resource section allows the IC to see what resources are available to the F&RS.

The Team section, was created on the left hand side of the interface to feed back the status of each member in the team, showing what each member is doing [P11 and P12]. The Base section was designed to represent the two-way communication with the control room IC and the headquarters [P12]. This section would allow the IC to request information or help from the headquarters, whilst the headquarters would have an overview of the IC's system.

The Map section displays geographical information focusing on the location of the incident and overlaying information such as the people involved, the water sources, the risk assessment of the building and the firefighters' movement [P8]. The IC will have the ability to manipulate the information (filter, zoom and pan). P8 influenced the development of the map, timeline and video & audio boxes. So if the IC gives a firefighter an action to complete, the IC could indicate how long it should take and consequently help the IC to see if things have worked or not. The timings for the actions will allow the IC to be able to evaluate how well the actions are completed.

To support the temporal nature of an incident, the group designed a timeline to show what has historically happened, what is presently happening and any projected incidents, for example, if there is the possibility of a floor collapsing or a gas cylinder exploding. Information about the gas cylinder, such as the maximum temperature the cylinder was designed to survive, could indicate to the IC how long they have to evacuate the building. The group considered if there was a trapped victim, and whether the IC would want to know when the victim was trapped, as if they are losing blood supply to a limb you have to free them quickly. The participants wanted to use a time stamp so that the IC had a log of the order of things that had happened in the emergency. Whilst the inputted information will have time stamps on the timeline, the IC will be able to hide and filter these if he needs to.

The participants designed an Other button, without any information allocated to it. This is *"space"* where the IC can drop and drag specific information that might be of interest into the button, allowing the IC to build up his own situation awareness and develop his own picture of the unfolding incident. The group wanted operators not to become reliant on the technology nor complacent when exploring and building up their picture of the incident. A participant said this box was to *"expect the unexpected"*, for example the IC might need to know *"that a football match is going to be down the street and you are going to have a hundred thousand people walk through the street."* This area was designed to support the IC to build his own situation awareness.

7.3.4.2 Activity Two: Eliciting Useful Principles

Activity Two asked the groups to annotate the prototype that they created to indicate which principles had influenced each part of the system design, table 7.3.

Results show that the majority of the principles were used and discussed. Group One identified that they did not use principles 7, 8 and 13, but stated that they touched on parts of principles 7 and 8. Group two indicated that only principle 9 had not been included in the system design. Whilst the group had discussed principle 9 in great detail, they felt that the operator should not be given this functionality.

Group One	**Original Design Principles**	**Group Two**
The IC's goal is to search for objects, people and location. Information was categorised and organised around this goal.	P1. Organise Information around Points	The IC's goal is to gather all information, understand the unknowns and diagnose the risks whilst ensuring the safety of the crew and the people involved. The principle informed the overall layout of the interfaces, particularly the category boxes and summary of information to support the IC's priorities.
The system supports the IC to recognise cues associated to the type of incident and projection of the incident in the environment box. It informed the important information for each category.	P2. Design for Emergency Identification	The category boxes were designed to support situation recognition by providing cues for new or critical items, or to highlight anomalies through system alerts (i.e. colour, flashing and audio). The map also supports the IC's SA.
The principle influenced the design of the first level of the interface, the homepage, to understand the type of emergency and the key things that will be affected by it.	P3. Design to Determine and Analyse the Emergency	The timeline and map were developed to support the IC to determine and analyse the emergency, supporting discussion regarding the emergency call, risks, incumbents, plus button and the reliability and completeness of the information.
The IC is at the centre of the system design but the other operators that interact with decision-maker were also considered. The group considered how the decision-makers set up and consequently how the other operators work with the IC.	P4. Single or Multiple Decision-Maker(s)	The hierarchical structure of the IC, second in command, team, firefighters and people back at base. So the firefighters might make local decisions about where to spray the water but ultimately it is down to the IC how they are going to tackle the fire.
This principle influenced how the operator would interact with the device.	P5. Operator's Environment	This principle affected the entire system and hardware. Based on this principle a tablet was designed which would be locked in the fire engine. The participants discussed the environment in the fire engine, at the scene which affected the design of the interface and the interaction method.

It was felt this principle was used a lot to influence the summaries on the first level. It was also used to influence the key information in the individual categories, information presentation on the map and influenced how the information should be presented on the system.	P6. Time to Absorb Information	The information was prioritised by displaying the most important at the top of the interface. The layout would be consistent and allow the IC to see all the information in one glance, both for the welcome screen and on the map button. In the category boxes, the information was summarised for ease of understanding.
The system identifies how to cut into the car, water sources, and potential hazards, but the system does not tell you exactly what to do.	P7. Support the identification of a course of action	The participants did consider this principle but felt that the IC should not be led down a particular route.
The map helps the user to visualise all the collected information on the map, but it was felt that perhaps this principle was not used as much as the others.	P8. Mental Simulation	This principle influenced the development of the map, timeline and video & audio boxes. The resources button was included to show the blue prints of the cars and access to all databases, which support simulation in the map feature.
This was represented in the real-time information regarding the fatalities, which indicates the number of people that need to be rescued.	P9. Confirm success of the course of action	The participants did not want the system to make the decision – so they didn't consider this for the system.
Influenced all three SA levels; individual items, details within the scenario and the environment section which allows the IC to build a holistic view and tries to predict how the fire could behave. Participants stated that they disregarded a lot of information to highlight the most information.	P10. Support for Individual Situation Awareness	The whole concept was about building up the picture of the emergency to inform the design. This principle linked to principle 2 and they designed the map and timeline to give the IC SA. The participants indicated that projection of the emergency could be seen through the timeline, time stamping, etc.
Influenced the discussion regarding how the operators interact with the IC, i.e. via pictures or walkie-talkies.	P11. Team Situation Awareness	This influenced sharing information with different displays, the design of the video & audio, base, team, maps and timeline buttons.

Similar to P11.	12. Communication	This principle was used to understand the team communication in a number of ways including through walkie-talkies and influenced the design of the video & audio feed and the design of the displays, team button.
Not considered.	13. Verbalisation	It was indicated that the IC would verbalise everything with the second in command and that the timeline would slow down the IC's thinking process.
The system supports workload by collecting information and keeping track of how the emergency is evolving. Also, the system categorises the information and the method of interaction was designed to reduce the IC's workload.	14. Workload	Workload would be reduced by the summary on the welcome page and by bringing immediate attention to the important things in the system through alerts.
This principle was used to generate the type of incident, calculating ambulances and automation in the map. Complexity creep was also considered.	15. Automation	The information from the emergency call, procedures and the timeline are automatically generated. Participants discussed out of loop syndrome.
Crosschecking of the type of incident	16. Monitoring and Crosschecking	This influenced procedures, timeline and video.

Table 7.17: Activity Two Results

7.3.4.3 Activity Three: Ordering and Grouping Principles

Activity Three asked the groups to order the principles according to how useful they felt they were and grouped them into themes, figure 7.3.

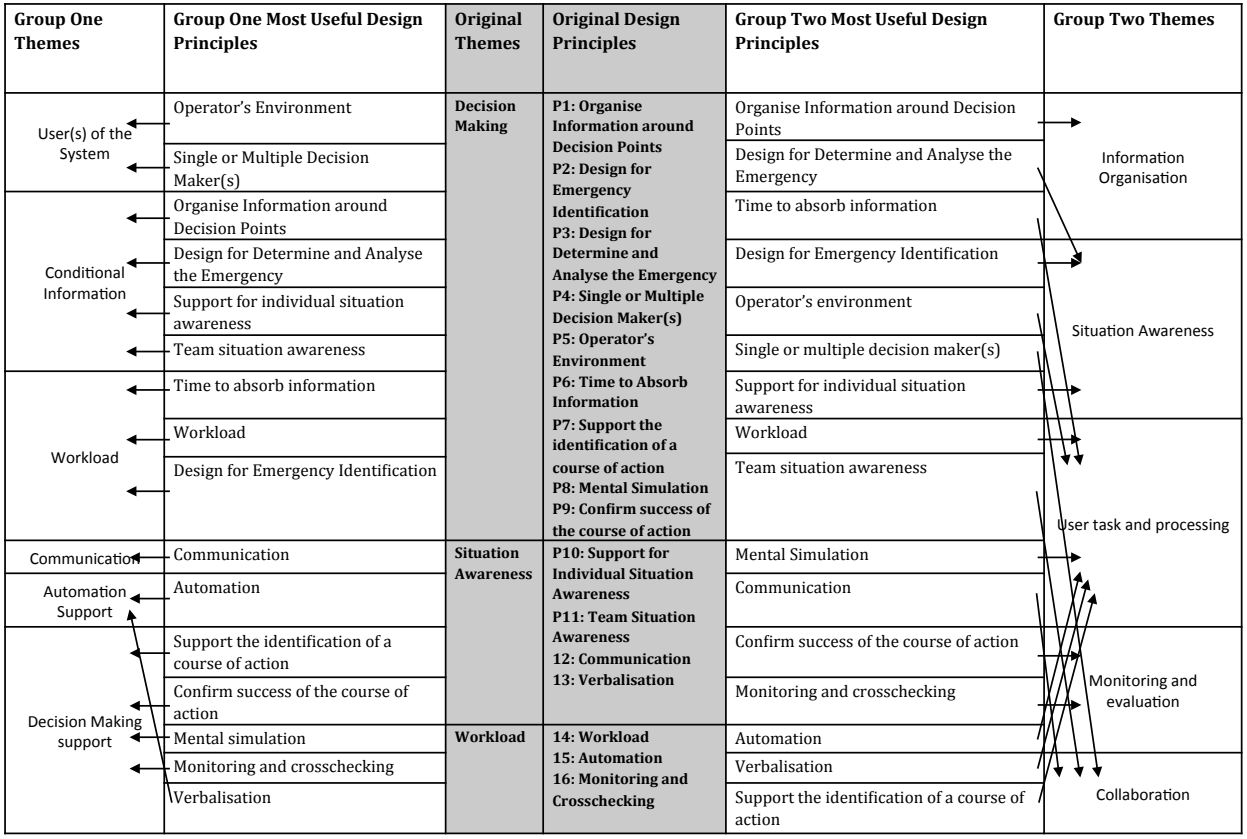


FIGURE 7.3: Activity Three Results

The centre of the table shows the original themes and design principles which were presented to the participants. The columns on either side of the original themes and principles shows each groups order of most useful design principles, based on table 7.17. As the groups were asked to order the principles from most useful through to least useful, the top rows show the most useful principles through to least useful at the bottom of the table. The outside columns show the themes that the HF experts identified. Group One identified six themes and Group Two identified five themes. The arrows in the table show how the sixteen principles were divided into each theme.

7.3.4.4 Activity Four: Focus Groups

This section outlines the outcomes from Activity Four. A focus group was carried out at the end of the workshop to gauge the groups' comments regarding the use of the design principles.

The discussion began with participants considering the most useful points that influenced the design of the prototype. Group one highlighted that time constraints, the variation in the types of incidents that the IC attends and the temporal nature of change within the emergency, is key in shaping the initial design of the prototype. The participants' felt that these points needed to be emphasised in the Operator's Environment Principle and should be introduced at the beginning of the principles. Group two outlined that the operator's clothing (personal protective equipment), when attending an emergency and how the IC interacts with the system was key to influencing the design of the prototype. The group felt that this would influence not only the way the software is designed, but it would also influence the design of the hardware. The group also stated the designer needed to think about *"what equipment operators currently use and how this equipment may affect the use of the new system?"* Group two were also concerned that the new device needs to fit into the existing system of how the operator resolves the emergency.

The participants outlined the following amendments to the design principles:

- **Data Collection:** Both groups indicated that the designer needs to consider how the decision-maker collects information to get a holistic view of the whole situation. The groups also consider how the information is stored and then disseminated to the team, for example the IC collects information on a flip-chart.
- **Extending Communication:** Group one highlighted that the Communication principle should be extended to include all types of communication in the situation, for example, between operator and system, system to system and operator to operator. The group felt this would give the operator an understanding of what is

happening and consequently help them with decision-making and the dissemination of information in the system. Participants also suggested that communication and verbalisation should be merged. Group two also highlighted that under communication they wanted two-way communication in the principles. This is where not only the decision-maker communicates to the team, but the members of the team report back to the decision-maker. For example, the team may be providing the decision-maker with more information about how the incident is unfolding. The participants also stated that the guidance should provide the designer with prompts to consider how the IC would attempt to monitor the rest of the team.

- **Training:** Group one indicated that the documentation does not highlight how much training is required to use the system. In some contexts, for example, in the F&RS the operators have limited time to train to use a system, whereas, in the aviation industry pilots spend considerable hours training for the system. This difference could influence the way the system is designed and how the information is presented to the operator.

- **Extending Automation:** Group one highlighted that automation could be presented as a solution to the "problems" the decision-maker may have, further supporting decision-making.

- **Checklists:** Group one felt that the design principles should include a shorter list of the design principles in the form of a checklist. Participants felt that the checklist should be presented after the full definitions of the principles so that the designer first reads the definitions and then uses the checklist to work through them systematically. Participants also felt that the questions under "consider the following" should be included for each design principle in the checklist. The participants stated that after the first read of the principles they only referred to the main body of the text for each principle if they were unsure about a meaning of a principle/or associated question.

  Group one felt that the titles of the principles needed to be short and easy for the designer to remember. For example, the "single or multiple decision-maker(s)" title should simply be called "decision-maker". The participants wanted to be able to say "Communication done, operator's environment done, etc." and easily find the principle that they had not yet thought about for the design of the system.

- **Supporting Evidence:** Group one felt that the definition for each principle was important in order to ensure that each designer would interpret them in the same way. They felt that it could be important to highlight why the design principle is important. The group suggested that each design principle could start with a case study, followed by examples. Group two also wanted more theoretical background

information about the principle, the participants wanted information about how the principle was developed and also wanted to know the evidence that informed the development of the principle. The participants felt more examples for each of the principles would be beneficial for the designer as it would indicate how much weight to place on each principle when designing the prototype.

The following new principles were highlighted by the groups during the focus group:

- **System Goals:** Group one indicated that the design principles did not include a principle which investigates the goals of the system. The group stated that the designer should consider "what are the goals of the system?" and should be prompted with investigative questions such as: "How should the system support the operator?", "What does the system need to achieve?", "Which goals should be determined for the system?", "What is out of scope for the system?" and "What is the extent of the system?" Participants felt that this would lead to investigating the available datasets that are available to the operator, and how these can be incorporated into the prototype system.

- **Hardware:** Group two stated that the designer needs to consider "how the operators physically use the system", prompting the designer to investigate the physical hardware of the system. The participants outlined the following questions: "What will the hardware of the device look like?", "How will the operator use the device?" and "Will the device need to be used in special conditions?" For example, in heat, noisy areas, bumpy roads, next to an accident, etc. The participants felt that the designer needs to consider how the operator will interact and input information into the device. This might be influenced by what they are wearing, what the environment is like, for example turbulence might affect the way pilots input information into the system and in the fire and rescue service, the operators wear personal protective equipment, which would make touch screen interaction difficult.

- **Third Party:** The participants also wanted the designer to consider third parties and/or systems in the emergency that the decision-maker did not have any control over. For example, the participants referred to the ambulance service which would also attend an emergency in the F&RS scenario. Group Two also indicated that the designer may need to consider that the system may be used in conjunction with other third parties who are involved in resolving the emergency and the designer may need to consider "how information needed to be shared".

- **Debrief:** Group two stated that the principles did not explore how the operator would deal with an incident after it had been solved, the participants outlined that a principle was needed to consider the debriefing that would occur after the incident

has been resolved. For example, the group thought the following questions would support the designer: "How can the system support the operator at the end of the emergency?" and "How can the system support debriefing of the incident?"

- **Information Representation:** The designer needs to consider how and when the operator will receive information at the emergency. For example, the IC would have limited information at the beginning and more information when arriving at the incident. A principle that advises the designer regarding information could be included into the guidance, supporting questions could include:
  - How and when the decision-maker will receive information?
  - What information will the decision-maker get at different points in the emergency?
  - How will the decision-maker collect and store information?
  - How will the decision-maker identify the missing and uncertain information?
  - How will the decision-maker narrow down information?
  - How would new information be made aware to the decision-maker? How would new information be represented?
  - What information is currently available?
  - What information is needed to support decisions?
  - Does the information need to be presented in different levels?

Both groups indicated that principles were useful for not only the F&RS but cited the following domains; emergency services, military, nuclear, traffic control, automotive, search & rescue robots and medical & healthcare. Group one indicated that it was applicable for all performance oriented systems, whilst Group two stated that the principles could be applied to domains where there are time constraints and the operator does not have the time to exhaustively go through the information, requiring all the information quickly and in one place. A participant gave the example of a lab she had worked in, where they had to deal with active ingredients and if something went wrong they needed to quickly test the ingredients, understand what was happening and resolve the issue.

7.4 Discussion

The results show that the HF experts could use and understand the principles by using the definitions, case studies and prompts to design a system for emergency situations. Activity one and two showed how the principles were used in the design of the system. From observations the guidance was used in a variety of ways, some participants skimmed the document to find the topics that they wanted to discuss, other participants had a topic in mind and searched the guidance for associated questions and others used it like a checklist. The HF experts first understood the domain and then using this understanding designed the system to support the IC. Analysis shows that participants discussed multiple principles in quick succession at the beginning of the workshop, whereas once the participants had an understanding of the domain, they spent more time discussing specific aspects of the principles, going in to greater detail. The participants also revisited certain principles several times to support the design.

Content validity was the first measure which investigated if the guidance was complete and measured all the relevant parts of the concept it claims. Based on activity three, both groups indicated that the following principles P1, P3 - P6 and P10 were the most useful for developing the prototype. Both groups started activity one by thinking about the hardware of the system, however, once they realised that they needed to understand the domain, the participants began building their understanding using principles such as P1 – P4. The designers not only built up an understanding of the domain they were designing for, but also an understanding of the IC's decisions. Once the participants had this understanding they were then able to consider how to design the hardware and present the information.

The principles need to support the designer to start the design process by thinking about the domain, the environment, the importance of lack of time, the tasks and priorities when beginning to design the system and then present the design making principles about the decisions. Emphasis is needed to highlight the variety of different incidents that the operator may attend to and questioning if the system needs to support all the different types of emergencies.

To understand the IC's decisions, both groups used the task analysis of the decision points and made a list of the questions that the decision-maker would be asking. The principles need to include prompts to get the designer to think about these questions, particularly the different decisions that need to be made at different points and what information needs to be given to support this decision-making process. Participants stated that the designer needs to be careful of the decision path the system sends the operator down and

if they are sent down a typical decision path, then the operator should be able to get back to novel situations. This gives the operator flexibility as the situation evolves in the emergency.

Activity four highlighted the changes needed to better support the designer through the design process, including new principles and extending the principles presented. Additional layout comments were stated including checklists, shorter titles and a further supporting evidence. A new draft of the principles will be developed to incorporate the participants' comments. These are presented in chapter 8.

7.5 Chapter Summary

The chapter presents a synthesis of the findings from the previous chapters in the form of an initial set of design principles and identifies three questions to further investigate and develop them. The principles were evaluated to investigate if the principles were usable, understandable and complete, as well as identifying domains they could be applied to. This chapter contributes to aim three which seeks to further develop the design principles. Through four activities, HF experts were given the opportunity to use and apply the design principles to create a paper prototype for the fire and rescue service. The participants then critiqued the principles and provided constructive feedback. The study showed that the principles are usable and understandable for creating NDM systems as HF experts were able to use them to design a F&RS system. A number of amendments have been highlighted which will be integrated into the next version of the design principles presented in chapter 8. We recognise that these principles have only been applied to one domain and further research needs to be carried out investigating the use of the principles in other domains.

Chapter 8

Cognition Informed System Design

8.1 Chapter Overview

Chapter 8 presents a new method called Cognition Informed System Design (CISD), which consists of 22 design principles to support designers creating systems for real-world decision-making, these are developed from the design principles presented in chapter 7. The principles are based on the findings from investigating Naturalistic Decision-Making (NDM) and the human factors issues in NDM environments. This chapter contributes to aim three, developing guidance to support NDM system designers.

8.2 Introduction

The Naturalistic Decision-Making (NDM) field understands and improves decision-making in real-world contexts that are meaningful and familiar to the operator. In particular, NDM seeks to understand how operators manage complex tasks and environments, examining the context of the situation and where they are found. Zsambok and Klein (2009) provide a formal definition:

> "The study of NDM asks how experienced people, working as individuals or groups in dynamic, uncertain, and fast-paced environments, identify and assess their situation, make decisions and take actions whose consequences are meaningful to them and to the larger organisation in which they operate" (Zsambok and Klein, 2009)

The NDM environment has been studied in a number of domains including the emergency services (Klein, 1999, 1989), military (Hutchins et al., 1996), aviation (Orasanu and Martin, 1998), healthcare (Lighthall and Vazquez-Guillamet, 2015) and nuclear (Gualtieri et al., 2012).

A key claim of NDM is that decision-makers do not generate alternative options, compare them, nor develop probability and utility estimates for different courses of actions (CoA) or generate decision trees (Klein et al., 2008). Klein and Klinger (1991) further support this, and state their research also shows that operators make effective decisions without performing analyses. Randel et al. (1996) found that experts base their decisions on the nature of the situation using their expertise; they have a large repertoire of past experiences to inform the current situation. The operators are acting and reacting on the basis of prior experience (Klein and Klinger, 1991). The decision-maker spends little effort in deciding how to react to a situation, once they have understood the situation; the reaction is often obvious.

In NDM it has been suggested that you not only have to look at the NDM process, but also consider additional factors that impact the decision-making process when designing for real-world environments (Lipshitz et al., 2001). This research has identified seven human factors issues that need to be supported when designing for NDM settings; situation awareness, mental models, workload, human error, uncertainty, team and communication. The way in which the system and information is presented to the operator greatly influences real-world decision-making, the decision-making process and human factors issues were studied. Based on real-world case studies, 22 principles were identified to form Cognition Informed System Design. The goal of the principles is to provide a practical method to support designers creating systems for real-world decision-making. The principles consist of three parts; a description, illustrative examples and points to consider when designing. The principles do not provide a step-by-step guide, rather they should be used as guidance when designing for NDM settings. Applying this approach in the design process will provide better outcomes for decision-making in real-world contexts.

Figure 2.6, provides an overview of the typical steps when resolving an emergency and the factors that need to be supported when making decisions.

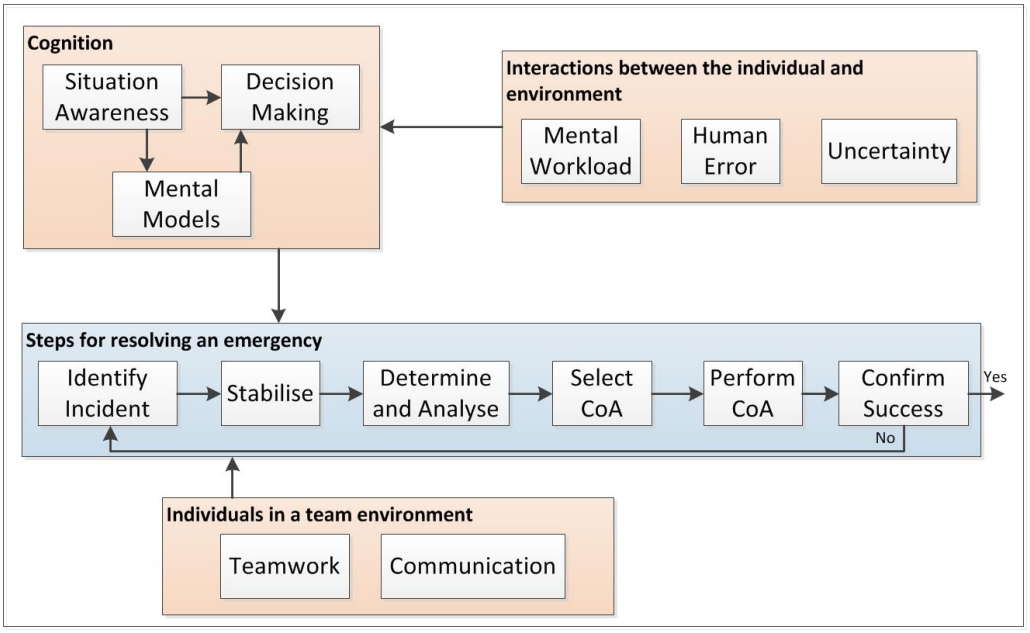


FIGURE 8.1: Overview of Cognition Informed System Design

At the centre of figure 8.1, the steps of resolving an emergency are presented and outlines the relationship of the human factors issues. These steps are based on the RPD model but also include the two additional steps identified in chapters 4 and 5. Typically, steps to resolve an incident include:

- **Identify an emergency:** the operator is alerted to an incident.
- **Stabilise situation:** the operator stabilises the incident, which would give the operator time to understand the situation, liaise with operators and make a decision.
- **Determine and analyse the problem:** the pilot identifies the problem, often trying to understand the root cause, the severity and the criticality of the problem. This allows the pilot to understand and determine what needs to be done.
- **Identify and perform course of action to address emergency:** the operator identifies the course of action and carries out the necessary steps.
- **Confirmation of success of the course of action and monitor incident:** The operator will confirm that the course of action has resolved the incident and continue to monitor activities.

If the outcomes are successful, usually there are limited actions that need to be completed. However, in the event that it has not been successful, the diagram loops back to the problem being detected. The seven human factors issues in the diagram are split into three groups; cognition, interactions between the individual and environment, and individuals

in a team environment. Decision-making is presented within the cognition group. The Cognition Informed System Design principles centre on both the steps to resolve a NDM incident and the HF issues that support the naturalistic decision-making process.

8.3 Cognition Informed System Design Principles

The following 22 principles consist of descriptions, illustrative examples and points to consider when designing for real-world decision-making. It is suggested that the designer should use the design principles as a complementary support in combination with other methods when investigating the domain they are going to design for. This will give the designer an understanding of the key human factors issues to consider when examining the naturalistic decision-making in a domain. Once the designer has an understanding of the decision-making environment and when ready to select requirements and design features, the designer should refer back to the design principles to ensure that each principle has been considered. At this point it is suggested that the designer refers to the checklist and the "points to consider" at the end of each principle.

8.3.1 Domain

8.3.1.1 Principle 1: Environment

The operator's environment is usually complex and challenging. Orasanu and Connolly (1993a) highlights that NDM environments can be challenging for the following reasons:

- **Ill-structured problems** – The decision-maker must generate hypotheses about what is happening and establish options that are an appropriate response. The decision-maker is required to relate observable features of the setting to one another by complex causal links, interactions between causes, feedback loops, etc.
- **Uncertain, dynamic environments** – The NDM environment is a dynamic and continually changing environment (Randel et al., 1996). Information in NDM domains is typically incomplete and imperfect; information that is available may be ambiguous or of poor quality.
- **Shifting, ill-defined or competing goals** – The decision-maker may be motivated by multiple goals, some of which may be unclear or conflicting. As a situation changes, this may lead to a shift in the goals. Over the course of the situation,

various goals and sub-goals may need to be redefined as new information is received, which in turn could impact the priorities of the goals and sub-goals.

- **Action/feedback loops** - In the NDM setting typically, a series of events occur, a string of actions over time that are intended to deal with the problem and/or to find more information about it, or both. When a decision-maker identifies a mistake, they have the opportunity to take corrective actions. The actions and results may only be loosely coupled, which may make it hard to attribute effects to causes.

- **Time constraints** – In NDM settings, decisions are made under significant pressure, where the decision-maker only has minutes and seconds to make each decision. O'Hare (1992) states time criticality is one of the distinguishing features of decision-making in complex and dynamic systems. This has important implications as it can result in high levels of stress (including exhaustion and loss of vigilance) and workload, which could see the decision-maker shifting their thinking to use less complicated reasoning strategies.

- **High stakes** – The outcomes of the decisions could have a significant impact on the participants involved e.g. loss of property, careers, or ultimately life itself.

- **Multiple players** – In the NDM setting, usually several operators will actively work together as a team. This could include one decision-maker and a single subordinate or a whole group of individuals. The multiple players work together towards the goal by sharing information to inform the decision process.

Examples

Aviation: An aircrew experiences an emergency warning mid-flight at 30,000ft. over dangerous terrain. The situation would be more complex and dangerous than an emergency on the ground; where the pilots would have support from other personnel and the flight could be abandon.

F&R Service: When the F&RS is asked to attend a road traffic incident with a trapped passenger, the IC would get key information regarding the incident. This would include location information, type of incident and any details taken during the emergency call. Whilst in the fire engine, the firefighter would usually have between 5-10 minutes to absorb as much information as possible from the their mobile system before arriving at the incident. Viewing and processing this information can be difficult as the fire engine is travelling at high speeds, it's chaotic, bumpy and there are varying amounts of light. In addition, firefighters will usually be wearing personal protective equipment including heavy gloves and visors.

Points to Consider:

- The decision-maker's environment. Investigate what makes the environment complex and challenging, as well as what makes it difficult for the decision-maker to make decisions.
- The observable features of the setting including complex causal links, interactions between causes, feedback loops.
- The information that the operator will need, including the uncertainties that may arise with this information.
- The environment the decision-maker will be in when trying to absorb information. For example, will the operator be in a fire engine that will be travelling at high speeds? Are there alarms going off?
- Variations in the types of incident that the operator attends.
- The decision-maker's goals; identify if the incident can change and consequently alter their goals.
- The time constraints in the environment and the strategies that will be employed by the decision-maker to cope with the time constraints.
- The decision-maker's stake, this could include the number of casualties, damage to environment or property, etc.

Table 8.1 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Section 2.2
Chapter 4: Sections 4.3.3.1 and 4.4
Chapter 5: Table 5.8
Appendix E

TABLE 8.1: Research Evidence: Principle 1

8.3.1.2 Principle 2: Decision-Maker(s) and Team

The users of the system should be identified, highlighting their role as either decision-makers or team members. In the NDM setting, there could be a single decision-maker or multiple decision-makers, this could change how the information is presented and interactions taking place. Multiple decision-makers who collaborate may all need access to the information to make a joint decision.

Examples

Aviation: Two pilot aircrews consist of a pilot in command (PIC) and a co-pilot (CP). The aircrew share the responsibilities of pilot flying and pilot monitoring roles. The pilot flying is typically responsible for controlling the vertical flight path, horizontal flight path and energy management through supervision of the autopilot or by manually flying the aircraft. The pilot monitoring actively monitors the flight parameters, calling out excessive deviations and assisting the pilot flying. The pilot monitoring also manages radio communications, supervisors system configuration, monitors aircraft status, performs actions called by electronic/paper checklists and coordinates with the pilot flying throughout the whole flight. The aircrew is supported by ATC who provide additional information, clearances and deviations.

F&RS: The team consists of an incident commander (IC), second in charge and firefighters, as well as a supervisory officer for larger incidents. The IC is the main decision-maker and responsible for resolving an emergency, with the support of the second in charge who also supports in the decision-making process. Firefighters implement procedures as delegated by the IC and second in charge. The supervisory officer will be deployed to incidents, which are more complex and will monitor the incident to ensure that the emergency is resolved successfully and that the firefighters are following good practices.

Points to Consider:

- Who the decision-makers are and their goals.
- Multiple decision-makers, who work and interact together.
- The types of decisions expected to be made by the decision-maker.
- The support required by the decision-maker to support their decision-making process. For example, from other operators or parties to collect information.
- The team that the decision-maker will need to work with. Identify the role of the team and how the team is expected to support the decision-maker(s).
- The users of the system, this could include only the decision-maker, team or both.

Table 8.2 shows the evidence of where the principle was derived from.

Evidence
Chapter 4: Sections 4.3.3.2 and 4.5.6
Chapter 5: Section 5.2.2

TABLE 8.2: Research Evidence: Principle 2

8.3.1.3 Principle 3: Third Parties

The decision-maker and team may interact and work with third parties during an incident. The third parties are those parties that do not make up the core team and may have their own objectives during the incident. The third parties may work towards the decision-maker's goals, but they may also have their own goals.

Examples

Aviation: A captain in the Spanish air force described a situation where she was flying a Cessna Citation V with a 2 pilot aircrew and 1 passenger who was a photographer. The flight was a simulation task for the military and she had been asked to carry out two missions in the aircraft. First, to simulate a hijacking of the jet aircraft, which was a joint mission with the French air force, and secondly, to take an aerial picture of an aircraft at a particular location (Zaragoza). In this scenario, the PIC had to coordinate with her usual team (CP, ATC and Spanish Airforce) as well as the French Airforce.

F&RS: In the F&RS, as IC described an incident where the F&RS control room were notified by the ambulance service that they needed the support of the F&RS at the scene of a road traffic collision. The IC's first job on the scene was to liaise with the ambulance service and develop an understanding. The F&RS may also work with other third parties including water and environmental agencies.

Points to Consider:

- The third parties the decision-makers may work and liaise with.
- The objectives of the third parties.
- The interaction between decision-maker and the third parties.
- Whether the system will be used by third parties or whether the third parties may need visibility of the information the decision-maker may have.
- Information sharing between all parties.

Table 8.3 shows the evidence of where the principle was derived from.

Evidence
Chapter 4: Sections 4.3.3.2, 4.6 and 4.5.6
Chapter 5: Section 5.2.2
Chapter 7: Section 7.3.4.4

TABLE 8.3: Research Evidence: Principle 3

8.3.2 System

8.3.2.1 Principle 4: System Goals

The goals of the system which is being developed needs to be identified so that the aims of the system are clear and the design can identify how the system will support the decision-makers in the NDM setting.

Examples

Aviation: The pilots use cockpit systems, which include flight instruments and controls to enable them to fly between two locations. The systems goals may be transporting passengers, cargo or carrying out planned missions. In addition, the systems support the aircrew in identifying and resolving non-normal situations in the cockpit.

F&RS: The systems primary goal allows the officer in charge to have a full view of the information that the service has about the incident. The system is a portable information bank, which contains multiple datasets, including best practices, building plans, geographical and building occupancy data.

Points to Consider:

- The goals of the system.
- The purpose and scope of the system.
- The functionality of the system.
- The system support the decision-maker requires in the NDM setting.

Table 8.4 shows the evidence of where the principle was derived from.

Evidence
Chapter 7: Section 7.3.4.4

Table 8.4: Research Evidence: Principle 4

8.3.2.2 Principle 5: Hardware

The method operators will physically use to interact and input information into the system needs to be considered. This may need to be considered alongside other technology currently being used in the environment.

Examples

Aviation: The cockpit systems are a complex set of interfaces that the aircrew has to manage. They consist of technology such as radio equipment, sensors, transponders, etc. Using the systems can be made more difficult in challenging environmental conditions such as turbulence which might affect the way pilots input information into the system. The pilots will usually load the flight path on their iPad and use this as an additional resource.

F&RS: The operators wear personal protective equipment, for example, they wear gloves, helmets and breathing apparatus which could make it difficult to interact with the systems. The firefighters use a number of technologies, including radio communication with each other and control, a board that presents information to the team and risk assessment forms.

Points to Consider:

- The aesthetics of the hardware of the system.
- The interaction and use of the system by the operator.
- Whether the device needs to be used in special conditions. For example, in heat, noisy areas, bumpy roads, next to an accident, etc.
- Other systems and technologies that already exist within the team and identify how the new system will integrate with them.
- The equipment the operator may use to resolve an incident. For example, a firefighter uses a hose to put out a fire, which makes it a wet environment.
- How the decision-maker will interact with the system? Consider input type: touch-screen, buttons, stylus, etc.
- The decision-makers clothing and how this could impact their use of the system. For example, in the F&RS the firefighters wear gloves, which could make it difficult for them to interact with touchscreens.

Table 8.5 shows the evidence of where the principle was derived from.

Evidence
Chapter 7: Section 7.3.4.4

TABLE 8.5: Research Evidence: Principle 5

8.3.3 Cognition

8.3.3.1 Principle 6: Organise Information Around the Operator's Tasks and Decision Points

The recognition primed decision model (Klein, 1993a, 1999), which investigates how individuals effectively make decisions in complex situations (Klein, 1993a, 1999). Recognition primed decision involves non-optimising and non-compensatory strategies, which require minimal conscious deliberation. Recognition primed decisions do not compare options, but instead involve recognition matching which highlights the most likely action (Klein and Klinger, 1991). Klein et al. (1989) highlight that the decision-maker develops a potential course of action, considers the constraints imposed by the situation and selects the first course of action which is not rejected.

There are three main decision points in the recognition primed decision model, which need be considered to support the decision-maker (Klein, 1999):

1. **Situation Recognition:** The decision-maker decides if the situation is typical or novel using critical cues which distinguish the type of situation and casual factors. This explains what is presently happening and what could happen. Based on the above, the decision-maker sets plausible goals and appropriate actions given the goals and expectations. Typical and familiar situations will result in typical actions, which are usually well rehearsed. However, the operator needs support for novel situations, which they have not come across before as they are challenging and unfamiliar.

2. **Serial Option Evaluation:** Evaluates the different course of actions until a valid one is found. Each action is selected from an action queue and arranged according to typicality.

3. **Mental Simulation:** Evaluates if an action is satisfactory, in this phase the decision-maker performs the course of action in his or her imagination; plays out the steps, the potential outcomes and the problems that might occur, and how these problems may be handled.

Information should be organised according to the operator's major tasks and decisions. The system should be organised so that the information needed for a particular goal is co-located and directly answers the major decisions associated with the goal (Endsley and Jones, 2011).

Examples

Aviation: During an emergency, the aircrew's goal is to ensure the safety of the aircraft. The pilots will first investigate the information related to the alerts in the system to determine what is occurring. For example, in the event of an engine failure, the pilots will investigate information related to the engine and fuel, as well as investigating information about the general flying condition of the aircraft. Based on this information, the pilots will make decisions related to which actions need to be performed from memory, which procedures and checklists need to be performed, whether a may day call needs to be made and if an immediate landing is necessary.

F&RS: When an incident commander attends an emergency, he/she will need to understand as much information as possible before arriving on the scene of the incident, and use this to determine what actions may need to be taken immediately. This will help the incident commander understand the decision points which take place on arrival. The incident commander will then need identify the risks, select a course of action, implement the course of action and identify what after care may need to be delivered. This will improve the chance of reaching their goal of safety and reduced destruction of property.

Points to Consider:

- The decision-maker's goals in the emergency situation. For example, is the decision-maker trying to minimise the number of fatalities, reduce the damage to the environment or aviate safely to the closest airfield? Consider the primary goals and secondary goals.
- Prioritise the decision-maker's goals.
- The tasks and decisions that need to be made to achieve the goal(s).
- How will the decision-maker identify an emergency, determine and analyse the problem, stabilise the situation, identify a course of action to address the emergency, implement the selected course of action and confirm success of resolving the emergency? Identify how the system will support these tasks.
- The information that is needed for each goal. For example, is the first decision to stabilise the situation? What information does the decision-maker need to stabilise the situation? By stabilising the situation, the operator may have more time to make further decisions to resolve the emergency.
- The different types of emergencies the decision-maker could attend to. In addition, consider how these could be similar or different.

Table 8.6 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Section 2.2
Chapter 4: Section 4.4
Chapter 5: Section 5.3.4
Appendix E

TABLE 8.6: Research Evidence: Principle 6

8.3.3.2 Principle 7: Design for Emergency Identification

When an emergency occurs, the decision-maker will either be alerted to a problem by using scan patterns to identify that there are anomalies, or alternatively they may be alerted by a system or person. Support needs to be given to the decision-maker's information needs to understand what the emergency is and why it is occurring. If for example, the system is alerting the decision-maker, consider providing information regarding the anomalies in the system, what impact that has on the system and the time available before the emergency progresses.

Examples

Aviation: There are two methods of identifying an emergency in the cockpit. First, pilots can be made aware of an emergency by the alerting system in the cockpit, which also provides specific information regarding the warning. Secondly, the pilots monitor the cockpit systems and crosscheck the two sets of instrumentation in the cockpit.

F&RS: In the F&RS, the IC receives an alarm from the control room. The control room predominately takes emergency calls from the public, recording all the details and passing them onto the IC. The IC receives this information in the form of a tip sheet.

Points to Consider:

- How are decision-makers alerted to the emergency?
- How will the decision-maker identify anomalies in the system?
- If the decision-maker scans the system for anomalies or has he/she been informed by another party?
- The information support required in the initial identification of an emergency.

Table 8.7 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Figure 2.2
Chapter 4: Section 4.4.7 and Figure 4.8
Chapter 5: Section 5.3.4, table 5.8
Appendix E

TABLE 8.7: Research Evidence: Principle 7

8.3.3.3 Principle 8: Individual Situation Awareness

Situation awareness is the foundation for decision-making and performance (Salas and Klein, 2001). In order to match situations, the decision-maker must have an understanding of what is going on. Situation awareness is developed through the situation assessment process in the recognition primed decision model. Endsley (1988) defines situation awareness as *"the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future"* or simply put *"knowing what is going on."* Situation awareness gives the operator an understanding of what is happening around them and an understanding of what that information could mean in the future. Situation awareness is dynamic in nature and the repetition of the process continuously updates the decision-maker's understanding of the environment (Parasuraman et al., 2008).

Three levels of situation awareness should be supported in the NDM setting (Endsley, 1995b):

Level 1: Highlight the individual values that are relevant to the status, attributes and dynamics of relevant elements in the emergency environment. Highlight the individual pieces of information that are required to gain an understanding of what is happening.

Level 2: Support for the comprehension of the current situation. Perception of the elements in the environment is based on the synthesis of disjointed elements. Comprehension of the current situation includes an understanding of the significance of those elements in light of the operator's goals. The operator will form a holistic picture of the environment based on the Level 1 elements and the patterns that emerge. The operator will get a comprehension of the significance of information and events.

Level 3: Ability to support the projection of future status. The third level looks at the ability to project the future actions of the elements in the environment, at least in the near term. This is achieved through knowledge of the status, the dynamics of the elements and a comprehension of the situation (Both Level 1 and Level 2 situation awareness).

Examples

Aviation: The pilots received and analysed the briefing package, which contains the details of the flight. The PIC focuses on the flight plan, whilst the CP focuses on the constraints in the Notice to Airman (NOTAMS). NOTAMs are a written notification which outline issues before a flight, and any circumstances that relate to the state of the flying, this typically advises the pilots regarding potential hazards along a flight route or at a particular location.

Pilots also constantly develop individual situation awareness by monitoring the flight deck systems whilst the aircraft is in autopilot to identify any anomalies in the systems. Pilots are looking for data that does not fit "normal behaviour" that they have been trained to expect.

F&R Service: Usually a single firefighter will scan the available information to build up their knowledge regarding the area of the incident, including the type of building that they might be attending, checking for any harmful substances at the location, the closest water sources in the event of a fire, etc.

Points to Consider:

- The appropriate information to support situation awareness as well as presenting it in a manner that supports analysis and projection of future events.
- Endsley et al. (2003) presents types of questions that need to be asked at each situation awareness level:
  - Perception: What information within the environment does the decision-maker need to attend to in order to address critical task decisions?
  - Comprehension: How are the operator's perceptions of system states and the environment related to their goal? What information does the decision-maker need to integrate to understand the state of the system? What do certain pieces of information mean with respect to the decision-maker's capability to execute a method?
  - Projection: Based on the operator's observations of the system states and the environment, and understanding of what this information means to achieving task goals, what projections can the decision-maker make about future states of the system? What projections should the decision-maker make about future states of the system and environment?

- The information on the missing data, data precision, reliability and credibility on possible errors connected with data processing or information transformation.

Table 8.8 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Section 2.3.1.1
Chapter 4: Table 4.1
Chapter 5: Section 5.2.4.3 and Table 5.7

TABLE 8.8: Research Evidence: Principle 8

8.3.3.4 Principle 9: Mental Models

In the NDM setting, as stated in the recognition primed decision model, operators use their experience in the form of a repertoire of patterns (Klein et al., 1989). Expertise constructs the mental models required to find one explanation more plausible than another. Mental models are described as the internal psychological representations of an operator's conceptualisation and understanding of a system (Kieras, 1988, Norman, 1983a). Wickens et al. (1998), further extend the mental models definition as *"internal representations of objects, actions, situations or people. Built on experience and observation and are simulations which are run in mind to produce qualitative inferences in order to underpin our understanding of a system and allow us to describe, predict, and explain behaviour, and to test "what-ifs" and "what wills"".* Moray (1998) describes a mental model as a mapping of the properties of the task to its representation in the mind of the operator. The importance of mental models is that it presents what people have in their heads and how this guides their use of things.

Examples

Aviation: Pilots spend considerable hours training for the system, they thoroughly practise completing procedures for normal and non-normal procedures in the simulator.

F&RS: In the F&RS, the operators have limited time to train to use a system but spend considerable time training for the procedures to resolve different types of incidents.

Points to Consider:

- The operator's mental models and the long-term knowledge they will have (Endsley, 2000b).
- The training the decision-makers and team undertake.

- How does the decision-maker's mental models guide them in making decisions? Consider their experiences, perceptions and understandings of the world.
- The use of mental models to filter and sort new information.
- The decision-maker's mental models impact on their use of the system. How will the operator learn and reason with the system (Willams et al., 1983)? Consider the errors that may occur and support them (Janosky et al., 1986).
- The learnability, functionality and usability of the system (Norman, 1983a).
- The invisible parts and processes of the system, and make these visible to the user, provide feedback, building in consistency and presenting functionality through a familiar metaphor (Mayhew, 1991).

Table 8.9 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Section 2.3.1.2
Chapter 4: Section 4.4 and Table 4.1
Chapter 5: Section 5.2.4.3 and Tables 5.6

TABLE 8.9: Research Evidence: Principle 9

8.3.3.5 Principle 10: Design to Determine and Analyse the Emergency

The operator will need to determine and analyse the emergency by developing an understanding of what is happening at the incident. The decision-maker may try to understand the root of the problem, the severity and criticality of the problem. Identifying the root of the problem, may support the identification of the course of action.

The system should allow the decision-maker to determine if the situation they are attending is typical or novel (Klein, 1999). The decision-maker will identify critical cues that mark the type of situation and causal factors that explain what is happening and what is going to happen. These are needed to support the operator in identifying the goals and then to take an appropriate action. Typical and familiar situations will result in typical actions, which are usually well rehearsed. In these situations, there is perhaps less system support needed. For those who may have not attended that particular type of incident or simply those who might like a reminder of the actions that may be needed, may require greater system support. The operator may need support for novel situations, which they have not come across before as the situation may be challenging and unfamiliar (Klein, 1999).

Examples

Aviation: For a suspected engine failure, the aircrew must analyse the situation to understand what failure has occurred. Often pilots experience false positives of an engine failure, which means there usually is uncertainty regarding whether a failure has actually occurred. The pilots will investigate the information to identify that it is really a failure, for example, investigate information on the engine interfaces and also try to visually see if there is smoke or signs of a fire.

F&RS: When attending a property fire, analysis takes place on arrival, where the incident commander may send the second in charge to identify access points, gas and electric cut off points. The incident commander will investigate hazards, entrances and identifies what the fire looks like at the back of the property. The incident commander will speak with the occupier of the house to get further information and identify the root cause.

Points to Consider:

- How will the decision-maker determine and analyse an emergency?
- The decision-maker's method of data collection. In addition, consider how the information is recorded and presented to the team.
- The dissemination of information to the team.
- The cues the operator is looking for to identify the type of emergency. This could be in the environment, people, systems, etc.
- The casual factors, which explain what is happening and what is going to happen.
- The anomalies in the situation or system.
- Is this a typical or novel problem? If the situation is typical can you provide the operator with checklists, procedures or information on past similar situations?
- The senses the decision-maker will use to diagnose the emergency. For example, visual, auditory, haptic, etc.
- Will the decision-maker test the problem to determine the cause of the emergency? For example, can the decision-maker test the system to see how different the system behaves from normal procedures?
- Give the operator information regarding how long the situation can run safely before the emergency progresses.
- Identification of false positives in the system.

- The uncertainty in the information the operator has, for example, what is the reliability of the data? What information may be missing? Is there conflicting information or ambiguous data that they must deal with?

Table 8.10 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Figure 2.2
Chapter 4: Section 4.4.7, Figure 4.8 and Figure 4.12
Chapter 5: Section 5.3.4, table 5.8
Appendix E

TABLE 8.10: Research Evidence: Principle 10

8.3.3.6 Principle 11: Time Constraints

Whilst time constraints are mentioned in principle one, this principle emphasises the importance of time constraints. During an emergency the decision-maker has limited time to search, understand and utilise information in these challenging real-world environments. It is key that the decision-maker identifies the key information that affects the situation to determine a course of action. Depending on the time constraints the designer needs to consider how and when to present information to the operator.

Examples

Aviation: For an engine fire, pilots will first receive warnings visually and aurally in the system, the PIC will then need to implement the memory items to ensure that the aircraft is stable. Once they have control of the aircraft, the pilots will then have time to absorb the information to determine the emergency and identify the procedures and checklists that need to be completed.

F&RS: In the example of a firefighter attending a road traffic collision, the IC will have three opportunities to absorb information.

1. Travelling to the incident: whilst travelling to the incident the IC has a mobile database of information, which he/she explores information about the local environment, the things that could be of risk, where the closest water hydrants are, what kind of property it is, etc.

2. Arriving at the incident: the IC will quickly get an understanding of what is occurring, this could be visually assessing the scene, speaking to other emergency services involved and the public. Here the IC needs to determine if any immediate actions need to be taken.

3. Once the immediate actions are completed, the IC will ensure that there is stabilisation and then gather more information about the incident: investigating the scene further, carrying out a risk assessment, implementing counter measures and then go on to implement the course of action.

Points to Consider:

- The length of time the decision-maker has to absorb information before having to make a decision or action.
- The information which is a priority to the decision-maker. Also, consider the secondary information that the operator may require.
- The availability of the information.
- The information required to support decisions.
- The operator's interaction, for example, how will the operator view or search information in the system? Could this be time consuming? Can a summary of the key information regarding the emergency be automatically generated for the operator?
- Presenting the information so that it can be absorbed in a single glance.
- How and when will the decision-maker receive information?
- The required information at different points in the emergency.
- How will the decision-maker collect and store information?
- How will the decision-maker identify the missing and uncertain information?
- How will the decision-maker narrow down information?
- How would new information be made aware to the decision-maker? How would new information be represented?

Table 8.11 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Table 2.1
Chapter 4: Section 4.4.7
Chapter 5: Section 5.3.4
Chapter 7: Section 7.3.4.4

TABLE 8.11: Research Evidence: Principle 11

8.3.3.7 Principle 12: Support the Identification of a Course of Action

The recognition primed decision model identifies that the decision-maker develops a single course of action based on the constraints in the environment. Randel et al. (1996) find that experts base their decisions on the nature of the situation using their expertise; they have a large repertoire of past experiences on which to base the current situation. The decision-maker spends little effort in deciding how to react to a situation, once they have understood the situation; the reaction is often obvious. The decision-maker wants "workable", "timely" and "cost effective" actions (Klein and Klinger, 1991).

Examples

Aviation: Once the aircrew has identified that a real engine failure is occurring, and which engine has been affected, the PIC will implement the immediate action items from memory. This includes putting the thrust lever to idle and shutting down the engine. The co-pilot then implements the associated emergency checklist, which reconfirms the immediate actions and checks the engine fire status.

F&RS: For a property fire, once the incident commander has all the information from all sources, he/she will then make the decision of how to resolve the fire. For an extensive fire, the incident commander may split the crew into two teams. The first team is tasked with extinguishing the fire from outside the property, whilst the second team is sent into the adjacent property to investigate if that property has been affected by the fire and ensure this does not spread.

Points to Consider:

- The course of actions that are typical for the emergency.
- The impact of the course of action on the incident.
- The system support required for the generation of courses of actions as well as the rationale behind each action.
- In the event of several courses of actions, highlight how satisfactory each action is, the success rate of completing the action.
- Prioritise the courses of actions based on the available information and constraints.

Table 8.12 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Figure 2.2
Chapter 4: Section 4.4.7, Figure 4.8 and Figure 4.12
Chapter 5: Section 5.3.4, table 5.8
Appendix E

TABLE 8.12: Research Evidence: Principle 12

8.3.3.8 Principle 13: Mental Simulation

Mental simulation in the recognition primed decision model evaluates if an action is satisfactory. When simulating, the decision-maker performs the course of action in his or her imagination; plays out the steps, the potential outcomes, the problems that might occur and how these problems may be handled. The decision-maker either implements the action, or modifies it, or rejects it and goes on to the next action (Klein, 1999). Mental simulation appears in at least three places when decision-making; diagnosing to form situation awareness, generating expectancies to help generate situation awareness, and evaluating a course of action (Klein, 1999).

Examples

Aviation: When an emergency has occurred, the pilot in command may need to simulate a number of things, for example, calculate how much fuel is remaining to identify which airport would be appropriate to land. In addition, when a failure occurs and the pilot is determining and analysing a failure, he/she may use the information to simulate the root cause of the incident.

F&RS: In this extract, the incident commander was asked to attend a casualty who was trapped in a vehicle. The incident commander simulates how to extricate the casualty:

"The paramedics made it understood that the casualty had pre-existing medical conditions and for safety, the ambulance crew requested that the F&RS remove the roof of the car. The incident commander was hesitant to remove the roof as the car had no damage to it and the incident commander was trying to reduce the financial loss of the vehicle. There were a number of other options to consider first. The incident commander discussed if the ambulance crew had considered a splint, an extraction device, which is used by the ambulance service. However, it was decided that the casualty was too heavy for this device. Another option, was removal of the door and the doorposts. However, this was not considered as the crew could not get above the casualty to lift her out."

Points to Consider:

- The operator's mental simulation for possible courses of actions.
- The elements in the course of action that may not successfully resolve the incident.
- The elements in the course of action that could present risks.
- Additional resources that could support the operator's mental simulation including blueprints, images, information from past incidents and system simulations.

Table 8.13 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Figure 2.2
Chapter 4: Section 4.4.7, Figure 4.8 and Figure 4.12
Chapter 5: Section 5.3.4, table 5.8
Appendix E

TABLE 8.13: Research Evidence: Principle 13

8.3.3.9 Principle 14: Support the Performance of Course of Action

The decision-maker(s) and team carry out the steps that are required to complete the course of action. These could be actions that the decision-maker decides on, and/or based on procedures rehearsed during training.

Examples

Aviation: Typically, once the aircrew have determined and analysed what is occurring in the cockpit, the pilot in command will ask the co-pilot to find the corresponding procedure and checklist to resolve the incident. Usually, the co-pilot will find the item and verbalise each step. The pilot in command will complete the action given by the co-pilot and confirm that the action is complete. Both pilots will monitor the systems whilst completing the procedures.

F&RS: Usually, the incident commander will delegate the performance of the tasks to the firefighters, who will set up the equipment and follow procedures as rehearsed in training.

Points to Consider:

- The implementation and procedures of performing the course of action.
- The information that is required when completing the course of action.

- The decision-maker's task of monitoring the incident and systems.

Table 8.14 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Figure 2.2
Chapter 5: Section 5.3.4, table 5.8
Appendix E

TABLE 8.14: Research Evidence: Principle 14

8.3.3.10 Principle 15: Confirm Success of the Course of Action

Once the course of action is performed, the decision-maker will need to identify the success of completing the course of action and identify if further actions are required. Outcomes of performing the course of action include:

- Correct with no errors, which would require the decision-maker to take no further action;
- Correct with errors, which would mean the actions for the decision are correct but this has resulted in another action which needs to be addressed; or
- Simply incorrect, which would require another decision and set of actions.

Examples

Aviation: Once the pilots have completed the procedures using the checklist, they will continue to monitor the systems to ensure that the course of action has been resolved. In the example, where the pilot is experiencing a stall warning, there would be a lot of vibration and noise in the aircraft, where the aircraft is indicating that the aircraft is approach a stall. The pilot will complete the procedures to stop the stall occurring and monitor the systems, as well as identify if the vibration and noise in the aircraft has returned to the normal level.

F&RS: The IC will monitor how the emergency is being resolved from a distance and ensure that the correct procedure has been completed. In a road traffic collision where a passenger is trapped, the incident commander will identify success once the passenger has been retrieved safely out of the vehicle and handed over to the ambulance service for medical care.

Points to Consider:

- Supporting the decision-maker to identify the success of a course of action.

- Errors that could occur after the course of action has been performed.

Table 8.15 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Figure 2.2
Chapter 4: Section 4.4.7, Figure 4.8 and Figure 4.12
Chapter 5: Section 5.3.4, table 5.8
Appendix E

TABLE 8.15: Research Evidence: Principle 15

8.3.3.11 Principle 16: Debrief

Once the decision-maker has implemented the course of action and identified success, typically, they will perform debriefing activities with their team and/or organisation. The decision-maker will discuss a summary of the incident and draw conclusions. The summary may include discussing actions that went well and those that did not.

Examples

Aviation: After an emergency has been identified and the aircrew has landed safely, an accident or incident report is written, which contains all relevant flight and technical data. The report is used to draw conclusions about the incident and to take precautionary actions, if deemed necessary.

F&RS: Once a fire incident has been resolved, the F&RS will determine how the fire started and need to answer the following questions: *"How did the fire start? What are the ignition sources? How can they stop it starting again?"* The crew then may go *"hot spotting"* where they drop off leaflets to the surrounding houses to alert the residents that there has been a fire in their area and also provide safety information.

A chat about the incident (called a hot debrief) is usually carried out to discuss *"What went well? What did not go well? Did each crew member know what they were doing? Did the IC inform each crew member what they were supposed to be doing? Did the crew have any difficulties?"* The crew may finish by collecting the equipment and then head back to the fire station. Here, there may be a second debrief, where the IC completes a debrief form and fills out the *"good bits and the bad bits"*. This is typically shared with the whole of the organisation.

Points to Consider:

- The debriefing actions the decision-maker needs to complete.

- The system support required by the decision-maker at the end of an emergency.

Table 8.16 shows the evidence of where the principle was derived from.

Evidence
Chapter 4: Section 4.4.7
Chapter 5: Section 5.3.4, table 5.8
Appendix E

TABLE 8.16: Research Evidence: Principle 16

8.3.4 Interactions Between Individual and Environment

8.3.4.1 Principle 17: Human Error

Human error has been identified as a factor in a high proportion of incidents in complex and dynamic systems in NDM environments (Stanton et al., 2004), including aviation (McFadden and Towell, 1999), rail (Lawton and Ward, 2005) and healthcare (Helmreich, 2000). Reason (1990) defines error as "all those occasions in which a planned sequence of mental or physical activities fails to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some chance agency." Latorella and Prabhu (2000) highlight human error as multifaceted and propose; "(1) human operators are organic mechanisms with failure rates and tolerances analogous to hardware/software of a system, (2) that human is a pejorative term for normal behaviour in often unkind environments, where only the outcome determines if this behaviour is deleterious".

There are four error categories; slips, lapses, mistakes and violations. Slips (attentional failure) refer to when the wrong control has been activated. Lapses (memory failure) refer to something that has been forgotten or a task step that has been missed. Mistakes (wrong intention) are those where the operator does the wrong thing due to a misunderstanding or misconception. Mistakes imply that the intended task was executed, but it was the wrong task given the context. Violations are where the operator performs an action that they know is not allowed, but they implement it anyway (Reason, 1990).

Error is a key aspect in NDM environments, it alerts designers to areas where performance can be improved (Lipshitz et al., 2001). The NDM setting rejects the notion of faulty reasoning, but instead attempts to understand why poor decisions were made. Klein (1993a) identifies weaknesses in NDM strategies linked to the three primary forms of inference used in NDM; feature matching, analogical reasoning and mental simulation. During feature matching, the decision-maker may use the wrong features or may weigh the features incorrectly. When the decision-maker is using analogical reasoning he/she may select

the wrong analogues or adjust the analogues incorrectly. During mental simulation, the decision-maker may build an inadequate mental simulation and fail to reject an inaccurate mental simulation. Human factors issues, including workload and inadequate communication have been identified as *"major determiners of a human error"* (Park and Jung, 1996); another is lack of experience (Lipshitz et al., 2001).

Examples

Aviation: In the cockpit, pilots use a number of strategies to prevent and identify errors. These include:

1. **Correct parameters are entered into the system:** Typically, the pilot in command will enter details into the system and the co-pilot undertakes a crosschecking activity; this ensures that the items programmed into the systems are correct.
2. **Correct procedures are completed:** The co-pilot monitors the pilot in command to ensure the correct procedures are completed, at the correct time, during the different phases of the flight.
3. **Incapacitation:** The co-pilot monitors the pilot in command to ensure he/she is not incapacitated at any time during the flight, this is particularly important during take off.

F&RS: In the F&RS, the second in charge supports and monitors the incident commander's actions and catches any errors. Firefighters also monitor the emergency and will report back to the incident commander with erroneous outcomes, this could include updates on fatalities and damage to the environment. For larger incidents, a supervisory officer will be deployed, who monitors the emergency, the team, the incident commanders and the firefighters to ensure good practices are implemented.

Points to Consider:

- The types of errors that may occur in the tasks and when using the system.
- The potential slips, lapses, mistakes and violations (Reason, 1990).
- The support required during feature matching, analogical reasoning and mental simulation (Klein, 1993a).
- The elements that require monitoring, including people, environment or systems.
- The system support the decision-maker requires for monitoring and crosschecking activities. Identify if the system can increase the accuracy and consistency of monitoring and crosschecking information.

- Errors from past incidents could be used to identify and support where errors could occur in the present incident (Flach et al., 2008).

Table 8.17 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Section 2.3.2.2
Chapter 4: Section 4.4 and Table 4.1
Chapter 5: Tables 5.6 and 5.8 and Section 5.3.4

TABLE 8.17: Research Evidence: Principle 17

8.3.4.2 Principle 18: Workload

Parasuraman et al. (2008) definition of workload *"the relation between the function relating the mental resources demanded by a task and those resources available to be supplied by the human operator."* Increased workload reduces the ability of the user to undertake efficient decision-making, thus the decision-maker needs to be supported when completing his/her tasks. These tasks include gathering information and identifying problems; reviewing causal factors with other team members; considering and sharing risks of alternative courses of action.

The NDM environment is a multi-task environment, where the decision-maker uses several different resources for information processing. Wickens (1984) identified four dimensions, these include:

- The stages of processing dimension which describes that perceptual and cognitive (e.g. working memory) tasks use different resources from the selection and execution of action.
- The codes of processing dimension highlights that spatial activity uses different resources than verbal/linguistic activity.
- The modalities dimension outlines that auditory perception uses different resources than visual perception.
- Visual channels dimension outlines between focal and ambient vision, a nested dimension within visual resources.

Two forms of technological intervention are therefore possible; technology that reduces workload by automating tasks that would otherwise consume mental effort (also known as "offloading") or technology that supports the process of decision-making itself (i.e., decision support) (Rogers and Scaife, 1998).

Examples

Aviation: When an emergency is detected in the cockpit, a pilot's workload increases. The increase in workload is due to the extra tasks of identifying the emergency, stabilising the aircraft and determining what is occurring. Workload could also increase if a take off time slot was missed, which in turn would increase stress. Pilots can rush through system tasks to meet a take off time and this could contribute to a later accident.

F&RS: The IC splits the workload amongst the team. In this scenario, the IC split the tasks between himself and the second in charge: *"The IC sent the second in charge to look at access points and for the gas and electric cut off points. He would also look for hazards, entrances and will inform the IC what the fire looks like at other locations. The IC will speak with the occupier of the building who will hopefully identify potential hazards or possible causes."*

Points to Consider:

- The operator's workload and identify how busy they are.
- Identify tasks that could impact performance.
- The complexity of the tasks that the decision-maker has to perform. Identify if the decision-maker can take on additional tasks (Young et al., 2014).
- The operator is able to respond to unexpected events (Young et al., 2014).
- The operator's additional workload.
- The mental resources and capabilities of the decision-maker's information processing system. Identify the limit and support the decision-maker's performance before it begins to deteriorate.
- Multiple resource theory, the decision-maker uses several different resources simultaneously. Consider the four dimensions; stages of processing, the codes of processing, the modalities and visual channels (Wickens, 1984).
- When the operator has high workload, the strategies they will employ to manage their tasks. Consider the individual characteristics, task characteristics and the workload levels.
- The use of automation to support workload and/or technology that support the process of decision-making itself (Rogers and Scaife, 1998).

Table 8.18 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Section 2.3.2.1
Chapter 4: Section 4.1
Chapter 5: Tables 5.6 and 5.7

TABLE 8.18: Research Evidence: Principle 18

8.3.4.3 Principle 19: Automation

Automation is a method to support operators with workload that they may experience. Automation can differ in type and complexity from simply organising the information sources; to integrating them into a summary format, to suggesting decision options that best match the incoming information, or even carry out the necessary action (Lin et al., 2010).

Automation can provide decision support, alleviate the heavy demand and augment system performance to reduce errors. Good automation reduces workload whilst maintaining the operator's situation awareness. Automation can improve precision, process large amounts of data from multiple sources, manage multiple systems as one, provide calculations and precise estimations. Automation frees the operator from monotonous tasks, and this will in turn free attentional resources and allow the operator to concentrate on more rewarding and safety critical elements. The system designer can introduce different levels of automation into systems, Kaber and Endsley (1998) present the levels of taxonomy, which present different levels of automation for monitoring, generating, selecting and implementing tasks.

Examples

Aviation: Cockpits are highly automated systems, with the use of autopilot. The pilot will typically use autopilot and only revert to manual flying when necessary. In the event of an emergency, the crew alerting system identifies errors in the system. For example, the cockpit usually has two sensors to identify altitude. If there is a discrepancy between the two sensors, the pilots will be alerted by the crew alerting system that this discrepancy has occurred.

F&RS: A system in the F&RS identifies the location of the incident and presents the known information to the IC. For consideration an IC's comment: *"When an appliance is mobilised, the appliance receives a mobilising message, which gives the firefighter information about the incident. This includes address information; type of incident (i.e. a house fire, property fire), additional incident information and the corresponding risk card is unlocked for the incident."*

Points to Consider:

- The different levels of automation, for example, the computer decides everything by acting autonomously or the operator must authorise the action.
- Access to raw data, its accuracy, precision and reliability at all stages and levels of automation.
- Provide reasoning of why the action is being completed by the automation.
- The design should keep the user informed of the actions, interpretations, errors, exceptions, changes of state and changes of condition that are relevant and of interest. This should be achieved through clear, concise and unambiguous language.
- Avoid target fixation, this is when the mind focuses on a single thing, which can result in the decision-maker missing other issues/information.
- Avoid out-of-loop syndrome, where automation reduces the operator's excessive workload, to a point of low situation awareness; where in certain cases the operator will not understand what is happening.
- Complexity creep, this is where the designer unwittingly unleashes complexity with the practice of feature escalation. This could lead to increased workload due to the design of the system.
- Use of consistent interaction metaphors for the interaction with devices, i.e. touch screen, switches, etc. This will reduce the learning curve required to use technology.
- Different levels of information for different levels of stress. For example, present an overview and then allow zoom into details only on demand. The system could even intelligently create an overview of the important information. This would reduce the amount of time needed to explore key information points but also gives the operator an option to zoom into the detail when and if they have time.

Table 8.19 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Section 2.3.2.1
Chapter 5: Table 5.8

TABLE 8.19: Research Evidence: Principle 19

8.3.4.4 Principle 20: Uncertainty

NDM environments have different types of uncertainty making the decision-making process difficult, these include; uncertainty about the information they have and uncertainty about the correct course of action. Below Riveiro's definition of uncertainty is presented:

> *"Uncertainty is a complex concept and there are many kinds of uncertainty that decisions makers must face. It covers the broad range of concepts like inconsistency, doubtfulness, reliability, inaccuracy and error". (Riveiro, 2007)*

There are a number of factors that cause uncertainty in data and uncertainty can be introduced at any step of investigating and acquiring the data, filtering and mapping operations, to the final representation (Griethe and Schumann, 2005). Griethe and Schuhmann (2006) sum up from numerous papers, the different concepts that are encompassed in uncertainty, these include; error, imprecision, accuracy, lineage, subjectivity, non-specificity and noise.

Examples

Aviation: Pilots experience uncertainty when determining the problem when experiencing a failure. The aircrew considers if the recognised failure is a false alarm. Is it a single failure or multiple failures? What is the cause of the failure? As well as identifying the severity of the emergency. Pilots need to identify how long they have to handle the aircraft safely, the time they have to resolve the situation and determine where a suitable landing can be performed.

F&RS: When arriving at a fire incident, the IC needs to consider the following questions: How developed is the fire? What does the inside of the property look like? What is the construction of the building? How badly has the fire affected the construction of the building? Is the building going to collapse? How long does the F&RS have to resolve the emergency before it gets worse?

Points to Consider:

- The errors, imprecision, accuracy, lineage, subjectivity, non-specificity and noise Griethe and Schuhmann (2006).
- The uncertainties that the decision-maker must answer; inadequate understanding, incomplete information and undifferentiated alternatives (Lipshitz and Strauss, 1997).

- The coping strategies decision-makers employ; reducing uncertainty, assumption-based reasoning, weighing pros and cons of competing alternatives, suppressing uncertainties and forestalling (Lipshitz and Strauss, 1997).

Table 8.20 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Section 2.3.2.3
Chapter 4: Section 4.4 and Table 4.1
Chapter 5: Section 5.2.4.3 and Tables 5.6

TABLE 8.20: Research Evidence: Principle 20

8.3.5 Individuals in a Team Environment

8.3.5.1 Principle 21: Teamwork

Teams are identified as two or more people who collaborate towards a common goal or objective, each person may be assigned an individual role which involves different functions of limited time duration (Salas et al., 1992). In the NDM environment, often the decision-maker will collaborate not only with people in his team, but also with third parties. When considering teamwork two key characteristics need to be considered:

Team Situation Awareness: Team situation awareness refers to a shared or distributed awareness or mental representation of the environment between team members. Lipshitz et al. (2001) outlines that team situation awareness is essential for effective decision-making, especially since obtaining and maintaining situation awareness in teams is far more complex than in individuals. Team situation awareness can be acquired when members of the team collect and exchange information and when the members engage in closed-loop communication (Orasanu, 1990). Endsley and Jones (1997) state for a team to successfully function, all team members must possess a high level of the same situation awareness on shared requirements.

Team Mental Models: Shared mental models are *"knowledge structures held by members of a team that enable them to form accurate explanations and expectations for the task, and in turn, to coordinate their actions and adapt their behaviour to demands of the task and other team member"* (Cannon-Bowers et al., 1993). According to Cannon-Bowers et al. (1993), shared mental models provide an understanding of how teams are able to cope with difficult and changing task conditions. Mathieu et al. (2000) suggest that team members who share mental models are able to anticipate each other's responses and coordinate effectively; in time critical situations and when communication is limited. Lipshitz et al.

(2001) indicates that having a shared understanding of the task allows the members to know who is responsible for what, as well as the information needs and requirements of the team. Having this understanding allows the team members to anticipate the others' needs, allowing them to better communicate, plan and improve decision-making performance (Stout et al., 1999b, Volpe et al., 1996a).

Examples

Aviation: Once the pilots have developed their individual situation awareness, they come together in a verbal briefing where they discuss the details and decide on the elements of the flight. ATC are then informed of the flight details. This briefing allows the pilots to discuss their findings, and any constraints that could affect the flight plan. The briefing allows the pilots to highlight any errors that could occur in each of the pilot's situation awareness.

F&RS: The incident commander and second in charge work together to develop a shared understanding of the situation. When there are gaps in the situation awareness, the firefighters investigate information that is missing and report back to the incident commander.

Points to Consider:

- The number of operators taking part in sharing their situation awareness picture.
- The four mental models; equipment model, task model, team interaction model and team model (Cannon-Bowers et al., 1993).
- The team situation awareness required for the incident and identify how the team will build it. For example, will there be a briefing activity? What materials will the operators have access to?
- Support coordination and information sharing activities (Endsley and Jones, 1997).
- The reporting method between the team, in particular when operators must share information.
- The method decision-makers will filter information to present to their team.
- The distribution of the team (Endsley and Jones, 1997).

Table 8.21 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Section 2.3.3.1
Chapter 4: Section 4.4 and Table 4.1
Chapter 5: Section 5.2.4.3 and Tables 5.6

TABLE 8.21: Research Evidence: Principle 21

8.3.5.2 Principle 22: Communication

Communication can be considered as the way one mind can affect another, it can be either verbal or non-verbal, intentional or unintentional (Eccles and Gershon, 2004). Hogg and Vaughan (2002) define communication as the *"transfer of meaningful information from one person to another"*, which involves the production and the reception of messages. The basic concept of communication requires a sender to send a message or information and for a receiver to receive this through a channel of communication. Isaac and Ruitenberg (1999) indicates that communication starts when a sender encodes an idea or message and sends it through one or more channels that can be either verbal or non-verbal. The receiver then decodes this message using long term memory to bring meaning to the message. The receiver may have different characteristics which include experience, culture and expectations which may affect decoding.

Isaac and Ruitenberg (1999) make a distinction between verbal and non-verbal communication. Verbal communication such as speech includes pitch, tone and rhythm have an important role in communicating and supporting the message and consequently the decoding. In contrast, non-verbal communication includes forms such as gaze, gesturing and facial expressions. Non-verbal communication can occur independently or in combination with other forms of communication. Hogg and Vaughan (2002) state "speech rarely occurs in isolation from non-verbal cues".

Examples

Aviation: Communication occurs throughout the flight to develop situation awareness, help make decisions, identify errors, obtain more information, etc. Communication occurs between pilot to pilot, and pilots to air traffic control. For example, pilots discuss the flight plan, make changes to the flight plan and exchange ideas. The aviation industry uses strict phraseology to avoid miscommunication and misunderstanding. This may be particularly important in the event of an emergency as noise may be a factor.

F&RS: Like the aviation domain, the F&RS team communicate to develop and understand the emergency, make decisions, as well as identify risks, place countermeasures, etc. Communication is done face-to-face, or via technology such as radios, involving a number of different parties.

Points to Consider:

- The actions that need to be communicated.
- The communication between the operator and system, between system-to-system and operator-to-operator.
- The verbal and non-verbal communication, direct and indirect communication, as well as addressed and non-addressed communication (Isaac and Ruitenberg, 1999).
- Method of communication, for example, how will the operators communicate with each other? Will it be face-to-face or will they need the support of technology?
- Information sharing with others in the team, for example, is it another pilot who will have the same systems in front of him/her or a firefighter who has to report to the incident commander.
- The third parties the decision-maker needs to communicate with, for example, air traffic control or ambulance service.
- Two-way communications, where not only the decision-maker communicates to the team, but the members of the team report back to the decision-maker. For example, the team may provide the decision-maker with more information about how the incident is unfolding.
- Verbalisation activities where actions and tasks are verbally communicated. For example, in two pilot aircrews the co-pilot will read out the procedures on a checklist and the pilot in command will complete the procedure and acknowledge the items are complete. This allows both pilots to know what the other is doing and to understand what impact that has on the aircraft and/or flight plan.

Table 8.22 shows the evidence of where the principle was derived from.

Evidence
Chapter 2: Section 2.3.3.2
Chapter 4: Table 4.1
Chapter 5: Section 5.2.4.3 and Table 5.6

TABLE 8.22: Research Evidence: Principle 22

8.4 On-line Tool

The principles have been integrated in to a website, which presents each of the principles including descriptions, illustrative examples and points to consider when designing systems for real-world decision-making. The website also provides case studies and an easy-to-use checklist which summarises the points to consider when designing. Figure 8.2 and 8.3 present the cognition informed system design website, which can be found at www.chrissiehare.com.

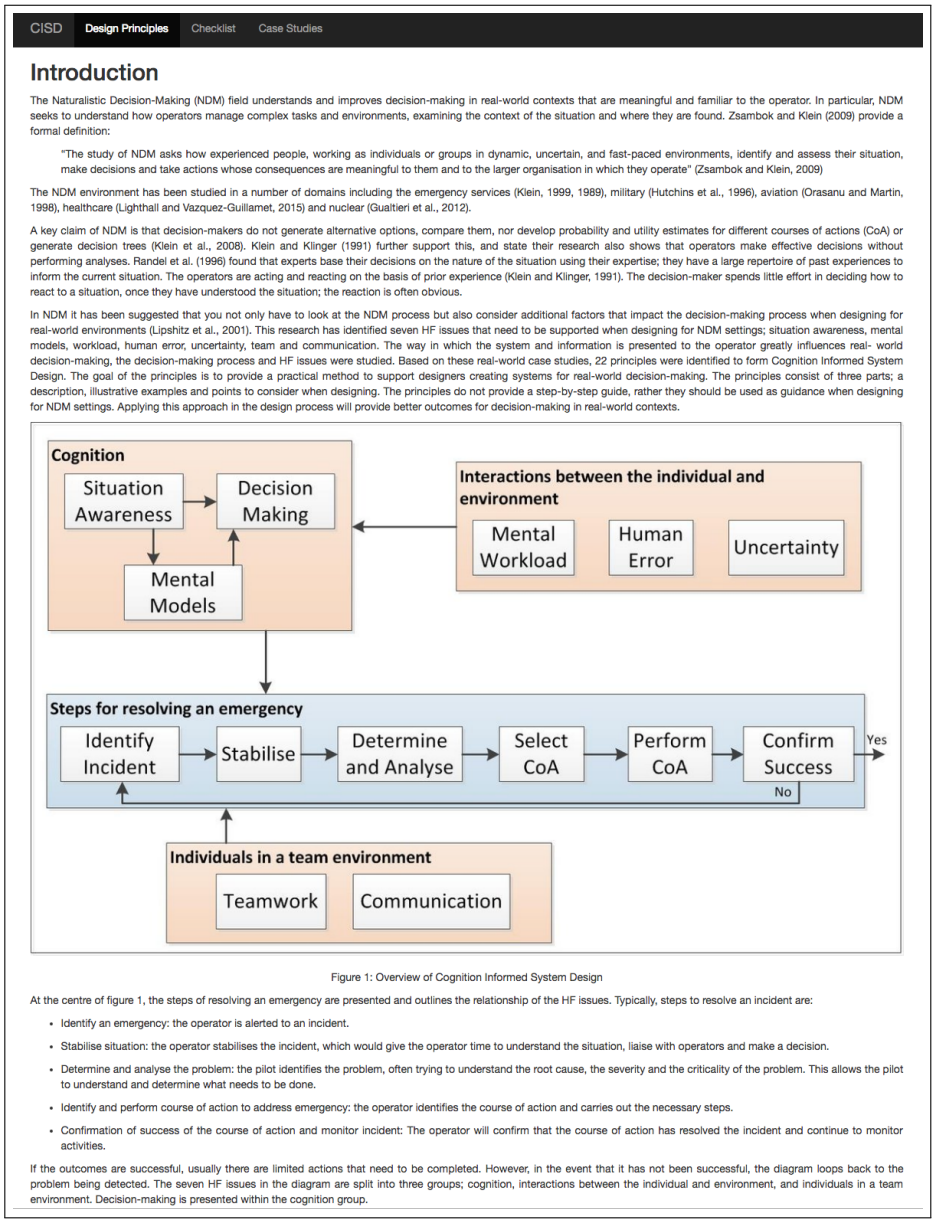


FIGURE 8.2: Cognition Informed System Design Website

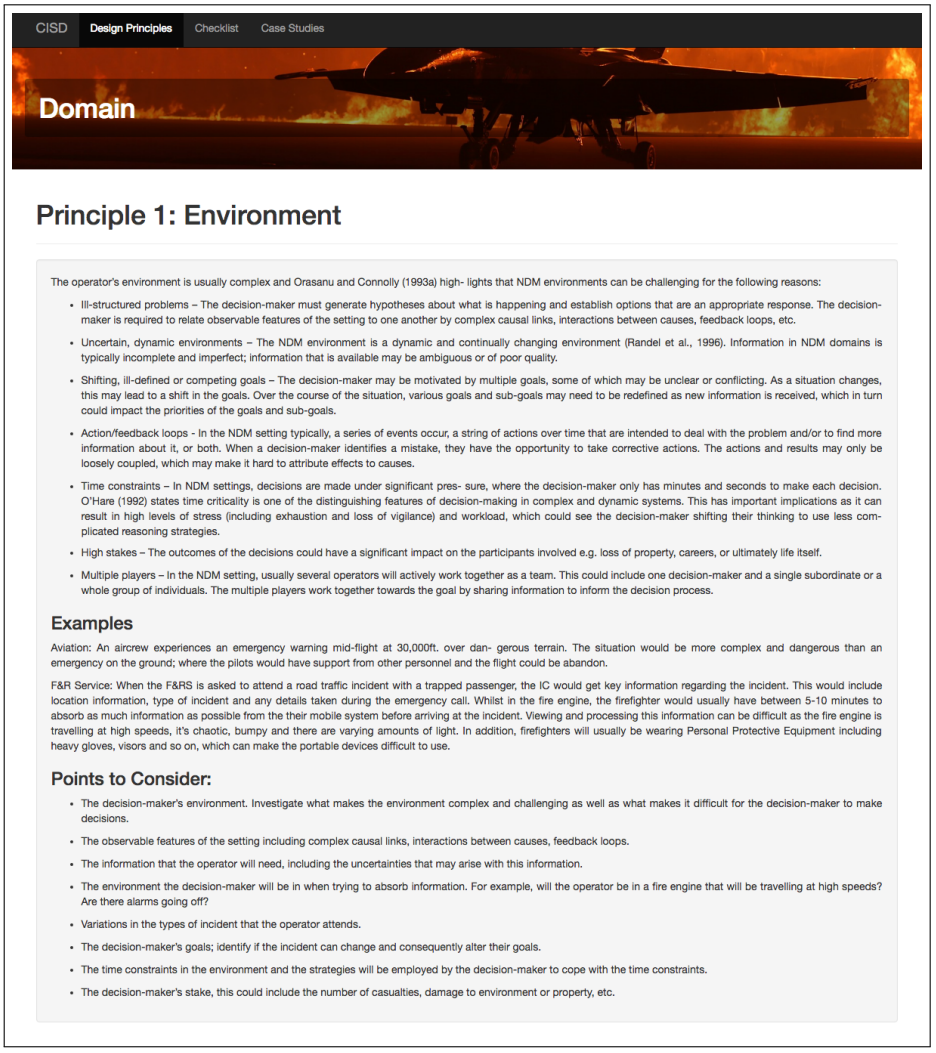


FIGURE 8.3: Cognition Informed System Design Website 2

8.5 Chapter Summary

This chapter contributes to the thesis by presenting an overview of Cognition Informed System Design, which presents the final 22 design principles. The principles provide an overview of the elements that need to be considered in the design of NDM systems. The contribution to theory includes the additional steps to resolve an incident in the RPD model (stabilise the incident and monitor the course of action). Another contribution includes the seven HF issues which are needed to support effective NDM. Overall the chapter presents a final overview of the design principles, which include literature, examples and points to consider when designing a system. The chapter also presents an on-line tool to disseminate the principles, example case studies and an easy-to-use checklist.

Chapter 9

Discussion and Conclusion

9.1 Chapter Overview

This final chapter presents how each research aim was achieved in this thesis, and it discusses the significant contributions and implications of the work to support the design of real-world decision-making systems. The thesis was concerned with investigating the guidance designers require to develop systems for NDM environments. For the thesis to have practical relevance, the research investigated the NDM process and the HF issues that affect the decision-making process. This work was required to address previous research gaps in human factors literature; to identify the HF issues for the decision-making process, and to identify the support designers require when creating NDM systems.

This chapter discusses the main research findings in relation to each aim. Studies of real-world decision-making were undertaken to investigate each aim. The F&RS and aviation environments (in collaboration with Airbus Group) were investigated to provide real-world examples of decision-making. The contributions of this thesis to understanding how to support decision-making in NDM settings are emphasised and discussed. The chapter acknowledges the research limitations and the attempts to control for them, followed by suggestions for future research. The thesis concludes with a summary of the main findings and contributions of the thesis.

9.2 Reflections on Research Aims

The achievement of each aim is first described, and is then followed by a discussion of the main findings. The contribution to the overall thesis is then emphasised and implications of the results are discussed.

9.2.1 Identify The Typical Human Factors Issues That Affect NDM Environments

The NDM process and the HF issues that influenced real-world decision-making were investigated at each stage of the research. Seven HF factors that affected the decision-making process were identified in collaboration with Airbus Group: situation awareness, mental models, workload, human error, uncertainty, teamwork and communication. A literature review of peer-reviewed conference and journal papers confirmed that each factor was reported to be present in the NDM environment and identified the aspects that needed to be considered for each aspect. Some factors are well documented in the NDM literature when compared to others. The literature frequently identifies the relationship of situation awareness, teamwork and uncertainty (Lipshitz et al., 2001). Human error and communication in aviation (Helmreich et al., 1999) are documented, however, they are still yet to be investigated in detail in the general domain of NDM. Further, there is limited research which investigates the impact of all seven factors on the decision-making process. Using the findings, a research framework was created, which grouped the HF issues and identified the relationship during the tasks that need to be completed during an incident. The seven HF issues served as the basis of the research scope and were investigated in real-world NDM settings. The HF issues also identified the aspects that need to be supported in the design of systems for real-world decision-making and consequently were used as a basis for the design principles, including descriptions and points for the designer to consider.

Throughout the development of the thesis, the factors were investigated in individual research studies with the support of experts. Table 9.1 summarises the factors that were included for consideration for each research study.

Factor	**Literature analysis**	**Expert knowledge elicitation**	**Experiment**	**Evaluation**
Decision-making	✓	✓	✓	✓
Situation awareness	✓	✓	✓	✓
Mental models	✓	✓		✓
Workload	✓	✓	✓	✓
Human error	✓	✓		✓
Uncertainty	✓	✓		✓
Teamwork	✓	✓		✓

Communication	✓	✓		✓

TABLE 9.1: HF Issues Included for Investigation for Each Research Study

For pragmatic reasons, three key factors (decision-making, situation awareness and workload) were examined for deeper analysis in the experimental study but all factors were reintroduced for the evaluation study.

9.2.2 Examine NDM And The Human Factors Issues In Real-world Environments

An important aspect of this research was to investigate NDM and the HF issues in at least two real-world environments. By understanding how decision-making and the factors occurred in NDM environments, it could be identified how to support the decision-maker. To address this aim, two studies were implemented in the F&RS and aviation domain.

Both experimental and field-based studies contributed to achieving this research aim, summarised in table 9.2.

Domain	Setting	
	Lab	**Field**
F&RS	One-to-one interviews with system managers, focus group, 3 CDM interviews, cognitive work analysis.	-
Aviation	One-to-one interviews with a commercial aircrew. 10 CDM interviews	Observations on a flight

TABLE 9.2: Setting for Each Domain

For each domain, the types of tasks that were implemented during an emergency and the types of decisions the operators must make, were investigated. Once the decision-making process was understood, the researcher with the support of experts, investigated how the seven HF issues occurred in the domain to support the NDM process. By identifying the tasks and decision points, the researcher was able to identify how the decision-makers needed to be supported in their environment. The CDM interviews and analysis methods identified the presence of the HF issues in the two NDM settings and provided examples

of how each manifested in a variety of incidents. The CDM interviews provided a set of case studies for the principles to be based on and extracts were used to provide evidence of each principle in the NDM environment. Although, there are similarities in the outputs of the analysis, two different NDM settings were used to identify the context specific nuances that need to be considered when supporting the decision-maker.

Identifying where the decision-maker required support, allowed the researcher to identify design solutions. For example, for single pilot operations it was identified that one of the phases during resolving an incident included identifying and performing a course of action, which would usually be performed in collaboration with the co-pilot. However, when removing the co-pilot, further automation of procedures would be needed to support this task through the use of electronic checklists, which could prioritise the procedures according to how critical they are.

An experimental study was performed to integrate the decision requirements into the design of an aircraft for single pilot operations. This study investigated how the requirements were integrated into the design. This study allowed the researcher to identify design points to consider when designing for NDM systems and showed how supporting the decision-maker could have a positive impact on the decision-maker's performance. The findings show that the designed NDM system had the same effect as that of the system that pilots had trained and used for many years. This shows that the new NDM system, operated by a single pilot, could support the pilot in making real-world decision-making. The study also identified further points to consider for the principles.

9.2.3 Develop Guidance To Support NDM System Designers

The way in which the system is designed, and the information is presented to the operator, greatly influences real-world decision-making. The goal of the design principles is to provide designers of NDM systems with guidance to support the operator's decision-making process and support the HF issues that can impact this process. The findings from aims one and two of the thesis were integrated into the design principles. The principles consisted of three parts: a description, illustrative examples and points to consider when designing. The principles are concepts that the designer should consider, but they should not be used as a step-by-step guide.

The researcher identified three questions to further develop the principles, including investigating if the principles were usable, understandable, complete and applicable to other domains. An evaluation study of the principles was performed with HF experts to address these questions and further develop the principles. The HF experts applied the principles

to the design of a real-world decision-making system in the F&RS, and were explicitly asked to identify how they were used. The outcomes of the evaluation study gave the researcher an understanding of how designers want to use the principles and how they needed to be further developed. For example, an output of the evaluation study showed that in addition to the principles, the participants wanted a checklist so that they could quickly run through it whilst designing. They felt that once they had an understanding of the principles, they would want to go through them quickly to ensure that they had considered all the points. The findings from this study were then integrated into the final design principles and named Cognition Informed System Design. The descriptions, examples and points to consider, were further developed and presented in the form of an on-line tool.

9.3 Contributions Resulting From This Thesis

The main contribution of this thesis are the final design principles, which are presented as Cognition Informed System Design. The principles address a gap in the literature of understanding the complexity of naturalistic decision-making in emergency situations. The NDM process and the HF issues have been integrated into the principles to support designers to explore and consider the complex factors associated to real-world decision-making in system design. Cognition Informed System Design consists of 22 design principles which include; descriptions, examples and points to consider when designing. Descriptions and examples are based on literature analysis and the field studies (CDM interviews). Points to consider are incorporated into a checklist and were identified from literature analysis, CDM interviews and experimental study. To better support the design process, the findings from the experiment study support how the principles should be presented to the designer to ensure they are usable and understandable.

The research investigated a total of thirteen different emergency incidents, the general steps of completing an emergency are in-line with the complex RPD Strategy (figure 2.2). Section 4.4.7 summary of CDM interview findings, identify that there are two additional steps which are not outlined in the RPD model. The first additional step is where the decision-maker first stabilises the situation so that the emergency does not deteriorate. In the F&RS, it was identified that if the emergency is critical then an immediate course of action is carried out to stabilise the situation and then the decision-maker will then gather more information and then perform a second course of action. If the emergency is found not to be critical then the decision-maker has no need to stabilise the situation and will only develop one course of action to resolve the incident. Similar findings were also found in the aviation domain.

The second additional step in the NDM process is a monitoring step. Once a course of action has been implemented, the decision-maker spends considerable time monitoring and ensuring that the implemented course of action had been successful and that the emergency had either been resolved or had not deteriorated (section 5.3.4). This is not mentioned in the RPD model, however this could be due to the fact that the model stops once the course of action is implemented and does not consider any further steps. In this thesis the participants in the field studies emphasised the importance of monitoring the emergency after the course of action had been implemented as this could lead to further decisions. The additional identified steps have been included into the final diagram of Cognition Informed System Design (figure 8.1). Future work should be done to extend the RPD model to include the stabilisation step and monitoring period.

Whilst the RPD model considers the steps of NDM, it does not consider the additional factors that support effective NDM to resolve a situation. Previous research identified either single factors or a small sub set of factors to investigate naturalistic decision-making (Endsley, 1995b, Helmreich et al., 1999, Lipshitz et al., 2001, Salas et al., 1997), however, this research champions multi-factor issues that impact the decision-making process. For this reason, the thesis investigated seven HF issues, which provide practical examples of where the human factor occurs in the real-world, further illustrated in Table 4.1. For example, one CDM interview shows that the incident commander used a mobile data terminal to develop his understanding of how to cut into a car. In the aviation domain, the pilots develop their situation awareness in a number of ways. For example, each pilot in the aircrew initially examines the pre-flight material individually and then both pilots come together and discuss the flight to develop a shared understanding. The understanding of each HF issue to support the NDM process identifies a combination of factors that need to be supported for effective NDM. Furthermore, the HF issues highlight the areas that system design needs to support, and each of the seven HF issues have been included in the design principles.

As Klein (1993a) highlights, designers require a clear picture of the key decisions, and how decision-makers make decisions, to build systems and human centred interfaces. A second contribution of the thesis, is the outputs from investigating two real-world NDM settings. Two contributions are presented from investigating the F&RS setting. First, the CDM interviews identify the tasks to resolve an incident, the decision-making process and the HF issues that impact them in a number of different incidents. Secondly, the cognitive work analysis provides an analysis of the constraints and complex relations in the F&RS work environment. This creates an understanding of the environment that the tasks are carried out in. A key contribution of the outputs of the investigation are the decision ladders,

which identify the information processing steps and the types of questions the decision-maker will ask in each step. In the aviation context there are several contributions. First, the decision centered design method is used to understand the domain by performing CDM interviews which identify, in a second NDM environment, the tasks to resolve an incident, the decision-making process and the HF issues that impact this process in a number of different types of aviation incident. This understanding also identified the decision requirements, critical cues, expert strategies and design ideas in order to support their tasks. For both NDM domains, the critical decision method provided several case studies. These studies are important for understanding how designers need to support the decision-maker in these challenging settings.

The initial understanding from the decision centered design framework was used to form a hypothesis as to how the aviation domain could move from two pilot aircrews to single pilots operations. With this move, the single pilot's role will change, and this research contributes to an understanding to begin creating a system for single pilot operations, which supports both the pilot's NDM process, as well as supporting the HF issues.

The contributions bridge the gap between the human factors and the systems engineering domains. This is achieved through the identification of the human factors that impact the operator in NDM domains and which need to be considered by the developers who create systems supporting operators.

9.4 Reflections on Approach and Methods

The literature review provided an informative and comprehensive overview of the NDM environment. A summary of previous research supported the development of research hypotheses and identified gaps in research. As with any review, there is the possibility that relevant research findings and articles may not be identified in the search process. However, this concern was mitigated through the use of a structured literature search with comprehensive search terms. The review provided a comprehensive overview of the research areas of interest, which was particularly beneficial for the early stages of the research.

General models of information processing package decision-making as a single step in the process whereas, NDM theory presents decision-making as an activity which is a complex, embedded process and needs to be considered from a number of aspects. NDM theory encourages the researcher to consider decision-making from a naturalistic viewpoint and exposes the complexity in emergency situations. NDM can not be explained by a mathematician who rigorously tests to produce the best solution, instead it is an organic process

based on a number of complex factors. This research extends the complexities of NDM by investigating the social, cognitive and environment factors that affect the decision-making process.

The thesis used a variety of methods to investigate NDM and the associated HF issues. Several of the methods including ethnographic study, CDM interviews, CWA and DCD, have been used in past research to investigate complex and challenging domains such as emergency situations. The initial interviews with decision-makers and ethnographic study introduced the researcher to the domains and the critical points during an emergency.

Due to the often dangerous and unpredictable nature of emergencies it is difficult to attend in person, a complementary method called CDM was used. The interviews investigated the critical points in the emergency, reaffirming the majority of the steps in the RPD model. The strength of using CDM is that the researcher could investigate incidents using a retrospective technique to provide an overview of the steps to resolve an incident and the key tasks that the decision-maker makes in the NDM environment, as well as, highlighting how HF issues occur in real-world environments. The output of the interviews was detailed and provided significant input for the design principles. The interviews allowed exploration of the information and investigation of a number of different types of emergencies. This gave understanding to where the decision-maker makes decisions and needs to be supported during the emergency.

The limitation to CDM is that it is a retrospective technique; for most participants there was a substantial amount of time between the incident date and interview date. This could lead to inconsistencies between what happened and what the participant could recall. The significance of which will most likely be linear to time. Future research should use incidents which occurred closer to the interview date, ideally the CDM technique including investigation of the seven HF issues, could be performed straight after the incident.

The CDM is a lengthy process, each interview took between 1.5-4 hours in the aviation domain, with further time needed to transcribe the interview and for liaison with the participants to check for factual accuracy. This method required dedication from the participants involved in the interviews, including patience to explain the intricate and complex relationships in their domain. A great deal of time was spent sourcing decision-makers who could talk about emergencies and further time was required to complete the procedures to allow them to partake in the studies. It is advised that this method should only be used if the available resources in time and participants are available.

CWA was used to analyse the NDM environment separate from the individual tasks the decision-maker completes. The outputs of the CWA framework provides the researcher

with an understanding of the components of the environment, calculations made, the team involved including external parties, as well as, the NDM process in the form of decision ladders. An important output of the CWA are the questions the operators ask during the steps of resolving a incident. These questions indicate the type of information required by the decision-maker and the step in RPD model, which could be developed into future technologies.

The methods used to investigate the F&RS (CDM and CWA) effectively highlighted NDM in emergency situations. However there are a number of weaknesses with the methods used as they provided limited support to transfer the knowledge acquired from NDM into system design. Furthermore, there was little support to investigate the domain during normal procedures. For these reasons, the DCD framework was used to investigate NDM in the aviation domain. DCD consists of five stages which provide the researcher with tools to investigate normal procedures (ethnographic study) and emergency procedures (CDM interviews). The findings from normal and emergency decision-making are integrated into design requirements for a system, the system is prototyped and tested. As in the F&RS, the outputs from DCD identified the steps of resolving an emergency are in line with RPD model. The CDM interviews identified further examples of how HF issues occur in the real-world and points to consider to support the NDM process. A weakness of the all the methods used in the thesis is the lack of consideration of the HF issues in the NDM environment. The researcher has included additional tables in each of the methods to gain an understanding of the HF issues which affect the NDM process. Considerable work should be performed in order to investigate the most robust methodology to examine the seven different HF issues.

The limitations of DCD is that the framework does not account for developing a system in a complimentary domain (the move from two pilots to one pilot). For this reason the researcher included an additional section at the beginning of chapter 6 (between stage 3 and 4 of DCD) to investigate the impact on the steps in the NDM process and the associated HF issues, which then generated further design requirements. Future work could develop an additional step in DCD to include this investigation. The experimental study (stage 5 of DCD) evaluated whether using the decision requirements could match a system that pilots have spent many years using. The study identified that there was no effect when using the different types of systems, or in any of the scenarios. Further work could include providing pilots with extensive training on the new NDM system as this could provide better outcomes.

Due to the sensitivity of the project, only Airbus employed pilots could be used for the study, which restricted the number of participants. This study should be further extended

using a larger set of participants, which could show further outcomes of using the decision requirements in the design of real-world decision-making systems. Further, due to limited resources, the pilots were given limited training on the new cockpit philosophy. However, for the pilots to fully understand the philosophy, they would require extensive training and self-study to become completely accustomed to the cockpit.

The method of evaluating the initial design principles with HF experts provided an insight into how the design principles need to be ordered to support the designer. The evaluations identified how the principles were applied and how the principles needed to be extended. The findings also highlighted the need for checklists to allow the designer to have quick and fast access to the items that need to be considered. This study should be extended by replicating the study with additional HF experts from a wider range of domains and applying the principles to systems for other NDM environments. The final principles, presented as Cognition Informed System Design and disseminated through an on-line tool should be further evaluated to ensure accuracy of the principles and validate that the tool supports the designers design process.

9.5 Limitations of the Research

The initial set of HF issues were controlled by using expert opinions from Airbus Group, this restricted the number of HF issues that influenced the decision-making process to a set of seven factors. It is therefore possible that other factors also occur in NDM environments, which were not included for consideration in this work.

Several challenges were faced during the CDM interviews, first, the difficulty of sourcing decision-makers, who had the time to speak to the researcher. This domain is a highly specialised domain, with fewer participants than domains such as classical decision-making. Furthermore, these domains are highly sensitive and the impact of mistakes can have severe consequences. Therefore, there is a reluctance to talk about emergencies, especially those that were not resolved as planned. In the aviation domain, only those incidents that were successfully resolved could be investigated, due to the nature of emergencies in aircraft. Further understanding from unsuccessful decision-making could give an even greater insight into how decision-making needs to be supported. Some participants were reluctant to identify and explain why they did not follow procedures and tried to revert to what should have been done, instead of what they actually did in the incident. Not following procedures in this domain is unacceptable and pilots are thoroughly trained to follow the procedures that are described in their operational manuals. As self-reporting

measures are vulnerable to biases or participant deception (Dane, 1990), the researcher attempted to control this by emphasising confidentiality and anonymity of results.

CDM interviews were challenging to implement. It was difficult to record all the steps and information that the pilot had completed, and often, once the participants started to explain the steps in detail, they frequently found further details and points to discuss. The CDM interviews were somewhat an iterative process throughout the interview and when reviewing the write-ups. Whilst the researcher attempted to control this by asking the participants to review the write up of each interview, it is difficult to identify if the participant missed any steps. Further, only one researcher identified the types of tasks and decisions, increasing the risk of reporting errors. The questionnaires and interviews in the research were vulnerable to various biases. This work attempted to control for the limitations by using a number of methods. Biases were controlled by ensuring the accuracy of interviews and analyses, by getting the participants to review what had been written up.

The experimental study applied the decision requirements to a system that is currently being developed in industry to address a new developing domain. However, due to the novelty, many parts of the project were restricted, for example the type of simulator. The main limitation of this simulator is that it did not present contextual characteristics that the incidents would occur in. It is suggested that high fidelity simulators are used, as well as simulating the challenging environmental characteristics the systems will be used in.

The experimental study used situation-present assessment method (SPAM) to measure situation awareness (as it does not disrupt the simulation) and this was deemed a good solution in the aviation domain as pilots often liaise with ATC. Further, the method generates data frequently throughout the different points of the flight. The method considers the time of participant response to the situation awareness question, but the method does not consider the quality or accuracy of the answer. Further, the method does not consider the extremes, for example, a pilot crashing the aircraft. The SPAM measure also takes workload measures into consideration, but the reliability of the measure for workload is not entirely accurate. 3D SART questionnaire was implemented, as it was a quick and easy method, requiring limited training. However, there is the possibility that pilots rate their situation awareness with their task performance, furthermore, there is the possibility that participants could not identify low situation awareness, as they may not even be aware that they have low situation awareness (Endsley, 1995a). It was attempted to control this by using both qualitative and quantitative measures workload and situation awareness.

9.6 Suggestions for Future Research

Future research may investigate other factors that may be present in the NDM environment that were not included in this research and investigate the impact of these on decision-making. This remains a gap in the literature and may further inform the decision-making process. Future research may extend factors such as teamwork, including team situation awareness and shared mental models. Further investigating other NDM domains will highlight additional examples for the principles and develop cognition informed system design principles. By building on the findings in this thesis, a more comprehensive understanding of what is needed to support designers creating systems for real-world decision-making, could be developed.

Due to time and resource constraints, the investigation of integrating the design requirements were not validated in a high fidelity simulator with realistic conditions. It is proposed that future research uses high fidelity simulations to confirm and extend findings. In addition, future research could extend the current findings by including both male and female participants. A larger number of participants would be beneficial to increase statistical power and additional analyses may be then appropriately applied.

The research attempts to integrate the findings, especially the design requirements, and it is suggested that future research examines further contexts by applying the principles to the design for NDM systems. Investigating in detail how the designer creates systems, would give a greater understanding of how the design principles need to be presented for optimal use. The principles in this research were evaluated with a team of five in the evaluation study. Future research could vary the design, as well as investigating the use with individuals.

Further work should conduct similar CDM interviews to identify the tasks, types of decisions and HF issues, however, these CDM interviews should also consider the perspectives of a number of different parties involved in the same incident. Analysis of the cross perspective CDM interviews would not only highlight what is needed for decision-making to the local user, but also that of further afield. For example, a cockpit that displays the right information at the right time, for the pilot, but also the right information the pilot needs to relay to ATC.

The on-line tool created to disseminate the principles to designers is useful in its own right. However, evaluation of the usability of how the tool supports the designers when creating systems for NDM contexts should be performed. This would lower the barriers of use by designers and would improve future systems.

Future research could apply the design principles to the creation of new systems and then assess their success in not only the F&RS and aviation domains, but in different NDM contexts. This would further validate their general applicability and could provide a deeper understanding. A cross sample of a wider variety of domains could also identify general advice for designing for real-world decision-making.

As the results investigate human factors influence on decision-making in real-world environments, the findings are applicable to any field, however they should be validated against other fields for nuances that may not have existed in the aviation and fire & rescue domain. Other safety critical domains could include transport, manufacturing, nuclear, oil and gas. Methods and analyses outlined in this research may be replicated and adapted as appropriate to the specific domain.

9.7 Concluding Statement

The research presented in this thesis has addressed research gaps within the NDM literature, and reported findings to support designers creating systems for real-world decision-making. Findings suggest that not only does the NDM process need to be supported in the design of the system, but also the HF issues that influence the decision-making process need to be taken into consideration. By supporting the decision-making process and the HF issues in the design of the system, better outcomes will be achieved. Real-world applicability has been demonstrated when the design principles were applied to a research project within Airbus Defence and Space. In addition, the design principles were evaluated with designers to create a system for the fire and rescue service. This research therefore provides a foundation from which to develop a valid and comprehensive understanding of the decision-making behaviours operators will use. The behaviours then need to be supported in system design, achieved through the use of Cognition Informed System Design.

Appendix A

Critical Decision Method Interview Outline

A.1 CDM Interview Overview

The aim of the interview is to understand how a decision-maker deals with an emergency, the decision points they make and the information they require to resolve the incident.

A.2 CDM Interview Procedure

1. First decide on the incident that the operator experienced and involved NDM. Consider the following prompts:
   (a) "Can you think back to a situation where an emergency occurred and involved decision-making?"
   (b) "Could you talk about what happened? Why did it happen?"
   (c) "When did the incident occur?"
   (d) "What was the general situation like?"
2. In the event that several possible incidents are identified, decide on the best incident to discuss, think about how recently it happened.
3. Ask the operator to give you a general overview of the incident.
4. Step-by-step explain what the operator did in the incident.

5. Once a description of the incident is gained, develop a timeline of activities in the incident with the operator.
6. Probe the participant for more information:
   (a) "If I was there with you what would I see you do? and hear you do?"
   (b) "What information were you looking at?"
   (c) "What actions/options were you considering?"
7. Identify the key decisions made:
   (a) What cues were used/attended to.
   (b) The knowledge was needed to make the decision.
   (c) What situation assessment was made?
   (d) What option were considered?
   (e) The basis for the final choice, what-ifs?
   (f) Training or knowledge or information that would have been useful in that situation.
   (g) Did you consider alternative scenarios?
   (h) How did you know this was the best solution?
   (i) What difficulties do they experience?
8. Ask participant to give opinion on the expected performance of a less experienced pilot when faced with the same situation.

Appendix B

Observations: Two Pilot Commercial Jet Flight

Task Breakdown	Observations and Examples
Phase One - Flight Planning:	
Analysis and Evaluation of the Briefing Package. Before the flight the pilots received a briefing package of information regarding the flight plan, weather and the Notice to Airman (NOTAM) which are paper based.	Before arriving for the flight, the pilots had pre-planned the flight path on their iPad. In the pilots lounge the pilots downloaded the briefing package and printed it off.
Flight Plan. Flight plan contains information such as departure airfield, destination airfield, the route (this consists of way-points and the airway routes), the information about the type of aircraft and the number of people on board.	The PIC checked the flight plan, to reconfirm the flight details. The pilot's stated that the PIC's role is to make the strategic decisions of the flight.
NOTAMS. NOTAMS contain short term information about the airport. Examples include: the closure of parking stands, bad weather (which would require instrument landing system), closure of airways, construction work at an airport, cranes which are inside the safety area, etc.	In the NOTAMs the CP received hundreds of pieces of information. The CP had to sufficiently analyse and evaluate key information points that might affect the flight. There were only 2 or 3 pieces of information that applied to the flight.
Walk around. The PIC is responsible for doing a walk around the aircraft to ensure that everything with the aircraft is in order.	Ensure physical safety of the aircraft.

Brief. The aircrew brief each other regarding their findings. They CP will brief the PIC with a condensed version of the information analysed from the NOTAMS to assist strategic planning. With all the information the pilots discuss any constraints and make a final flight plan.	On the day of the observed flight it had been snowing, initially there was a debate on whether to delay take off, as the snow on the runways may not be cleared in time. The flight had been slightly delayed to ensure this. The pilots spent substantial time analysing the NOTAMs and understanding what impact the bad weather had on the flight. The NOTAMs revealed that the glide slope system, used for the approach at the destination airport had stopped working due to bad weather and that a manual glide slope would have to be calculated using checklists in the cockpit. Whilst the briefing period is a collaborative process between the two pilots. The PIC makes all the final decisions i.e. if there is bad weather the PIC will need to decide whether to deviate from the route to make it safer however, this may make the journey longer and consequently require more fuel which is more costly. The PIC must check the fuel consumption and calculate for the new route, the distance and what is needed for the required extra fuel.
Notify ATC. ATC needs to know where the aircraft will be at which point, allowing ATC to know where all aircraft are, schedule the approach and landing of the aircraft and avoid collisions in the air. Knowing the location of the aircraft at all times allows ATC to predict where the aircraft is in the event of radio communication loss.	The pilots informed air traffic control (ATC) regarding the details of the flight including planned route, number of passengers, etc.
Phase Two – Pre-flight Checks and Clearances:	

Pre-flight Checks and Clearances and Taxi. Upon entering the cockpit the pilots must prepare the aircraft for taxi and take-off. The pilots must do the following tasks: • Start the APU (auxiliary power unit – small engine) and start up the navigation systems, start the computers • Take off briefing by the PIC • The pilots must confirm that the cargo is loaded • Before start the engine checklist is completed • Get clearance for engine start • After start checklist is completed • Several checks must be implemented which include flight control checks (i.e. the electronics and hydraulics) and system checks. All the systems the aircraft has on board. The before taxi checklist is used to complete this step • Ask for taxi clearance • Taxi checklist or Before the take off checklist (differs from aircraft to aircraft) must be completed • Then taxi to the runway • Get clearance to go on the run way and take off	In this phase the PIC programmed the FMS and set up the aircraft whilst the CP implemented the set up and crosschecks in the FMS programming. The CP found and read each item in the checklist and the PIC implemented the item the CP had read out. The PIC acknowledged each item once the item had been implemented.
Phase Three - Take-off:	
Initial speed call outs. Three speeds are announced: • V1 – the decision speed, whether you abort take off in the event of a major failure • V2 – the safe flying speed • In between the V1 and V2 there is an in - this between speed is known as the rotation speed which is used to get the best angle of climb	The CP called out the speed from the airspeed indicator, for example '80 knots'. The PIC answered with 'checked' to indicate that he had 80 knots on his airspeed indicator. The pilots stated that confirmation from the PIC is needed to cross check the CP's airspeed indicators with the PIC's and to ensure that the PIC is not incapacitated. The aircrew stated if the PIC provides no confirmation then the CP will take over immediately. If the CP had to take over he would have two options either to abort the take-off or to continue as planned.

Monitor pilot. The CP is a constant monitor of the PIC ensuring the correct aircraft operation.	Throughout the flight especially taking off and landing (this is a high priority task and deemed a high workload task) the CP must monitor the PIC on all parameters. Things that the CP was looking for included if the aircraft loses an engine, if there was a malfunction, the PIC might get focused only on the speed or the altitude, which results in the PIC missing the glide path. This is the point where the CP needs to speak up and say something like "glide path alive" to get the pilot out of his target fixation. Another example of monitoring the pilot is if the PIC pulls up the nose too aggressively and the nose goes too high, the CP will call "check pitch".
Monitor systems. The aircrew monitor both sets of instrumentation for errors.	Both pilots cross checked that both sets of instrumentation, especially the primary flight instruments (speed, altitude, heading/track, etc.), are the same if consistent then the pilots would need to investigate.
CP implements actions given by the PIC. The PIC will request actions from the CP who will then implement them.	For example, during the stabilisation phase where a safe altitude is reached, the PIC reduced the power from the take off power to maximum climb power and accelerated to the flap retraction speed. So the PIC announced "flaps 1" and the CP checked the speed and called "speed checked" and then the CP selected the flap lever to one and checked that the flap levers had moved to position one. The CP announced "one" and the aircraft accelerated further. The CP checked the speed and selected flaps 0 and then announced "flap zero".
After take-off checklist. After take-off procedure was completed using the after take-off checklist.	The PIC asked for an "after take-off" checklist and the CP went through the checklist and announced the items and after each step was completed the PIC said "Rodger".
Radio communication. The PIC operates the aircraft while the CP liaises with ATC.	Whilst in this flight there was minimal radio communication with ATC. An example communication could be when ATC redirect the aircraft on a short cut to the destination. In this case, if the PIC is in autopilot the PIC will go into the flight management system (FMS) and put in the destination, however, if the PIC is flying manually then the CP would go into the FMS and activate the new way-point.
Phase Four - Climb, cruise phase and descent:	

Updates via ATC. An hour before the destination the CP received weather updates and information about the runway that will be used for landing.	The CP was especially interested in the wind, the clouds, the visibility, if the runway is covered in snow or is wet which will affect the breaking/landing performance.
Phase Five – Approach and landing:	
Program the approach system. The PIC hands over the controls to the CP – in case of a deviation, so that the PIC will go into the FMS to program the approach. Once this is done the CP will hand controls back to the PIC and then go through the FMS to check what the PIC has done	The CP confirmed all the speeds, the minimum speed settings and all the programming has been done in the correct way.
Approach briefing. The controls are handed back to the CP and the PIC carries out the approach briefing.	The PIC checked the aircraft weight at landing, the speeds, which flap settings he would use for landing, talked about the approach, what he planned to do if he could not land. The CP was happy with the PIC's briefing and both pilots were aware of the sequence of actions that would come.
Before Approach Phase. Either the CP will request for descent or ATC will request it – this is dependent on the situation. Upon confirmation of request the aircraft will descend.	The descent involved reducing power, setting a lower flight level to the autopilot. The autopilot will then descend. At level 100 the pilots switched on the landing lights for low flying VRF flights. The CP switched on the signs in the cabin so that all passengers are seated and belted. The transitional altitude (switching from the standard pressure setting to the local QNH/actual reference pressure) was announced by the CP. Both pilots set this in the altimeters and crosschecked.
Approach phase. The approach phase included changes in frequency, new headings, new waypoints – (either PIC using autopilot or CP who puts it into the FMS).	The PIC reduced the speed, then he asked for "flaps 1". The CP checked if they were in the safe speed range. He ensured that there was not over speed, which would damage the flaps. Set flap lever to 1 was completed and then the pilot announced "flap 1". The same procedure for flaps 2 and 3 was completed. Then gear down occurred and the CP checked this happened correctly. The aircraft intercepted the glide slope, the CP's responsibility is to monitor the speeds, deviations but it's the PIC's job to fly and maintain the safe parameters. The pilots completed descend checklists.
Land aircraft	This was completed with the support of landing checklist.

Table B.1: Observations: Two Pilot Commercial Jet Flight

Appendix C

Human Factors Impact in Two Pilot Aircrews

	HF Positive	HF negative
Phase One - Flight Planning:		
Briefing Package including flight plan and NOTAMS	• The tasks that are required to be completed before a flight are split between the two pilots, this results in spreading the workload and making it easier to focus on the task each pilot needs to complete. • During the briefing the CP must brief the PIC in regards to the NOTAMs and the flight plan. The briefing session is built into the procedures that the pilots must follow. This allows dedicated time for the pilots to build up an equal situation awareness of the route and what to expect. Verbalisation allows the CP to talk through all the points with the PIC, which might highlight any difficulties. Verbalisation allows both the pilots to catch any pieces of information that the other may not know about. • The two pilots in the cockpit weigh up ideas, which give the pilots a chance to evaluate the things that are needed.	• Each pilot builds up an individual understanding of the flight. This could result in two different SA's. For example, the CP will have gone through all the information and then will have briefed the PIC on the information that he feels is important. Consequently the CP might miss some important information that may affect the flight. • Even when the CP updates the PIC they might not have equal SA which could result in a mismatch of SA.
Phase Two – Pre-flight Checks and Clearances and taxi:		
Pre-flight Checks and Clearances.	• The CP monitors the actions that the PIC undertakes. This allows the CP to pick up on any errors that may occur • The CP crosschecks his instrumentation with the PIC to ensure that there are no differences. In the case of differences, the pilots would need to investigate what is causing it. The PIC carries out the flying procedures and the CP carries out the non-flying procedures. The CP retrieves each the checklists for all the different phases of the flights. He/she will then read each item out to the PIC and the PIC will carry out the task. The CP is verbalising the checklists for the PIC. The PIC then communicates back to the CP when the item has been completed.	
Phase Three - Take-off:		
Initial speed call outs.	• Checking of the pilot's health to ensure that he/she has not become incapacitated during take-off. • Verbalisation of the checklist items that are taking place, this allows for constant confirmation and checking of the correct speeds • The constant checking by the CP catches any errors that the PIC might make • If the decision to abort needs to be made this can be done together, the PIC can consult the CP to ensure that he has the correct information and confirm that he is making the correct decision based on the information in the cockpit • Both pilots can share the stress if there is a failure • Verbalising and talking through the problem between the pilot could slow down the thinking process which could be a positive thing as this would mean that the issues be better examined	• The pilots might have an increase in workload as they are constantly verbalising and updating the other pilot on what they are doing and thinking. • Whilst the pilot's undertake extensive training and use standard phraseology there still may be the possibility that misunderstandings occur. For example, the CP might call out set flaps to 0 but the pilot might hear something else.

The CP monitors the PIC and the aircraft.	• The CP is constantly checking what the PIC is doing –for example, is the PIC taking off correctly, is the pitch correct, are the procedures being followed correctly. The CP is mitigating human error. • The CP advises the PIC if the correct procedure or correct landing is not done • If the PIC is focusing his attention on one element of the flying procedure, the CP acts as a 'waking up' mechanism to get the PIC out of his 'target fixation'. • The CP is continuously updating his SA and helping to problem solve any issues that may occur.	• There will be a lot of times where the CP might not be doing anything, just monitoring the PIC. This could be thought of as a monotonous task which could cause fatigue • The PIC might feel that the CP is criticising the way he flying the aircraft • Conflicts between the CP and PIC might occur. This is an argument that holds true throughout the operation with two pilots: if both individuals do not like each other a "negative environment" can be produced which may reduce the positive effect of two individuals sharing tasks even to an extreme where this negative "mood" may reduce the performance of the individuals. • Whilst most pilots are "just happy" to be in the air some may experience job satisfaction/low morale. • CP's get a lower salary that the PIC. There is hierarchy so this might contribute to bad relationships. • The CP might be a distraction to the PIC if the CP is focusing on something that might need attention
Monitor both sets of instrumentation is correct.	• Having two sets of instrumentation means that if one fails then the other can be used, this increases the safety of the aircraft • If one fails then it is more obvious that something is wrong in the aircraft whereas if there is only one instrumentation this might not be picked up • Controls can be passed on to each other while other tasks are undertaken or when the pilot may experience high workload • They both have an equal overview of the aircraft – giving them equal situation awareness	• Both sets of instrumentation are constantly being monitored which takes a lot of time and effort. • Having two sets of instrumentation is costly. • The second set of displays increases the weight of the aircraft, it's double the amount of interfaces, gauges, wiring, etc. • Time is wasted when the CP's instrumentation fails and the pilots have to work out what went wrong • Maintenance of two sets of instrumentation have to be carried out by workmen • The instrumentation is difficult to update, once the instrumentation is in the cockpit, they are static • Insufficient monitoring of the instrumentation could lead to failures not being identified • Trust issues as devices can fail often in the cockpit
CP will implement actions given by the PIC.	• Here there is a team effort to crosscheck the inputs into the flight deck by monitoring each other.	• Miscommunication may occur
After take-off checklist.	• The pilots share the workload as the CP finds the right checklist, reads out the items whilst the PIC carries out the actions • The CP can adapt to the situation and adapt the way he reads out the checklist – he is responsive to the situation.	• Although there is usually time, it can be time consuming/cumbersome for one pilot to read it out and the other then to implement it • There is a chance of miscommunication • Paper checklists – takes time to find them • No identification or pointer to which checklist should be used • Although in majority of cases this is not a factor, there is a lot of page flicking that takes place

Radio communication.	• The pilots are able to share the workload • Allows the PIC to hand over the controls to the CP if the PIC is too busy • Allows both activities to be achieved successfully	• There may be a miscommunication or delay to the PIC from what the ATC say to the CP
Phase Four - Cruise phase:		
Updates via ATC.	• Collecting information for the planning of the descent – informed decision-making.	• The PIC isn't involved in this information collection, which will mean that the CP will have to brief the PIC.
Phase Five – Approach and landing:		
Program the approach system.	• Possibility to hand over to the CP if there is too much workload • Crosschecking to ensure that the right approach has been programmed	• A lot of swapping of controls. This could lead to a mistake occurring • Time consuming to swap and then double check what is happening – this is more an issue during an emergency
Approach briefing.	• Both pilots know what actions will come, they share the same situation awareness • A plan is created to land • An alternative landing plan is created if things don't go as planned for example; if the breaks aren't quite working correctly then an increased landing distance is needed. • Monitoring and crosschecking what the PIC is saying • Items may be picked up by the CP that may have been missed	• There might be a disagreement to how to complete the landing.
Before Approach Phase.	• The CP announces a value, which requires both the PIC and CP to put these values in to the system. They both declare that it has been done and that it is reliable • Checklists to help ensure all the procedures and tasks are complete • Monitoring and crosschecking	• Multiplying the work i.e. inputting values into both systems may be unnecessary – redundant only if the systems fail
Approach phase.	• Crosschecking and monitoring • Use of checklists	

TABLE C.1: Human Factors Impact in Two Pilot Aircrews

Appendix D

Aviation Critical Decision Method Prompts

Goal Specification	What were your specific goals at the various decision points?
Cue identification	What features were you looking for when you formulated your decision? How did you know that you needed to make the decision? How did you know when to make the decision?
Expectancy	Were you expecting to make this sort of decision during the course of the event? Describe how this affected your decision-making process.
Conceptual Model	Are there any situations in which your decision would have turned out differently? Describe the nature of these situations and the characteristics that would have changed the outcome of your decision.
Uncertainty	At any stage, were you uncertain about either the reliability or the relevance of the information that you had available? At any stage, were you uncertain about the appropriateness of the decision?
Information	What was the most important piece of information that you used to formulate the decision?
Situation Awareness	What information did you have available to you at the time of the decision?
Situation Assessment	Did you use all of the information available to you when formulating the decision? Was there any additional information that you might have used to assist in the formulation of the decision?
Options	Were there any other alternatives available to you other than the decision you made?
Stress	Was their any stage during the decision-making process in which you found it difficult to process and integrate the information available? Describe precisely the nature of the situation.
Choice	Do you think that you could develop a rule, based on your experience, which could assist another person to make the same decision successfully? Why/why not?

Analogy	Were you at any time reminded of previous experiences in which a similar decision was made? Were you at any time reminded of previous experiences in which a different decision was made?

Table D.1: Critical Decision Method Prompts

Appendix E

Critical Decision Method Interviews

This appendix describes ten critical decision method (CDM) interviews from the aviation environment.

E.0.0.1 CDM Interview 1: Engine failure

Description

Pilot 1, an Airbus test pilot, talked about an engine failure that happened in 2000 on a Dornier 328 jet in Granada, the pilot was acting as PIC on the day. The aircraft is a commuter airliner where the aircrew were performing an ice excretion test on the right engine behind an ice tanker. The ice had gathered to a very high degree with the engine inlet anti-ice switched off, when the pilots switched on the anti-ice, ice was ingested by the engine and the engine died down with a "rumble" from the aircraft. The pilots immediately realised that they had a failure as the caution feed highlighted that there was a right engine failure, they had heard a "pop" and a "rumble" and the CP called out that there was an engine failure. The system also alerted the pilots via "chimes", the master warning and master caution buttons "blinks" and caution warning field in the middle of the multi function display there was a caution and warning indicating right engine failure "blinks".

Pilot 1 indicated that both he and the CP were investigating the engine instruments and particularly focusing on the caution feed where it had highlighted that there was an engine failure and the other indicated that the right engine was not running any more. The pilots were evaluating the information to confirm which engine had "died down", even though

they knew which one from the beginning. The pilots needed to confirm that the right engine had actually stopped working. The pilot highlighted that in the aircraft there is no cue to which thrust lever needs to be shut down visually.

The pilots then completed the immediate action items (one of the pilots called for this – but could not remember if it was PIC or CP). Once the immediate actions were completed this would return the aircraft to almost normal, stabilised flying. PIC ensured that the aircraft was flying normally and did not go off to one side. The aircrew then continued to deal with the steps in the checklists, without interfering with any other air traffic. The pilots completed both the memory and non-memory items from the emergency checklist. Pilot 1 stated that there was not much to consider when it came to doing an emergency landing, as the aircrew already knew that Granada was the closest airport, which they then returned to. They also knew that the engine on-board was a brand new engine and that only engineers in Granada could fix it. They landed using the single engine checklist.

Task Decomposition Diagram

A task decomposition diagram of the steps to resolve an engine fire in a jet aircraft was developed with the pilot, see Figure E.1.

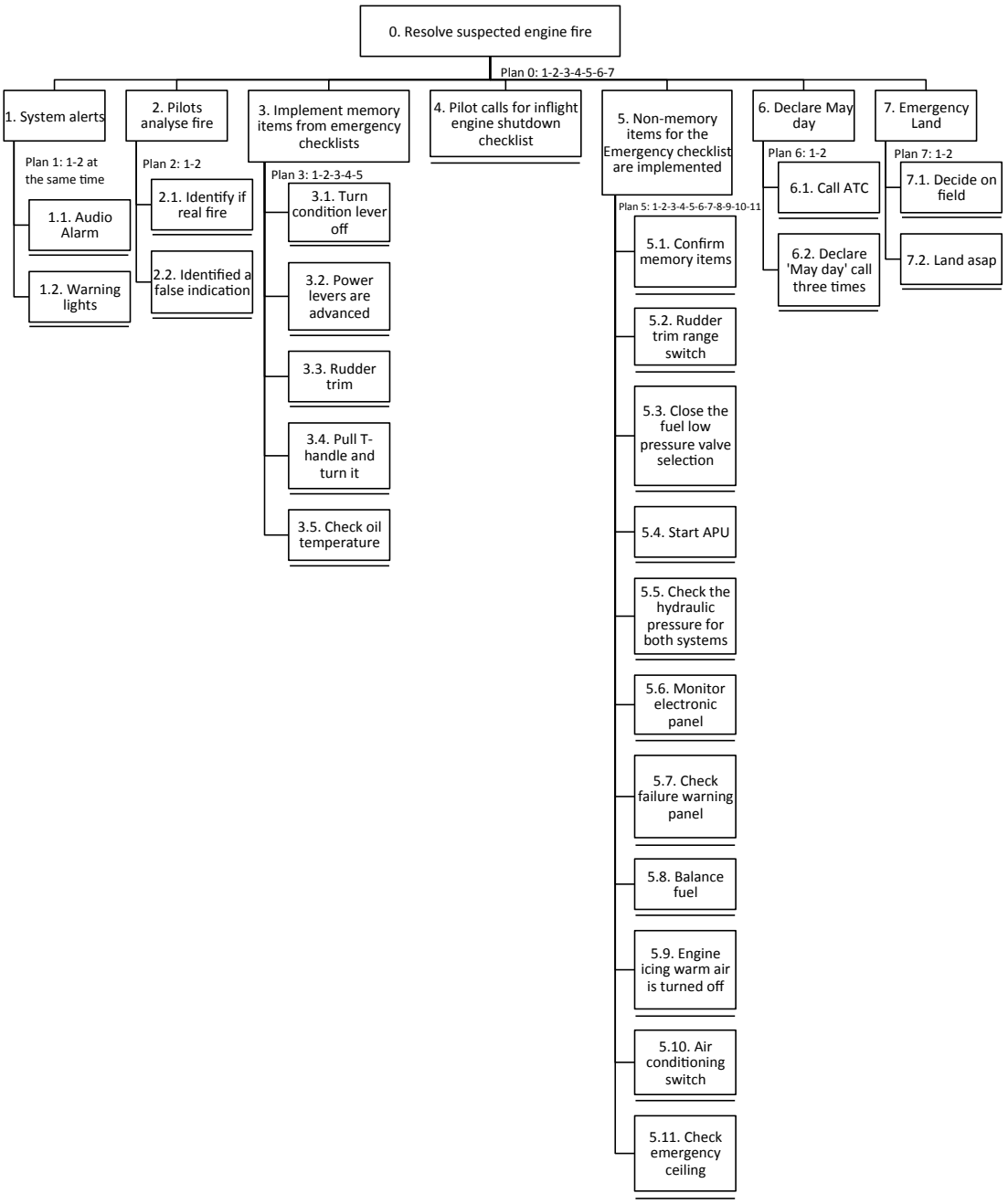


FIGURE E.1: CDM Interview 1: Engine Fire Task Decomposition Diagram

Decision Points

Six main decision points were identified, these are discussed below in tables E.1, E.2, E.3, E.4, E.5 and E.6.

Decision Point 1: Identify failure

To identify the failure, the aircrew analysed the situation to understand what failure had occurred, Table E.1. The pilot was initially alerted to the failure through visual and audio alerts from the system. Often pilots experience false positives of an engine failure, which means there is uncertainty regarding whether a failure has actually occurred. The pilots investigated the information to identify that it was really a failure by investigating engine interface information and visually inspecting if there was smoke or visible fire. The pilots needed to identify if engine fuel flow was irregular by checking the engine indication and the warning system.

The pilots looked for anomalies in the system, the PIC and CP worked together, communicating with each other, in order to get an understanding of what kind of failure was occurring in the aircraft and what impacts the failures could have. The pilot stated that at times, it is difficult to really determine which data is really wrong and describe it as "guesswork", "gut feelings" and "intuition". The pilot stated that they use their extensive training to manage failures, but they also use their past experiences to diagnose the failure. This expertise helps to validate the problem the pilots believe they have.

CDM Item	**Response**
Goal Specification	Identify what failure has occurred, where it's occurring and why it's occurring.
Cue identification	An audio engine fire alarm sounds and a visual light on the overhead panel lights up (the engine fire button highlighted in red). The aircrew look for signs of smoke and flames, even if they can not see any visual signs, the aircrew will react according to the emergency procedure.
Expectancy	This is a severe failure if it is identified to be real, this decision is not usually expected during the course of the event
Conceptual Model	If the alarm were a false positive, then the alarms would be turned off. The next decision would be to identify whether an emergency landing is required.
Uncertainty	There is a lot of uncertainty regarding whether the alarm is a real failure. Therefore, the aircrew needs to investigate the systems. The pilots have to constantly monitor the systems. The pilots also need to understand why the emergency has occurred and if it has impacted anything else.

Information	The pilots investigate the warning system and the engine indication. Also, depending on the location of the engine nacelle it might be possible to visually look at the engine and check for smoke/visible fire.
Situation Awareness	The pilots use the systems to check the engine indication, warning system and visual information outside. They also have all the information from the NOTAMS, weather and briefing.
Situation Assessment	The information available was used to decide there is a failure and which side.
Options	Whether there was a failure – positive or negative
Stress	Most of the time, it is a faulty alarm circuit due to some moisture in a connector of the fire detection system/hot air leak, which activates the alarm. However, in the event of a real fire, the situation can rapidly develop into a life-threatening situation (toxic smoke/fumes may enter the cabin and/or if the engine is mounted at the wing, a real fire may damage the wing to an extend that it may fall apart or at least the engine may fall apart thus producing a controllability problem do to shift of CG). A number of flashing lights and alarms will be going off to bring attention to the pilot that there is a failure.
Choice (rule)	As the initial action is always the same; shut down the engine, fight the fire, mayday call.
Analogy	Yes this has been practised intensively during training

Table E.1: CDM Interview 1: Decision Point 1 - Analysing situation

Decision Point 2: Identify affected engine

Once the pilots recognised there was an engine fire, they then identified which engine had been affected (right engine), see Table E.2. The pilots tested the system to ensure that they had identified the correct engine as the failed one.

The pilot also highlighted that during an emergency there is a higher chance that the PIC becomes fixated on a target or what is also known as tunnel vision, or target fixation and misses key information. It is the CP's responsibility to monitor the pilot and ensure that all the information is evaluated when trying to resolve the emergency, thus supporting situation awareness.

CDM Item	**Response**
Goal Specification	Identify which engine has been affected
Cue identification	Warnings are with respect to individual engines (e.g. audio warning for fire in general to catch attention, but then a red fire warning light for each individual engine).
Expectancy	Same as decision point 1, once the emergency is identified then this decision needs to be made.
Conceptual Model	No, this is the first thing that needs to be determined.
Uncertainty	The pilots also need to be sure which engine has been affected. The pilots have to constantly monitor the systems.
Information	Visual warning lights.
Situation Awareness	The pilots use the systems to engine indication, warning system and visual information outside. They also have all the information from the NOTAMS, weather and briefing.
Situation Assessment	Yes, all available information was used, anything the aircrew needs can be provided by ATC.
Options	Which engine is affected – left or right
Stress	Yes because there is an on-board failure.
Choice (rule)	Before one pilot or flight engineer shuts down an engine (or any other irreversible action) this has to be confirmed by another crewmember (e.g. CP does engine shut-down, PIC confirms correct handle before CP uses handle), using crew resource management.
Analogy	Yes, this has been practised intensively during training

TABLE E.2: CDM Interview 1: Decision Point 2 - Recognise which Engine is Affected

Decision Point 3: Implement emergency procedures and checklists

Once the aircrew had identified a real failure as well as the affected engine, the PIC then implemented the immediate action items from memory, see Table E.3. The pilot put the thrust lever to idle and shut down the engine. The CP then implemented the emergency checklist, which reconfirms the immediate actions, checks for engine fire, severe damage and normal engine failure.

CDM Item	**Response**
Goal Specification	Shut off affected engine and extinguish the fire
Cue identification	To make sure that this is the affected engine and that the wrong engine is not turned off. The PIC implements the immediate actions from memory, which shuts down the affected engine. The CP finds the related checklists. As an emergency can rapidly escalate, the checklists were performed as soon as the aircrew identified the failure and the side affected by the failure. Use of checklists.
Expectancy	This is a standard decision in the procedure to resolve engine failure.
Conceptual Model	Yes, if there was something else going on that is of more urgency. For example, if there is a problem in one of the engines due to high oil temperature this could of caused the failure and the pilot would usually shut down this engine, but if the other engine is on fire, then the pilot could keep the high oil temperature engine going.
Uncertainty	There could be uncertainty about whether the affected engine has shutdown correctly and the engine fire has been put out. The pilots need to continuously monitor the systems, as there might be something going on that the aircrew might not have identified.
Information	All the warning lights, sounds, and engine information. The pilot stated that it was not just a single piece of information used to identify the decision.
Situation Awareness	Same as decision point 1 and emergency checklist steps.
Situation Assessment	Yes the information was available. Checking the engine fire, whether severe damage has occurred and for normal engine failure.
Options	There is a second fire-extinguishing bottle, which can be fired if the first one does not extinguish the fire. However, there is no extinguisher left for the remaining engine. The other options are to "land as soon as possible", which is usually the last point in this checklist
Stress	Yes as turning off the wrong engine could be fatal.
Choice (rule)	Shut down affected engine and extinguish/fight the fire. Follow the checklist rules which are guidelines. Based on training and experience and full situation awareness. What could be a good decision in one situation could be a bad indication in another situation. It's the creativity of the human.
Analogy	Yes this has been practised intensively during training

Table E.3: CDM Interview 1: Decision Point 3 - Implement Emergency Procedures and Checklists

Decision Point 4: Mayday call

The PIC declared emergency or not. But with severe problems aircrew are advised to declare emergency to get priority handling by ATC, see Table E.4.

CDM Item	**Response**
Goal Specification	To make mayday call.
Cue identification	Depending on how severe the problems on-board the aircraft.
Expectancy	This is a decision that is made by the PIC
Conceptual Model	If a may day call is made, this is deviating from the expected flight path.
Uncertainty	The aircrew need to bring together information from a number of sources.
Information	Information regarding the distance out, weather, runway length & condition, support to be expected, limitations to the field (e.g. based on NOTAM information).
Situation Awareness	Monitoring systems, liaising with ATC and reviewing NOTAMS.
Situation Assessment	The whole crew working together to make this decision.
Options	To continue on route or deviate for an emergency landing. Between the different airports. Open field emergency landing
Stress	Yes, from the stress of determining if the aircrew should deviate the flight. There are a number of things to do.
Choice (rule)	If you have severe problems on-board make a may day call.
Analogy	Yes, from previous training.

Table E.4: CDM Interview 1: Decision Point 4 - Mayday Call

Decision Point 5: Implement abnormal checklist

Abnormal checklists were implemented to check for abnormalities in the system. See Table E.5, which outlines the decision point.

CDM Item	**Response**
Goal Specification	Ensure the abnormalities with the emergency are resolved
Cue identification	Ensure that the associated switches have been switched off, resolving fuel imbalances and looking for abnormalities
Expectancy	This is part of the procedure once an emergency has been identified

Conceptual Model	Looking for values that deviate from what the pilots normally see. For example, a fuel imbalance which is when there is more fuel in one tank in comparison to the other
Uncertainty	There is uncertainty if there is another failure occurring at the same time. Also uncertainty regarding what is causing the failure.
Information	The abnormal checklist is used as a cue to all the actions that need to be checked and completed
Situation Awareness	Monitoring of several systems including the engine format, the fuel format and the associated tappings pages
Situation Assessment	PIC and CP work together to look for anomalies
Options	How much fuel to balance, which switches to turn off and identifying if values are abnormal.
Stress	Yes, this was high workload and high stress. They were exploring the systems to ensure that what they were seeing was correct and that there was not another failure occurring. There is the underlying threat that the situation can become life threatening at any point, which contributes to the pilots' stress levels.
Choice (rule)	-
Analogy	Yes, this was well rehearsed, as the checklist is a standard procedure.

Table E.5: CDM Interview 1: Decision point 5 - Implement Abnormal Checklist

Decision Point 6: Decide which emergency field of use

The best emergency airfield for safe landing the aircraft was selected, see Table E.6.

CDM Item	**Response**
Goal Specification	To safely land the aircraft
Cue identification	Vectors to the closest air field. The air field specification – i.e. how long the runway is. Additionally, the pilots might spend some time (but not a lot) considering the suitability of the weather from the weather briefing/forecast from the briefing package/papers or from ATC. The pilots also check whether there are NOTAMS to see if there are any limitations on the airfield. Many aspects need to be put together here and the crew may find themselves in a situation where they do not have a good solution but some bad solutions. For example, there is an airfield nearby but there are bad weather conditions or there is a short runway. Another option the pilots might have is that there is an airfield that is further away with better weather and a longer runway. The pilot needs to make a decision whether to land at the close airfield with the risk of leaving the runway at the end, especially if the fire is confirmed and not extinguishable, or not. If the aircrew deems that the fire is not threatening they may decide to continue to the better airfield, which is further away. This is a good solution provided the assumption is correct. However, if the fire develops and becomes more sever this could turn out to be the wrong decision. Therefore, the pilot must be certain of the extent of the fire and how it is evolving.
Expectancy	The decision was already made but this is deviating from it.
Conceptual Model	Depending on the aircraft. Weather/NOTAM. Uncertainty No.
Information	Distance/flight time to the airfield, weather forecast, actual weather, NOTAM, available services at the field (e.g. are enough fire engines available/enough medical assistance if it is a passenger aircraft. Situation Awareness Could see on the system the way-points (flight management system, on a map).
Situation Assessment	-
Options	Options to two/three air fields.
Stress	The stress remained until after landing and when all people have left the aircraft safely.
Choice (rule)	There was a choice of which field to go to.
Analogy	This is less well rehearsed.

Table E.6: CDM Interview 1: Decision Point 6 - Decide which Emergency Field to Use

E.0.0.2 CDM Interview 2: Radio Communication Loss

Description

Pilot 2, a captain in the Spanish air force had described a situation where she was flying a Cessna Citation V with a 2 pilot aircrew and 1 passenger who was a photographer. Pilot 2 was the PIC in the aircrew with a higher ranking in the military, as well as more experience as a pilot than the CP (approximately 20 years). The flight was a simulation task for the military and she had been asked to carry out two missions in the aircraft. First, to simulate a hijacking of the jet aircraft, which was a joint mission with the French air force and secondly, to take an aerial picture of an aircraft, at a particular location (Zaragoza). The aircrew left from Getafe airbase, Spain, and would simulate the hijacking just before going over the French border. Here a Spanish fighter pilot in an F18 would meet them. The mission plan stated that they would need to ignore the Spanish fighter pilot's instructions as they were simulating that the aircraft had been hijacked, the aircrew did not have control of the aircrew and were to simulate that they did not have radio communication. The aircrew then would need to cross over to French airspace where the Spanish fighter pilot would leave and the aircrew would then be met by a French fighter pilot in an Eurofighter. Here the aircrew were to follow the French pilot's instructions, as it was planned in the simulation that the hijacker had been restrained and the aircrew had got back control of the aircraft. The planned route involved the French pilot escorting the aircrew to the French airport and then the aircrew would perform a "go around" and head back to Spain. This would complete the first mission. The second mission, returning to Spain, was to take an aerial picture of an aircraft at a particular time in Zaragoza and landing back in Getafe.

On the day of the flight, the PIC had been drafted in at the last minute, as the original PIC had not been able to do the flight. She was given the briefing notes as well as the mission plan before the flight and had sufficient time to review them. Upon reviewing the notes and plans she noticed that the times that had been scheduled for each part of the flight were very tight. The PIC spoke with the team who had developed the mission plan to inform them that she felt there was not enough time for her to complete everything and she asked what was of priority.

Takeoff, climb and cruise had initially been normal until they had started to experience partial loss of radio communication whilst still in Spanish airspace. The PIC explained that there are three radio frequencies that they can use and that they were having difficulty

understanding ATC and communicating with them so they had to keep changing the frequency in order to hear and communicate better, they spent approximately half an hour trying to resolve the radio communication issue.

Whilst trying to solve the radio communication problem, as planned, the Spanish fighter pilot came and the aircrew followed the mission plan where they ignored all communication with this pilot. The PIC changed to manual flying from autopilot to have better control of the aircraft as they were flying very close to the fighter pilot. The Spanish fighter pilot left them and the aircrew then crossed over in to the French airspace. Whilst they crossed over into this airspace, they experienced icy conditions as they were going in and out of clouds. The aircrew had to visually check the icy conditions to turn the anti-ice and de-ice on and off.

When the pilots went over to the French airspace they were met by the French fighter pilot who tried to engage with them by shaking his aircraft from side to side. However, the pilots realised that they were experiencing a real radio communication loss as it had been planned that they needed to communicate with ATC. The pilots continued to test the communication equipment including checking the hand radio, the head phones and the communication checklist. The PIC then asked the CP to turn all the radio equipment to listening, as they were not able to resolve the issue. However, the PIC did not want to do this and continued to test the equipment, as he wanted to find the frequency that would work.

The PIC then reduced the aircraft speed to allow herself to have more time to think about what she needed to do. The PIC then asked the CP to check the mission plan to see if there were any notes regarding what to do in a case of an emergency. However, the mission plan was not helpful as it stated to communicate the emergency to ATC, this with the current radio communication loss, was not possible.

The aircrew then started to hear some communication from ATC. ATC asked the aircrew to use the radar identifier if they could hear them. ATC asked three times and the PIC only identified two times. On one occasion, the PIC did not identify as she felt that they were not receiving all the communication and she was unsure whether to continue identifying. She was unsure if all the ATC communication was getting through as the communication coming through was of such poor quality.

The PIC decided that to abort the mission plan, including mission two, as there was a real radio communication loss. At this point, she told the CP that they should no longer think about the mission and focus on the safety of themselves and the aircraft. The PIC asked the CP to complete some additional tasks such as to change the transponder and input items into the avionics. However, the CP was not able to complete these actions

as he was still trying to investigate the radio communication equipment. The PIC stated that she had wanted to hand over the controls to the CP, but was not able to, as the CP was not able to cope with the stress of the emergency.

The PIC decided to follow the French pilots instructions as planned as the French pilot had more "awareness" than she had. The PIC asked the CP to put down the landing gear, which was the planned method for the aircrew to identify with the French pilot that they would be following his direction, however the CP did not follow orders and the PIC completed this action. At the same time, the CP had become quite anxious and unfocused regarding the flight. The PIC was trying to calm the CP down as the CP's focus was still on taking the photograph, even though this was not of importance at this point.

Whilst approaching the French airport, the aircrew started to be able to hear radio communication from ATC and a French fighter pilot. The pilots continued to the French airport and performed the "go-around". In the mission plan it had stated that they should go to a point in Zaragoza to take the picture and then back to Getafe military airbase, however, as the aircrew had experienced a radio communication failure, the PIC had decided to abort the mission and head straight back to the military base in Getafe. The PIC then realised that they were running out of fuel as they had spent approximately 1 hour trying to solve the problem with the radio communication equipment, and had reduced their aircraft speed. This meant that there was not enough fuel to complete the whole flight back to Getafe safely. From France to Zaragoza, the pilots had all radio communication. The pilot decided to land at Zaragoza to get more fuel and then continue to Getafe.

Once the pilot landed in Zaragoza, she was instructed to refuel and a couple of hours later to complete the second mission. The second flight allowed the aircrew to take the aerial picture using normal procedures. During the second flight, the PIC stated that the CP was far more tired than she was and wanted to rush through the flight.

Task Decomposition Diagram Figure E.2 presents a task decomposition diagram radio communication loss.

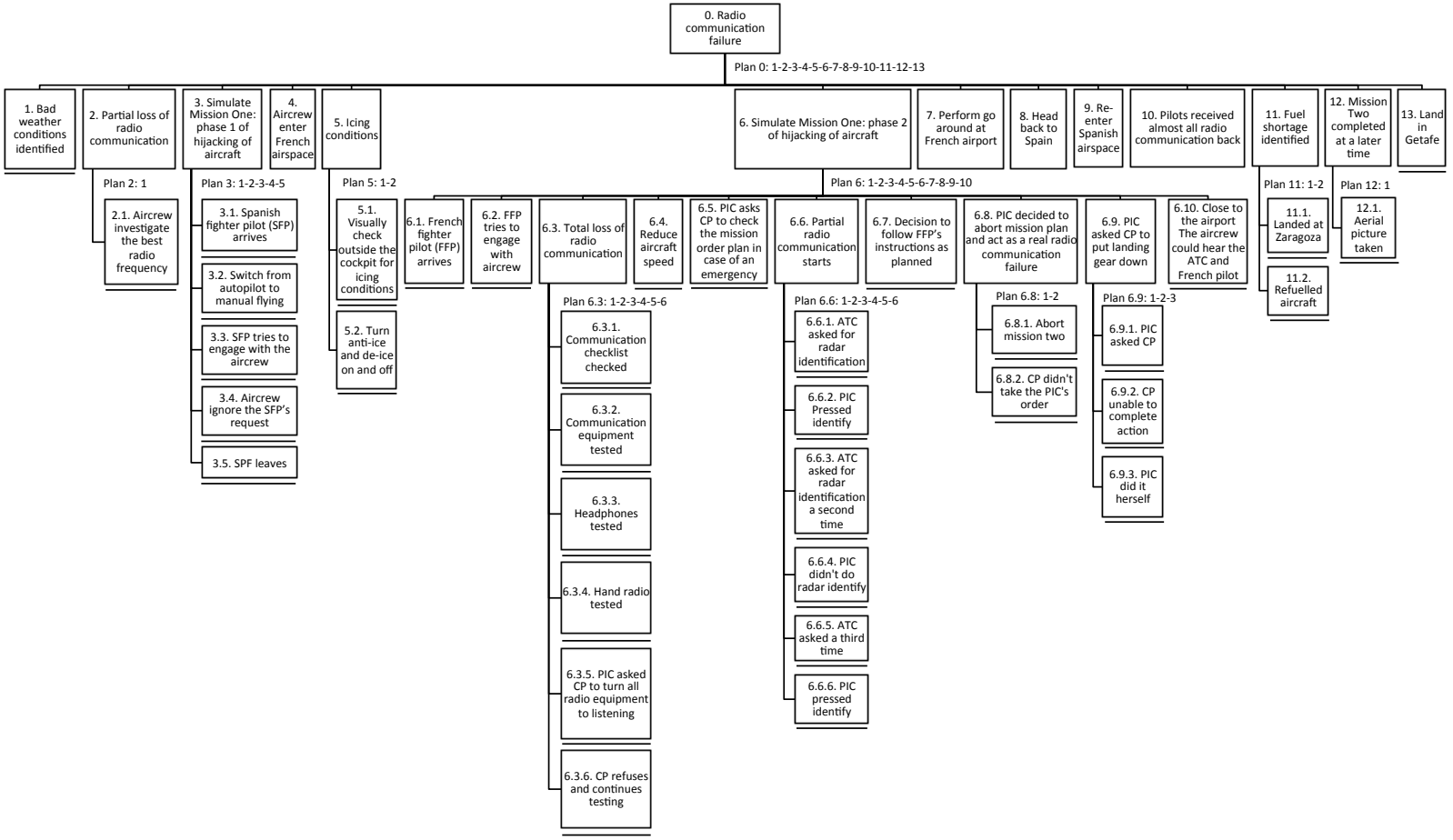


FIGURE E.2: CDM Interview 2: Radio Communication Loss Task Decomposition Diagram

Decision Points

Six main decision points were identified, these are discussed below in tables E.7, E.8, E.9, E.10, E.11 and E.12.

Decision Point 1: Turn all radio equipment on for listening

The PIC asked the CP to turn all radio equipment to listening to give the aircrew the ability to understand the little communication that was coming through.

CDM Item	**Response**
Goal Specification	The PIC identified that radio communication was lost and that they wanted to try and hear what ATC and the French pilot were saying.
Cue identification	As they could not communicate with ATC.
Expectancy	No
Conceptual Model	If the aircrew could not hear ATC then the PIC would not have asked the CP to turn all the equipment on, as in this situation they could hear some of the ATC radio communication and they wanted to make it clearer.
Uncertainty ‘	Uncertainty about what ATC was saying because it kept cutting out and the PIC wanted to make the communication clearer.
Information	The PIC wasn’t sure which frequency was working.
Situation Awareness	Three different frequencies of which only some were working and some weren’t and the PIC wanted to get the strongest sound.
Situation Assessment	The aircrew used additional information by using backup frequencies from the mission plan but the PIC could not determine the best one.
Options	Not turning all the frequencies to listening, for example only turning on one to listening.
Stress	There was stress, the PIC felt she was able to manage it but the CP was far more stressed, which resulted in the PIC having to complete not only PF tasks but also PM tasks.
Choice	“When there is no radio communication you need to have as many sources of communication open/on as possible.”
Analogy	Yes, it has happened previously. You try the second frequency.

Table E.7: CDM Interview 2: Decision Point 1 - Turn All Radio Equipment on for Listening

Decision Point 2: Reduce air speed

The PIC reduced the speed of the aircraft.

CDM Item	**Response**
Goal Specification	To have more time to understand the information and to try to calm the CP down.
Cue identification	Decisions needed to be made but there was not enough time with the current aircraft speed.
Expectancy	No because there was an exact flight plan for the mission.
Conceptual Model	No.
Uncertainty	Yes because the aircrew were not sure what to do and needed more time.
Information	Nothing was planned for this failure situation and the aircrew needed to think about what future decisions needed to be made.
Situation Awareness	The aircrew was within the pilot's acceptable limitation within the anti-ice limits and in the limit of being able to follow the other aircraft.
Situation Assessment	Yes.
Options	There was a possibility of holding at the same position and not going any further. – this was not the best option as there was no communication.
Stress	Yes.
Choice	"If you have to face something unexpected and with no clear checklist to follow, the best option is to slow down within the limits including aircraft, visibility and ATC, etc."
Analogy	The pilot had done this many times, it is a standard procedure and experienced pilots would do this.

Table E.8: CDM Interview 2: Decision Point 2 - Reduce Air Speed

Decision Point 3: Radar identifier

When ATC identifies that there may be communication loss they send a radar identifier to the aircrew to identify if the aircrew can hear ATC even though the aircrew cannot communicate with ATC. In this incident, the aircrew felt they were only getting partial communication and the PIC was unsure whether to identify on each occasion.

CDM Item	**Response**
Goal Specification	When not to identify – the goal was to communicate that the aircrew could not always hear the ATC.
Cue identification	Because the ATC might think that the aircrew could hear all the communication, but this was not true as the communication was going on and off.

Expectancy	No.
Conceptual Model	If the aircrew could hear ATC clearly.
Uncertainty	There was a lot of uncertainty as the pilot was not sure if she had missed some information from ATC. So the first time she pressed the identifier, she felt that she had missed some information. When ATC asked the second time she did not press the button to indicate to ATC that they could not hear everything. The third time ATC asked to identify, the PIC did press it but the PIC felt this was a "bad decision".
Information	Sometimes the radio communication was working and other times it was not working.
Situation Awareness	Partial radio communication and information from testing the communication equipment.
Situation Assessment	The PIC asked the CP for his opinion of how to communicate with ATC via the Radar intensifier. The CP said he would have pressed it all three times.
Options	To press each time they heard ATC.
Stress	Stressful.
Choice	"Always do what ATC tells you. Don't ignore them because they have more awareness than the aircrew."
Analogy	The pilot had never experienced this situation, this was the first time. The pilot did not follow orders because the communication was very bad.

TABLE E.9: CDM Interview 2: Decision Point 3 - Radar Identifier

Decision Point 4: Take the French pilot's orders

Even though the PIC had declared that there was a radio communication issue and was not able to follow the complete mission plan, she decided to follow the French pilot as planned.

CDM Item	**Response**
Goal Specification	To follow someone with awareness and radio communication.
Cue identification	The aircrew needed guidance to the airport in a safe and secure manner.
Expectancy	Yes but with communication with ATC.
Conceptual Model	If the aircrew had been in Spain the pilot stated they would have done things differently, and would have gone to an airport in Spain and landed.
Uncertainty	Yes, the PIC was not sure whether to continue with the pilot to the French airport nor were they sure about the track that the French pilot would take them to, as there was limited fuel.

Information	Based on the fact that the aircrew were in a foreign country and not acting in a controlled manner.
Situation Awareness	Mission plan, icy conditions, communication loss, stressed pilot, which resulted in following the French pilot.
Situation Assessment	All information was used. The PIC wanted to go back to the Echo point (back to the Border) however, she did not have the authorisation.
Options	To ignore the French pilot and go back to Spain. To land at the French airport.
Stress	There was considerable stress as the PIC was flying without autopilot and in manual flying. It was made even more difficult because there was icy conditions and the PIC had to turn on and off the de-ice whilst the CP was not following the PIC's instructions. The CP was really confused and focused on the incorrect procedures. The PIC stated that the CP could not deviate from the original plan. For example, the PIC asked the CP to put the landing gear, which was a confirmation to the French pilot that they had understood everything, but the CP was confused and said "but this is not part of the plan," so then the PIC put the landing gear down herself. She said this increased her workload. The PIC also asked the CP to change the flight management system display, as the flight plan had changed. However, she stated that the CP was just touching buttons but was not able to take the orders she was giving, so again the PIC did it herself.
Choice	"In the event that you need guidance then follow the aircraft that has the knowledge/awareness or more information than you."
Analogy	No.

Table E.10: CDM Interview 2: Decision Point 4 - Take the French Pilot's Orders

Decision Point 5: Disregard mission plan and act as a radio communication failure

As a failure had occurred, the PIC's main priority was their safety and the mission was no longer of importance.

CDM Item	**Response**
Goal Specification	To safely go to an airport and land.
Cue identification	The PIC stated that they based this on the fact that they were suffering a real failure and the mission was of less concern than the safety of the aircraft.
Expectancy	Yes this was in the original flight plan.

Conceptual Model	No.
Uncertainty	The pilot stated that they wanted to complete the mission and comply with the military instructions but only for the go around at the French airport but they would disregard the rest of the mission, as it no longer was of priority.
Information	Real on-board failure and the aircrew needed to be safe.
Situation Awareness	There was not enough fuel to continue as planned.
Situation Assessment	The picture would not be taken clearly – the quality of the picture might not come out good. The allocated time to take the picture had already passed.
Options	There is the option to not act as a failure but this was not the case or act with the mission plan.
Stress	CP was stressed about not taking the picture but this was not of importance to the PIC.
Choice	"First to be safe and then do the rest."
Analogy	Yeah to abort mission when you are at risk. However, a lot of people take risks in the military, as there is pressure from people above – higher in rank.

TABLE E.11: CDM Interview 2: Decision Point 5 - Disregard Mission Plan and Act as a Radio Communication Failure

Decision Point 6: Land at Zaragoza

Although, as a result of the failure, the PIC had wanted to fly straight back to Getafe airbase, she realised based on the calculations made before the flight, that there was not enough fuel to go back to Getafe and that she would need to refuel at Zaragoza.

CDM Item	**Response**
Goal Specification	To get more fuel.
Cue identification	The PIC had calculated that there was limited fuel.
Expectancy	The PIC had expected to do this even though it was not planned as she could see from the plan that each of the tasks was at its limit. So she had some expectancy that refuelling would be needed. Radio communication had degraded.
Conceptual Model	If there had been more fuel, then the aircrew would have gone directly to Getafe.
Uncertainty	No, she knew exactly the fuel amount and that they needed more.

Information	The amount of fuel available in the aircraft.
Situation Awareness	Information from fuel format, the fuel calculations made before the flight, and the flight management system
Situation Assessment	Even if ATC had instructed her to carry onto Getafe, she would not have followed the order, as she knew she did not have enough fuel.
Options	Landed in France however, the aircraft did not have authorisation, only in the event of a severe emergency, which was not the case. The fuel was limited but it was not an emergency and the aircrew knew they could carry on to Zaragoza.
Stress	Just the CP.
Choice	"If you don't have fuel get some more fuel."
Analogy	Yes the PIC had experienced similar scenarios but when she was a CP where the PIC at the time wanted to push the limit of already limited fuel.

TABLE E.12: CDM Interview 2: Decision Point 6 - Land at Zaragoza

E.0.0.3 CDM Interview 3: Engine Stall

Description

Pilot 3 was acting as the PIC in a two pilot aircrew for a ferry flight from Sevilla, Spain to Toulouse, France. The pilots were in an A400M aircraft and the flight time was approximately 1 hour and 45 minutes. There were between 8-10 passengers on-board the aircraft, with cargo hold. There were a further 2 load masters who were responsible for the cargo loads.

On the day of the flight, the aircrew had completed the normal procedures before takeoff, during take off, after take off and climb. At 10,000ft, the pilot stated that they performed a check and the aircraft was performing as expected. However, between 15,000-18,000ft, when the aircrew were still climbing, approximately 15 minutes into the flight and whilst they were crossing some clouds, the master warning aural sounded, a visual cue was presented in the ECAM with a caution warning and the associated checklist appeared. The caution warning indicated that engine 3 had stalled.

As soon as the caution warning appeared, the CP called "engine three stalled" which the PIC replied "stand-by". The PIC then ensured that he had the aircraft under control, he checked that the aircraft was still flying correctly and that the autopilot and auto thrust were still engaged. The PIC also checked that the aircraft was still in "open climb and

navigation mode". Then the PIC analysed the situation by "trying to understand the problem". The PIC stated that he was trying to understand a lot of information at once, first understanding the location, the available amount of fuel as well as investigating the engine parameters (RPMs, Power, EGT (temperature) and fuel flow). The PIC stated that he was not sure why the stall had occurred. He stated that if there had been icy conditions this could of caused the stall, but this was not the case as it was a spring/summer day. The other option could have been that something had come lose in the engine, however, they could not physically look into the engine itself. The CP also looked out of the window to see if there was any damage to the engine but did not identify anything unusual. One of the load masters was also asked to look out of the window at the back of the aircraft, to see if he could see anything unusual, but he also could not identify anything unusual. Once the PIC had an understanding of what was happening and had identified that they were in a stabilised situation to deal with the checklist, the PIC then said "ECAM actions" which indicates to the CP that he is ready to start the steps of the checklist. As a consequence of starting the checklist control, the radio is transferred from the CP to the PIC.

The CP read and completed most of the items on the checklist. However, there were certain actions that the CP can not complete as these must be completed by the PIC. For example, the engine master and thrust levers to idle. Here, the CP reads the item, the PIC puts his finger on the button, the CP then visually and aurally confirms that it is the correct lever. One of the steps in the checklist asks the pilots to investigate the engine parameters. The PIC decided to test engine 3 (affected engine) with engine 2 (which was functioning correctly). The PIC put engine two into the same position as engine 3 and "checked all the readings to see if they are more or less the same". The pilot wanted to see if engine 3 was performing at the same level as the good engine, and the PIC confirmed that it was. The pilot stated that "apparently everything was correct... they were the same" and they could not see a difference between the two engine parameters. The pilot stated that "the most important thing here was to check the EGT" as it is a good indicator that something incorrect is occurring and the engine isn't working correctly. The PIC stated that if they had seen a large difference they would have needed to shut the engine down.

Once the checklist was complete, the radio communication was passed to the CP and the aircrew discussed what to do next and what they should do in regards to landing. As the aircrew could not identify why the engine had stalled, they felt there was something wrong with the engine. Based on this reason, as well as only being into the flight for 15 minutes, the pilot stated that the decision was quite clear to return back to Sevilla. The aircrew decided to keep the engine at idle and monitor the engine as they were at altitude. They briefly considered shutting down the engine but this was not done as the engine

parameters were in the normal range and the aircrew wanted to preserve the engine in case of any other failures that could occur.

The pilots then informed the passengers that there had been an engine stall and they had decided to return to Sevilla. Approach and Landing was completed as expected.

Task Decomposition Diagram Figure E.3 presents task decomposition diagram of a engine stall.

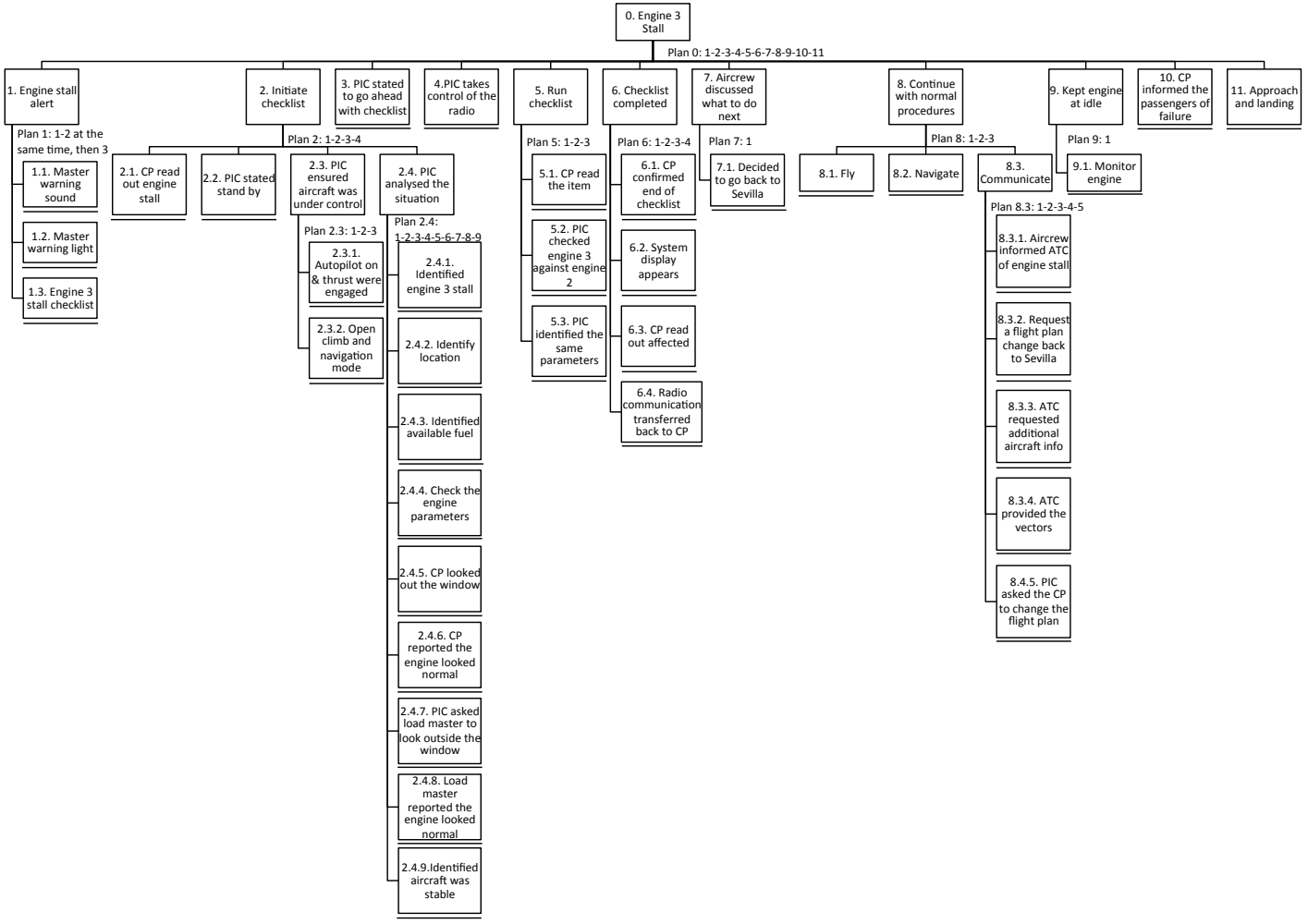


FIGURE E.3: CDM Interview 3: Engine Stall Task Decomposition Diagram

Decision Points

Three main decision points were identified, these are discussed below in tables E.13, E.14 and E.15.

Decision Point 1: Check engine 3 against engine 2

The PIC checked engine 3 (the affected engine) against engine 2 (the good engine) to compare the engine parameters

CDM Item	**Response**
Goal Specification	To see if the parameters of engine 3 (the affected engine) were normal by testing it against engine 2 (a good engine).
Cue identification	The two values matched in the engine status display. Checking the engine parameters was cued in the checklist but the choice of comparing the two engines was the PIC's decision.
Expectancy	The pilot had not expected to carry out this decision in the flight but once the checklist had started he knew he would need to do this.
Conceptual Model	The PIC stated that it was the easiest way to test the engine and it was a method that allowed the CP to also check the values of the engine. The PIC also stated it was a fast and objective way to check the values, without having to rely on memory, which means that "there is little room for error but you have to be in a situation that you can do this, for example, in take off you can't do this test as you need engine 2".
Uncertainty	No.
Information	Caution warning.
Situation Awareness	Master warning, engine parameters, checklist items and looking out of the window.
Situation Assessment	All the information was used.
Options	The other option would have been if the PIC knew the engine parameters off by heart, which he stated that he did not.
Stress	Stress increased a little bit.
Choice	"Compare the bad engine to a good engine".
Analogy	The pilot had experienced this many times in a fighter aircraft. This often happened as fighter pilots push the aircraft to its limits.

Table E.13: CDM Interview 3: Decision Point 1 - Check Engine 3 Against Engine 2

Decision Point 2: Keep engine 3 idle and not to shut it down (affected engine)

As the aircrew could see that the engine parameters for engine 3 were in the normal range and they could not determine the cause of the stall, the pilots decided not to shut down the engine.

CDM Item	**Response**
Goal Specification	The engine was not shut down in case the engine was needed. For example, if another failure occurred which was more severe, the aircrew may need this engine.
Cue identification	This was based on the fact that none of the engine parameters were out of line and were similar to a "good engine".
Expectancy	Yes.
Conceptual Model	If there was a parameter out of line.
Uncertainty	No.
Information	The comparison with engine 2.
Situation Awareness	Engine parameters and checklist items.
Situation Assessment	The pilot said he would have liked to see the interior of the engine to see if there was a lose piece in the engine.
Options	To the shut the engine but this was not ideal.
Stress	Stress went down from decision point one.
Choice	To save the engines for as long as the parameters remain normal.
Analogy	Yes, same as decision point 1.

Table E.14: CDM Interview 3: Decision Point 2: Keep Engine 3 Idle and Not to Shut It Down (Affected Engine)

Decision Point 3: Go back to Sevilla

As the pilots could not identify why the engine had installed they returned back to Sevilla.

CDM Item	**Response**
Goal Specification	The PIC's goal was to land as soon as practical in the home base airport as the airport had all the resources.
Cue identification	Time and distance to the destination. Weather conditions.
Expectancy	Yes, because the aircrew has to decide if they can continue the mission or not and the implications it has if they land in another airport.

Conceptual Model	If you were closer to Toulouse – if there was the same conditions. If you had to shut down the engine then the PIC would have considered diverting to closest and most suitable airport.
Uncertainty	No, it was an easy decision to make.
Information	The proximity of the airport and the severity of the emergency.
Situation Awareness	Weather and distance to airport.
Situation Assessment	No.
Options	To continue with the flight plan.
Stress	Same as decision point 2.
Choice	The pilot stated, "In case of doubt there is no doubt... if you are not sure, be conservative."
Analogy	Yes.

TABLE E.15: CDM Interview 3: Decision Point 3 - Go Back to Sevilla

E.0.0.4 CDM Interview 4: Engine Fire

Description

Pilot 4, an Airbus test pilot, outlined an engine fire that he experienced in a BR1150, maritime patrol aircraft. The aircraft was originally designed for patrol and anti-submarine warfare. It can also be used for search and rescue missions (SAR), surveillance and transport. The aircraft is equipped with two Tyne MK21 axial flow turboprop engines and has three cockpit crew including PIC, CP and flight engineer.

On the day of the incident, pilot 4 was the PIC and experienced a suspected fire indication in one of his first flights in this aircraft. Previous to the incident, the pilots were aware that the fire indication often gave false positives, the pilots were required to go through the procedures to ensure that there was not a real fire.

The aircrew initially became aware of the fire indication by an audio alarm and three visual cues:

- Red light warning in the condition lever
- Master fire warning light in the engine section of the centre panel
- Red light in the emergency T-handles.

The pilots first maintained aircraft control and then analysed the situation. They checked which engine had failed by checking the engine indication and the warning system in the cockpit systems. Then the pilots used emergency checklists; first completing the memory items, which are immediate actions and are highlighted in bold on the checklist. The memory items are actions that the pilot said they thoroughly train for. The first memory item was to turn the condition lever off so that no more fuel is given to the engine and then he *"feathered the propeller"* in order to reduce the aircraft drag. As a result the fuel flow goes down to zero on the fuel gauge and he watched the propeller through the window to see that it had reduced speed, this happened rapidly. The LP tachometer RPM (instrument measuring the rotation speed) went down close to 0. Pilot 4 then checked for smoke trails from the engine and saw that the turbine temperature had lowered in temperature.

The next item was to then advance the power levers, so that the good engine achieves maximum thrust to maintain the speed and stay as high as possible (maintaining altitude is usually not possible with only one engine). This increased the rpm, temperature, torque meter and the pilot heard the propeller getting faster. The pilot stated he could feel the aircraft *"reacting"*. In parallel to turning the condition lever and power levers up, he then rudder trimmed which reduced the force on the pedals.

The pilot then pulled the T-handle (which is situated in the overhead panel) and turned it. The pilot stated that by pulling the handle this closed fuel and hydraulic valves. The pilot waited until the propeller had come to a complete stop, this was done visually. When turning the handle this shot a fire extinguishing bottle into the engine. The fire warning light then went out. The pilot stated that if the fire warning light did not go out or if he could see that there was a fire through the window then he would have turned it in the other direction to fire the second bottle to put out the engine fire. For this incident he did not do this but it was something he was considering. The pilot then checked that the oil temperature had increased.

The pilot called for *"Inflight engine shutdown checklist"*, the CP found them and called out each procedure step. The memory items for the emergency checklist were reconfirmed, by reconfirming the three steps to ensure that they had been completed. Then each of the non-memory items are completed. Once the checklist was completed the pilot made a *"mayday call"* to ATC. He called *"May day"* three times to alert the ATC tower that it is an emergency call. He stated the call sign, type of aircraft, type of malfunction, weather, pilot's intention, present position, altitude, fuel in hours and minutes, number of persons on board. There was further dialogue between ATC and the aircrew but he could not remember specifics.

The pilot stated that the aircrew wanted to make an emergency landing. They determined that the suitable landing field was the destination airfield and made no alterations to the route and continued flying normally. The aircrew landed safely and post flight it was determined by the engineers that it had been a false positive and that there was no real engine fire.

Task Decomposition Diagram

Figure E.4 outlines the steps completed in the engine fire failure in the form of a task decomposition diagram.

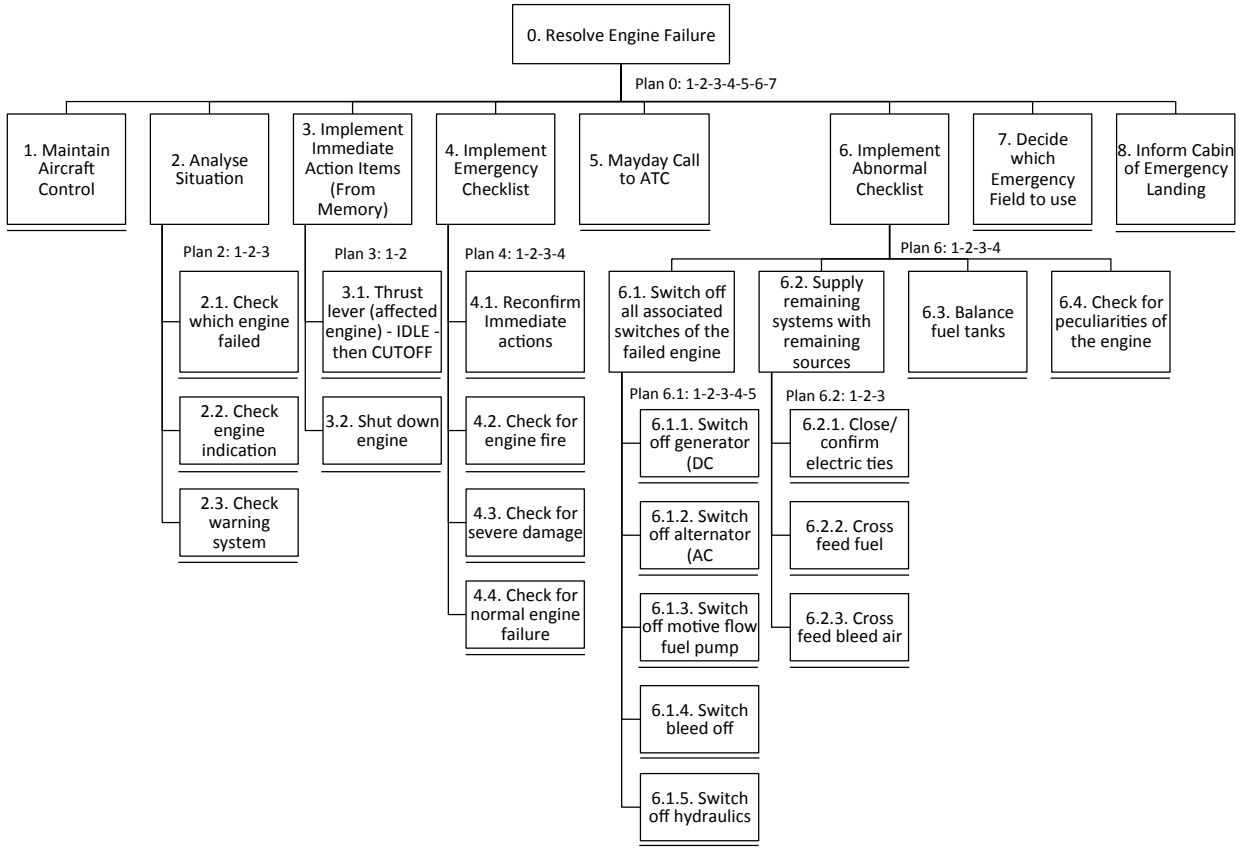


FIGURE E.4: CDM Interview 4: Engine Fire Task Decomposition Diagram

Decision Points

The pilot identified two decision points in the emergency; the mayday call and landing. These are discussed further in tables E.16 and E.17.

Decision Point 1: Mayday call

CDM Item	**Response**
Goal Specification	To declare emergency to ATC.
Cue identification	That one engine has been shut down.
Expectancy	Mayday calls are not expected only when there is a real emergency and there might be the need for emergency services.
Conceptual Model	No, once you have this alert you need to make a mayday call.
Uncertainty	No, once you shut down an engine. The procedure is to make a mayday call. So there was not much
Information	That one engine had been shutdown.
Situation Awareness	That they could continue flying normally but were not sure if there was a real fire inside the engine and what damage had been caused.
Situation Assessment	Nothing else needed.
Options	No.
Stress	A little stress.
Choice (rule)	"Alert ATC in the event of an emergency".
Analogy	Yes in other aircraft.

Table E.16: CDM Interview 4: Decision Point 1 - Mayday Call

Decision Point 2: Landing

CDM Item	**Response**
Goal Specification	To land as quickly as possible.
Cue identification	Investigating how much fuel there was onboard, how long we could fly for safely and how far the closest airfield was.
Expectancy	The end result was expected.
Conceptual Model	Yes if there was a closer appropriate airfield we may have diverted to this airfield.
Uncertainty	No.
Information	The fuel information and the distance to the airfield.
Situation Awareness	Engine parameters, fuel information and time to destination.

Situation Assessment	Used all the information, nothing else needed.
Options	No.
Stress	Lower than decision point 1.
Choice (rule)	*"Land at the safest and appropriate airport"*
Analogy	Yes many times.

TABLE E.17: CDM Interview 4: Decision point 2 - Landing

E.0.0.5 CDM Interview 5: Severe Turbulence

Description

Pilot 5 was a CP on a flight 5 hour in August 2015 that had severe turbulence on the approach to Sigonella (LICZ), an Air Force base, in Sicily. The flight was undertaken to perform a site survey to establish if a Spanish military unit could be developed in the base. The unit would carry out the surveillance of the Mediterranean for the immigration issues. There were approximately 10 passengers including two mayors, doctors and military personnel, the aircrew consisted of two pilots and a flight engineer.

The flight took off in Getafe, Madrid, the pilots had checked the weather, which forecasted "not too bad weather". However, the weather service forecasted that there could be storms in the afternoon but not during the flight hours. Approximately an hour before landing, the pilots started to experience a little turbulence. The pilot described that outside the aircraft they could see a lot clouds and in the distance they could see a storm. The pilot stated that they discussed flying around the clouds in order to avoid the storm. The CP turned the seat belt sign on to get passengers safely into their seats.

ATC then contacted the aircrew to advise that two other aircraft had missed the approach at Catania (LICC) (very close to Sigonella) as "they could not make it" and had landed at an alternative airport. The PIC asked the CP to turn the seat belt sign on, the CP replied to her that the seat belt sign had been on for some time. The PIC could see that there were a number of people walking around who had not taken their seats. The PIC then asked the CP to reset the seat belt sign a few times so that "people can see the light flashing... hear the sound going cling, cling, cling". No announcement was made as the speaker was not functioning.

Onboard the aircraft there was a table for the passengers to congregate around. The PIC again checked to see that the passengers still had not taken their seats and that people were standing around the table. The PIC then asked the flight engineer to go over to the passengers and ask them to take their seats. However, once the flight engineer got up and went into the cabin to tell the passengers to sit down, there was severe turbulence. Due to the severe turbulence, there was a wardrobe in the cabin which flew open and the wardrobe items fell out, the flight engineer was hurt with minor injuries (he scratched his chest with the corner of the wardrobe's door) and one of the passengers who was standing around the table was more severely hurt (dislocated arm and broken bone). The onboard doctor identified that the passenger had been hurt significantly but was in a stable condition. The flight engineer returned to his seat and reported back on what injuries had occurred.

The CP stated that the injuries at the time did not worry him as much as their heading, straight into the storm. Outside the aircraft there was hail and lightening, which could be seen and the hail could be felt. Furthermore, every time there was lightening, the radio communication was lost and they were experiencing crackling over the radio. As the aircrew had been descending the pilot said that he was comforted by the fact that he could see the ground and stated "when you can see the ground it always makes you feel better". As they were going hit the storm directly the aircrew discussed that they need to change their heading. Either to the left which would have taken them to the airport or to the right which was towards the sea and the pilots could see that there were good weather conditions. The CP then contacted the radio ATC to request a change of heading, which ATC changed to the direction of the airport for landing.

The radio ATC then changed the pilots frequency and put the CP through to the control CP at the airport for landing clearance. There the CP requested an ambulance to be present on landing that the onboard doctor had requested. The aircraft traffic controller then asked the CP if he was declaring an emergency but he said no because it was not a critical emergency as they would be landing imminently and the passenger was stable. The ATC then contacted a doctor while still communicating with the aircrew. The doctor asked the air traffic controller questions who in turn asked the CP questions on the passenger's health. The CP did not declare an emergency as this would mean that there would be several emergency services. On landing the passenger was taken to the hospital.

Task Decomposition Diagram

A task decomposition diagram of events presents the steps to resolve severe turbulence, see figure E.5.

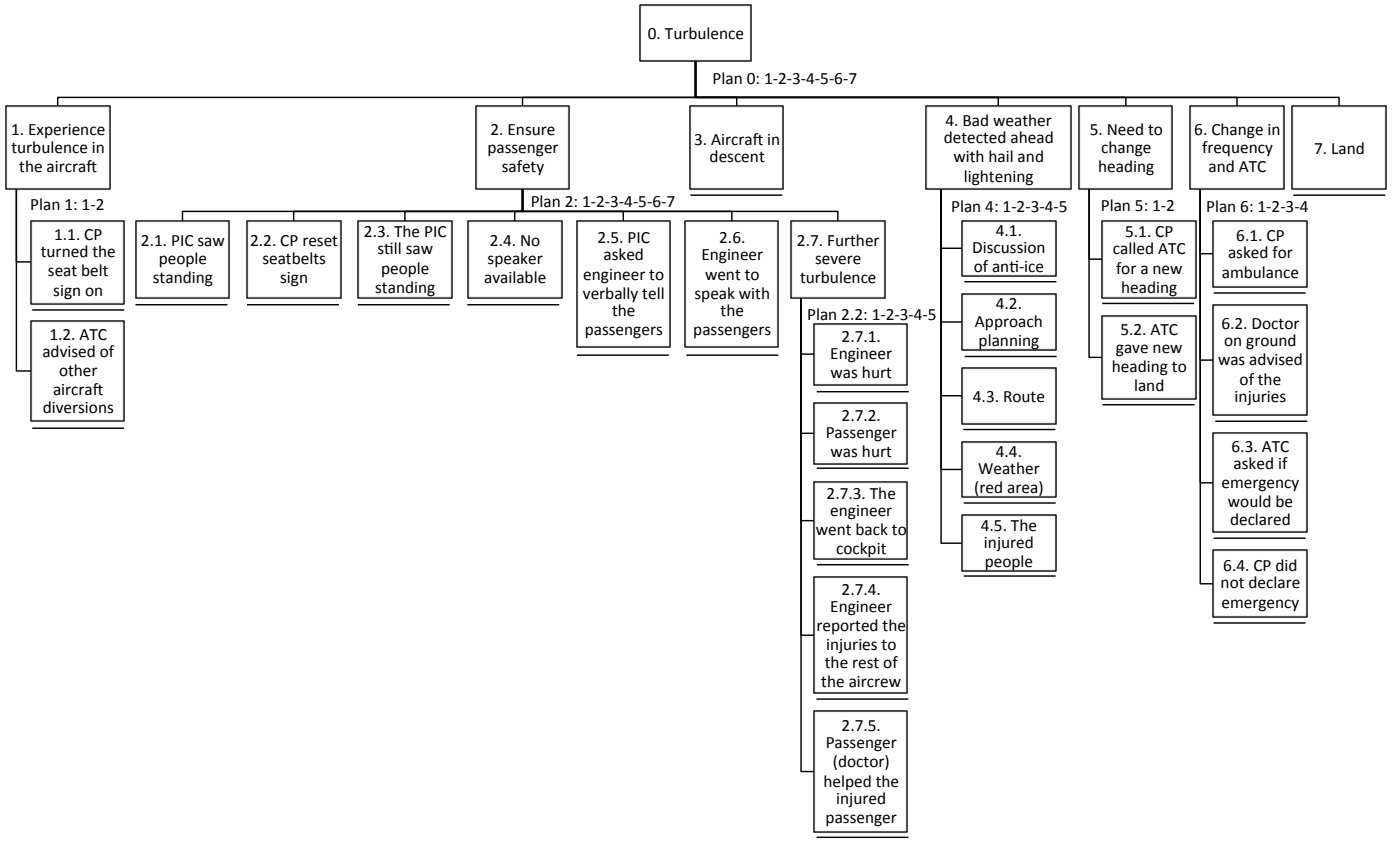


FIGURE E.5: CDM Interview 5: Severe Turbulence Task Decomposition Diagram

Decision Points

Four main decision points were identified, these are discussed below in tables E.18, E.19, E.20 and E.21.

Decision Point 1: Seat belt signs on and reset

As soon as the pilots experienced turbulence in the aircraft, the CP ensured that the seat belt sign was on. The PIC looked behind and she saw that the passengers were congregated around a table and asked the CP to reset the seat belt sign, which flashed on and off and also a sound is made when the seat belt sign is turned back on.

CDM Item	**Response**
Goal Specification	Ensure the safety of the passengers
Cue identification	Turbulence
Expectancy	Yes because the seat belt needs to go on when in the approach phase
Conceptual Model	No
Uncertainty	No
Information	Plane moving severely.
Situation Awareness	Yes
Situation Assessment	Yes
Options	Announcing through the speaker but it didn't work
Stress	Yes a lot
Choice	Turbulence = seat belt
Analogy	Turbulence before but without passengers

Table E.18: CDM Interview 5: Decision Point 1 - Seat Belt Signs On and Reset

Decision Point 2: Flight engineer to verbally tell passengers

The PIC looked behind into the cabin and noticed that the passengers still had not taken their seats and asked the flight engineer to verbally tell the passengers to sit down as the flight engineer was acting as a "flight attendant".

CDM Item	**Response**
Goal Specification	Ensure the safety of the passengers.

Cue identification	The PIC looked behind her and saw passengers around the table, planning their activities and they had ignored the aircrew and seat belt signs.
Expectancy	No.
Conceptual Model	Yes, if they had listened then the PIC would not have asked the flight engineer to attend to the passengers. If PIC had not asked the engineer to go and on used the seat belt sign. If the announcer/speaker was working.
Uncertainty	No, but the CP felt that he would not have done it and felt that the PIC had been too nice by sending the engineer.
Information	That the passengers were not sitting down and that she saw them.
Situation Awareness	The information from the cabin.
Situation Assessment	Yes.
Options	Not to send the engineer.
Stress	Yes.
Choice	- didn't feel there was a rule.
Analogy	Same as the previous decision point but the pilot had never had to tell anyone else to go tell the passengers to sit down.

TABLE E.19: CDM Interview 5: Decision Point 2 - Flight Engineer to Verbally Tell Passengers

Decision Point 3: Diverting to sea or to the runway (continue the approach)

The weather began to get worse, with further turbulence due to storm conditions including hail stones and lightening. The pilots realised that they could not continue on the course they were currently heading on needed to change direction straight to the runway or to the sea where the weather conditions were better.

CDM Item	**Response**
Goal Specification	To avoid the bad weather and ensure the safety of the passengers
Cue identification	The turbulence and the weather indication from visually seeing hail stones and lightening. Radar information highlighted a red zone indicating bad weather. Information from ATC stated that there was bad weather and that two other aircraft had been diverted to alternative airports. Through the window the pilots could see the sea and better weather.
Expectancy	Yes and no, when the pilots make a flight plan you try to make a plan of what other landing you might need to make – alternatives but the CP did not feel that it was going actually happen as bad weather had not been reported in the briefing package.

Conceptual Model	If ATC did not give clearance.
Uncertainty	Both the pilots knew that they needed to change the heading.
Information	Weather information and radar. The radar showed how big the storm would be.
Situation Awareness	Visual, ATC, briefing information, weather, radar.
Situation Assessment	No had everything required.
Options	Yes to the sea, fly in opposite direction.
Stress	Yes.
Choice	Don't fly in to a storm.
Analogy	-

TABLE E.20: CDM Interview 5: Decision Point 3 - Diverting to Sea or to the Runway (Continue the Approach)

Decision Point 4: Not to declare emergency

CDM Item	**Response**
Goal Specification	ATC could not do anything to help and the pilots were out of the storm so the goal was to land the aircraft.
Cue identification	Passengers were not badly hurt but the doctor on board asked for an ambulance. Declaring an emergency means that other emergency services would be called and it was evident that they did not require all these services.
Expectancy	No, they weren't.
Conceptual Model	If they passengers were badly hurt for example, an open wound. If there was damage to the aircraft.
Uncertainty	No, there wasn't.
Information	The pilots knew at this point that they were landing and the passengers were not badly hurt.
Situation Awareness	Doctor's advice.
Situation Assessment	No.
Options	No
Stress	Had got a lot less.
Choice	-
Analogy	No, that was the first time with injured people on the plane.

TABLE E.21: CDM Interview 5: Decision Point 4 - Not to Declare Emergency

E.0.0.6 CDM Interview 6: Error in Completing Aircraft Procedures

Description

This scenario presents a cargo flight in the Gulf Stream 1, where the aircrew was taking off in Barajas, Madrid to the Saarbruck, Germany to drop off resources and then complete the return flight to Madrid. The scenario describes an incident where the CP missed a step from the take off procedures for the return flight, which impacted the performance of the aircraft.

The participant was the PIC of the flight and worked for a cargo company that transport resources. The participant explained that the company did routine flights on behalf of other companies and on the day the incident occurred, the flight had been "on request" which meant that it was a non-routine flight and had been requested by a company who were unable to transport resources (automobile doors) between Spain and Germany due to a train strike. Consequently the cargo company were requested to transport these resources.

At the beginning of the flight it was reported that there was good weather conditions in both Spain and Germany. The pilot stated, "They did not have a previous relationship with the airport". For the assigned aircrew they were travelling to a new airport in Germany, which they had not flown to before.

The pilots took off from Spain and completed a normal flight to Germany and landed as planned. The resources were offloaded and the pilots were back in the cockpit to start the return flight. Once in the aircraft the pilots were ready to start the engines and requested the clearance from ATC. However, as this was a non-routine flight the pilots were asked by ATC if they had paid the handling costs and extra fees for landing and using the airport. The pilot stated that this is not an action that aircrews usually have to do, as there are contracts in place between the company they are flying for and the airport. Although the pilots had expected to pay the handling costs on this particular flight, they were not aware of the extra fees. There was a lot of confusion regarding payment, which resulted the aircrew leaving the aircraft and going to the tower to speak to ATC to clarify and pay the costs. This process took approximately two hours, as the company credit card the aircrew had was not initially accepted. The pilots were under pressure to resolve the issue quickly so that they could return the aircraft to the company as a second routine flight had been scheduled for the evening (approximately 11pm). They needed enough time to

take off, fly, land in Madrid and allow time for the next cargo containers to be loaded on to the aircraft.

Once the fees had been paid the pilots requested a landing slot in Madrid for approximately 4pm, however, they were allocated a slot for approximately 10pm, which was significantly later than they wanted. The PIC then re-planned the route to fly to Barcelona with "Madrid as an alternative". The participant described this as a "legal trick", where they re-plan the flight to get closer to the destination, once near to Barcelona (and before landing) they request an alternative landing in Madrid which would result in the aircrew arriving in Madrid sooner. However, the participant stated that this is a risk as they may not get a landing slot and would need to land in Barcelona which would result in additional handing costs and extra fees.

Once a landing slot to Barcelona had been secured, the participant stated that the pilots returned to the cockpit and restarted the procedures in the cockpit and requested engine start. The CP completed the necessary procedures and the pilots were ready for taxi and take-off, which the participant described as a "quick process from taxi to take-off, approximately 3 minutes". The pilots taxied and were cleared to take-off.

Upon taxiing on to the runway, the PIC applied thrust however, the PIC realised that the aircraft was not performing as he expected, as the aircraft did not have the expected thrust. The pilot stated that the "thrust was not high enough to continue the take-off". As the runway was short this was a problem, as the pilots would not be able to take off.

The pilot stated that this was "the point where they started to take a decision". The pilot then began to investigate the systems to identify what was happening. Here the participant stated that he was identifying "why with full levers [he] had lower than expected power". One of the things that the pilot wanted to know was if the engine parameters were lower than expected. The parameters were lower but looked normal considering the known conditions. The PIC stated that this aircraft has a system, which improves the thrust by adding a mixture of water and alcohol to the engine and the pilot stated that it occurred to him that this could be reason why the thrust was lower than expected. Then the pilot checked the water and alcohol mix indication, which was indicated as zero. The pilot stated that he could not remember the value it should have been but it was a value that he had calculated and ranged approximately between $1 - 100$. The pilot stated that the calculation had to take into consideration the weight of the aircraft and the temperature as well as trying to preserve the life span of the engine. In the aircraft there are two switches (one per engine) to turn on the water and alcohol mix. The pilot took the decision to continue with the flight and select both switches to maximum, which gave enough power

to take off. As soon as the pilot identified that this step had been missed out from the procedure the participant stated that he "instinctively" switched on the two switches that have been missed off the procedure.

The PIC stated that he felt that the CP was "absent minded" and concluded that the CP had missed "one of the most important checks" in the procedure which turned on the mix of water and alcohol to increase the trust. The PIC stated that at this point he monitored the systems and the thrust had increased and was able to perform the take-off as normal. The rest of the flight was performed normally.

Task Decomposition Diagram

A task decomposition diagram of the steps to error in completing aircraft procedures, see figure E.6.

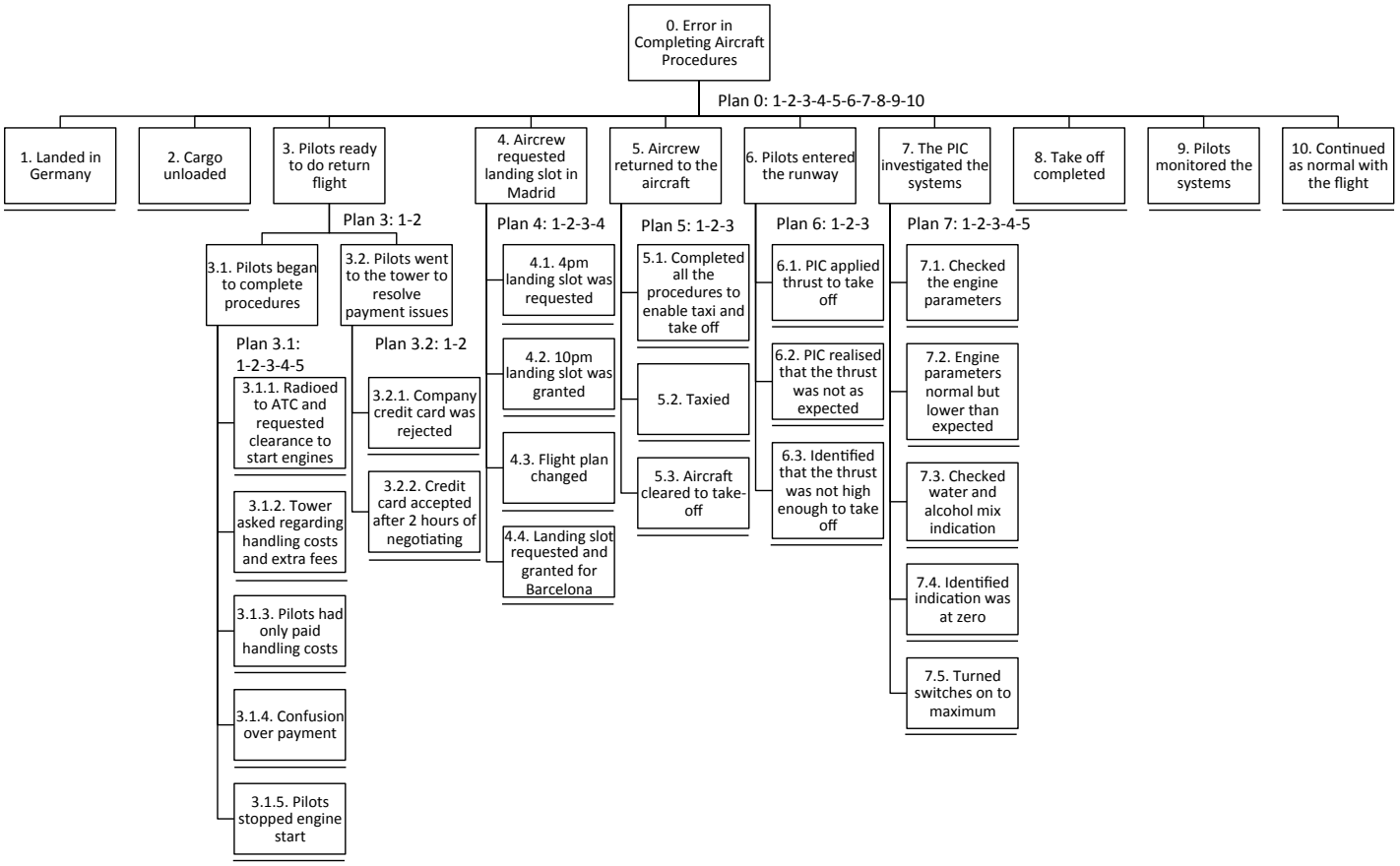


FIGURE E.6: CDM Interview 6: Error in Completing Aircraft Procedures Task Decomposition Diagram

Decision Points

Two main decision points were identified, these are discussed below in tables E.22 and E.23.

Decision Point 1: Alternative flight path to Barcelona

A new flight path was planned by the PIC in order to get back to Madrid sooner.

CDM Item	**Response**
Goal Specification	To get closer to Madrid.
Cue identification	Be ready to take off at 11pm in Madrid. To get closer to Madrid. The possibility to get clearance in Madrid once airborne.
Expectancy	Originally no because the pilots have to explain why they are landing at an alternative airfield.
Conceptual Model	Yes because there was no stress, and you had to get back on time.
Uncertainty	Yes as the pilot wasn't sure if on route to Barcelona they would get the clearance to deviate to Madrid.
Information	To be on time for the next flight.
Situation Awareness	Information landing in Madrid. As the original clearance for 11pm they weren't able to comply with.
Situation Assessment	No
Options	Could of used different routing but this was the shortest route.
Stress	Yeah, because the pilots did not want to land in Barcelona. There was a chance that they would need to land which would mean time wasted, extra costs occurred and requiring a new landing slot to Madrid.
Choice	"Follow the same legal trick" "To use the different possibilities that the system allows"
Analogy	Yes, a few times.

Table E.22: CDM Interview 6: Decision Point 1 - Alternative Flight Path to Barcelona

Decision Point 2: Turn on the mix of water and alcohol switch to increase the thrust for the take off

This decision centred on increasing the powering of the aircraft.

CDM Item	**Response**
Goal Specification	To increase the thrust, which an increase in power in the aircraft for take off.

Cue identification	The low power available for take off. Short runway. Elevation of the runway. Hot air, which means there is high temperature and requires more power. As the aircraft was empty, the weight of the aircraft was low. Taking into consideration the engine life expectancy.
Expectancy	No but it was instinctive.
Conceptual Model	If on another runaway that is longer, for example in Barajas, the pilot would have kept the original thrust and power. An already known airfield (as it was the first time for the aircrew to fly to the this airfield).
Uncertainty	It was clear as the PIC realised that the take off was not the same as usual, and then he confirmed with the instrument of the engine.
Information	Engine parameters and mix water/alcohol indicators.
Situation Awareness	All of the system parameters.
Situation Assessment	No other information required.
Options	To abort the take-off but the pilots were under a lot of pressure from people on the airfield to take-off.
Stress	No but there was pressure to take off and get back to Madrid and miss the landing slot in Barcelona. The aircrew did not want to abort the flight, as it would take another 2 hours to go through the whole take off procedures. Also the aircrew needed to get back for the routine night flight.
Choice	"To know the system and the conditions which helps to easily identify the situation." "Baring in mind for the consequence of aborting the take-off, do something."
Analogy	Yes based it on other experience in different types of aircraft.

Table E.23: CDM Interview 6: Decision Point 2 - Turn on the Mix of Water and Alcohol Switch

E.0.0.7 CDM Interview 7: Stall Warning

Description

This interview describes an incident where the participant experienced a stall warning in the aircraft. The participant was the PIC in a Gulfstream 1, who was carrying out a cargo flight at night. The aircrew took off from Barajas, Madrid and the destination airport was in Brussels. This was a cargo flight on behalf of federal express.

The pilot stated that when taking off there was a storm identified and a lot of traffic, which meant that it took the aircrew more than 25 minutes to take off. The aircrew took off from Barajas and once reaching 5000ft (approximately 5 minutes) after take off the wheel of the aircraft started vibrating and there was a hard repetitive alert, which sounded "clack, clack, clack". The pilot stated that "the vibration is normally due to a stall of the aircraft, it's a protection", this indicating to the pilot that the aircraft was about to stall.

The pilot investigated the cockpit systems to confirm that the stall warning that he had was not a real warning. He based this by checking the speed of the aircraft and checked the wing level (1g), which were within the normal parameters and not in stall parameters. The pilot described that the aircraft was flying at 160 Knots and even though he had encountered a stall warning, he knew that he was far from the stall speed. This was his first clue to indicate that it was an incorrect warning. The pilot described how a stall could occur, he described that in the wing there is a sensor that moves position depending on the angle of attack. The pilot went on to state that when the angle of attack is increased, the relative position of this sensor, related to the wing changes. When approaching the maximum angle of attack, the sensor sends a signal to a vibration on the wheel. The pilot stated that the vibration "warns you that you are close to the stall of the aircraft." The pilot described that if he had been at 160kn and pulled 2gs, then he would have expected a stall because the angle of attack had increased. However the pilot stated that aircraft was at "wing level, not pulling, it was [in] autopilot and the speed was 160. There were no conditions for stall, so it was a wrong indication".

Furthermore, when a real stall warning occurs the autopilot disconnects and the pilot has to take over with manual flying. This combination of clues indicated to the pilot that it was an incorrect stall warning. The pilot stated that he was aware that in this aircraft it could happen. As there was noise and vibration in the cockpit and the pilot identified that the indication was incorrect, the pilot wanted to increase the comfort but switching disconnecting the circuit breaker. The pilot selected the stall warning circuit breaker, which stopped the noise and the wheel from vibrating. This allowed the pilot to continue the flight comfortably. Once the pilots had gone through the icy conditions, approximately half an hour after turning the circuit breaker off, the pilot turned the circuit breaker back on. Upon turning the circuit breaker on, the pilots did not experience the noise and wheel vibration that they had previously experienced. The pilots completed the rest of the flight normally and did not experience any other problems in the cockpit.

Task Decomposition Diagram

A task decomposition diagram of the steps to resolve a stall warning, see figure E.7.

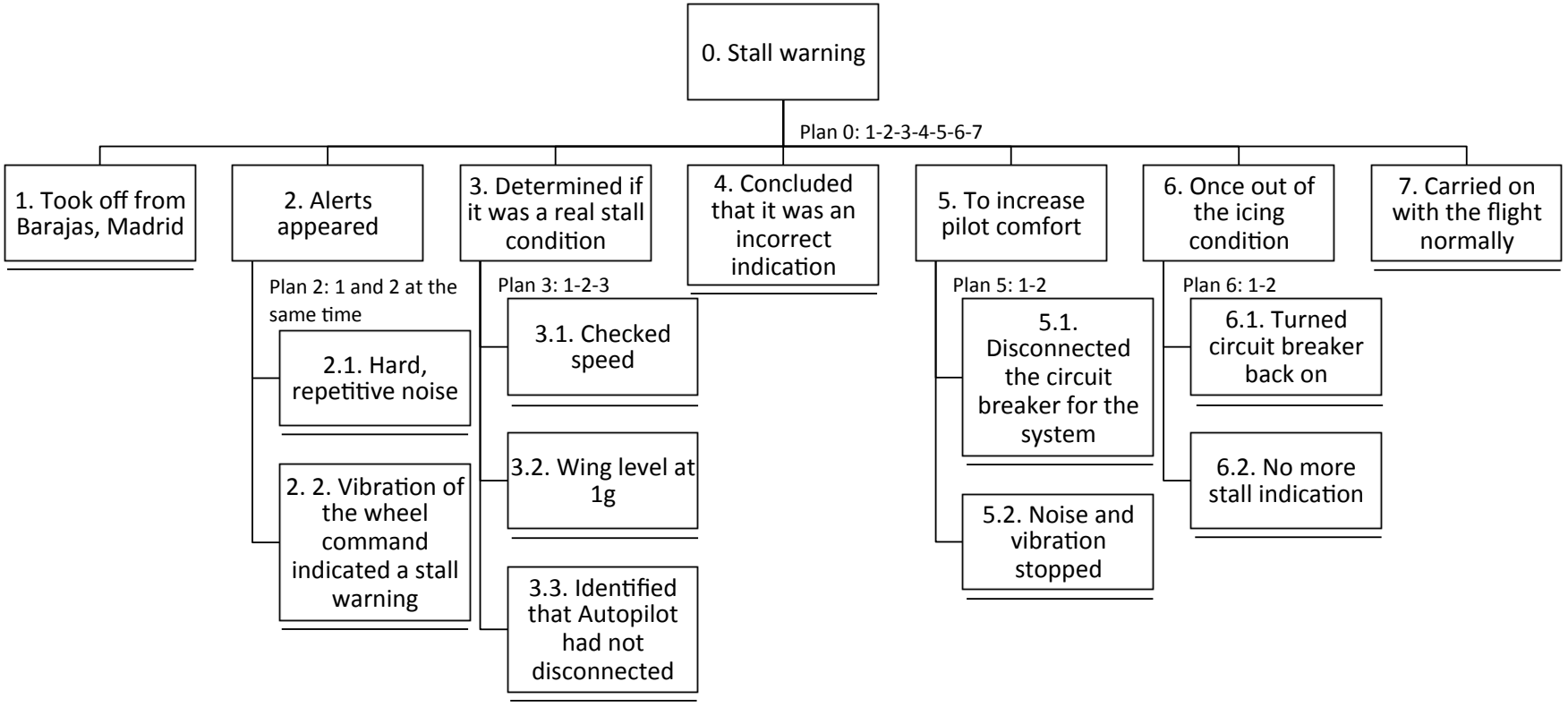


FIGURE E.7: CDM Interview 7: Stall Warning Task Decomposition Diagram

Decision Points

Three main decision points were identified, these are discussed below in tables E.24, E.25, E.26.

Decision Point 1: Identify if it is a real stall warning indication

CDM Item	**Response**
Goal Specification	Identify if the stall warning indication is real or not.
Cue identification	Speed was normal. There was no load factor applied. Icy condition.
Expectancy	No, this was not expected.
Conceptual Model	If the speed was close to stall speed then the pilot would have acted to solve the situation by manually flying.
Uncertainty	Yes there was uncertainty because it was a night flight, it was dark and cloudy which made it more difficult to identify what was going on.
Information	The speed was within the expected value, as well as the wing level.
Situation Awareness	All the system information, attitude of the aircraft, weather information, previous reports that reported this condition.
Situation Assessment	No other information required.
Options	Monitoring the icy condition.
Stress	There is a lot of noise and vibration, which is not the normal flight conditions.
Choice	"Try to identify if the condition of the aircraft corresponds to the stall situation".
Analogy	No but had the stall reports from past incidents.

Table E.24: CDM Interview 7: Decision Point 1 - Identify if it is a Real Stall Warning Indication

Decision Point 2: Turn the circuit breaker off

CDM Item	**Response**
Goal Specification	To increase comfort.
Cue identification	It was identified that it was not a real stall condition.
Expectancy	No.
Conceptual Model	In the event of a real stall warning.

Uncertainty	No.
Information	The noise and vibration and that it had been determined that it was not a real stall condition.
Situation Awareness	System parameters and continuously monitoring the systems.
Situation Assessment	Everything was there.
Options	To keep the breakers on.
Stress	No.
Choice	"If a non real stall warning is identified try to maintain normal flying conditions."
Analogy	No.

Table E.25: CDM Interview 7: Decision Point 2: Turn the Circuit Breaker Off

Decision Point 3: Turn the circuit breaker back on

CDM Item	**Response**
Goal Specification	To recover normal aircraft configuration.
Cue identification	Trying to see if the icy condition has disappeared. Everything seemed normal in the aircraft and there was no more noise and vibration in the aircraft.
Expectancy	No.
Conceptual Model	The normal situation and not expected to happen again.
Uncertainty	No.
Information	No icy conditions and normal aircraft parameters.
Situation Awareness	Weather, system parameters and aircraft.
Situation Assessment	No.
Options	To maintain off but trying to available the system for a real stall.
Stress	No.
Choice	"Trying to maintain all the systems operational"
Analogy	No.

Table E.26: CDM Interview 7: Decision Point 3 - Turn the Circuit Breaker Back On

E.0.0.8 CDM Interview 8: Bird Strike

Description

The pilot described a bird strike incident that had occurred approximately 4-5 years before the interview date. The pilot encountered the emergency during a certification flight with the certification authority and the customer who had purchased the aircraft.

The aircraft in question was the A330 MRTT, a two-engine aircraft. The aircrew took off from Getafe and had planned to do a 5 hour test flight to the south of Spain and then return back to Getafe. The aircrew was made up of PIC, CP and flight engineer as well as a pilot from the customer. There were a further two test pilots and two personnel from the certification body who were monitoring the aircrew's actions. The customer pilot had been cleared to fly part of the flight, he completed the take off while the PIC took on the pilot-monitoring role. At take-off, the pilot stated that they were above the maximum landing weight.

The pilot described when approaching the runway, there was a flock of seagulls sat on the right hand side of the runway. The pilot said "At take-off, I saw what looked like dozens of birds." He stated that birds at Getafe airport were very common, and usually they had procedures in place, where they used a domestic falcon to try to deter birds from sitting on the runway. The PIC verbally informed the aircrew that there were "birds". He described that due to the noise and movement of the aircraft the birds took off from their right hand side across to the left side of the runway. This meant that the birds were crossing directly in front of the aircraft and as the pilot described "they actually took off at the same time".

The pilots felt the birds hit the aircraft and the aircraft began to vibrate. The pilot said that he thought several seagulls hit the left engine (after landing they identified approximately seven birds hit), of which two or three entered into the engine. This resulted in engine 1 vibrating when taking off, which indicated that the engine had been damaged. The pilot recalled that there were advisory messages in the cockpit, which were flashing to indicate excessive vibration.

The pilots initially waited to see what impact they had in the aircraft and investigated the system. The pilot checked the engine parameters to look for an engine stall or an engine shutdown as well as investigating if one or two engines had been impacted. The aircrew also checked the vibration indication, which indicates the percentage of vibration, which showed that the vibration was above the limits, the pilot stated that it had increased from around 4%/5% to 17%. Once they had identified that the vibration was above the maximum level, the PIC reduced the thrust for the affected engine, which reduced the

vibration to below the maximum, below 3%. The pilots reduced the thrust of the engine slowly to reduce the amount of vibration in the cockpit, by reducing the vibration this reduces the chance of further damaging the engine and also increased the aircrew's comfort level.

The aircrew then discussed two options; the first option was to continue running the engine in its current state and the second to shut down the engine. The pilot stated that if they continued running the engine in its current state that "the engine wasn't giving any service but was giving us electricity with the generator." The aircrew climbed to 4000ft and the pilot stated as "they felt that the engine had been damaged that they would shut it down". The pilots increased their speed and altitude to get power, which allowed them to be at a greater distance from the ground, and the pilot stated, "to have energy." Once they reached 4000ft then the aircrew started the procedures and checklists to shut down the engine. The aircrew monitored the systems to ensure the engine had such down. Once the engine was shut down the aircrew continued to accelerate and follow the procedure to the next way point. The pilot informed ATC that they had experienced a bird strike and requested that ATC maintain their frequency.

The pilots then discussed whether they needed to turn back to Getafe or continue on with the flight plan as they had an amber warning in the cockpit systems which stated to "land asap". They decided that they needed to land in Getafe but the aircraft was over the maximum landing weight which made the landing in Getafe difficult as it had a short runway. The pilot stated "there are two choices, as we were above the maximum landing weight to either jettison fuel and reduce the weight of the aircraft or apply the procedure for landing above maximum weight." The pilot stated that as the certification authority was reviewing the aircrew they were not completely sure how to complete the landing. The pilot stated that they did "50, 50", which meant a little bit off both this was mainly due to the fact that the certification authority were on board the aircraft. The aircrew decided to proceed to flight level 150 above the city Toledo and jettison fuel to reduce the aircraft weight.

The aircrew asked ATC in Getafe to clear the runway to ensure that birds involved in the hit were recovered and safe for next flights. The aircrew were then transferred to ATC in Madrid and they requested to climb from 100 to 150 level. The controller cleared the aircrew to jettison fuel in Toledo and they stayed in Toledo for approximately 10 minutes. They ejected approximately 1500kg per minute, approximately 15 tonnes in total. The aircrew then requested clearance back to Getafe for a "full stop landing". The aircrew flew back to Getafe and performed the approach and landing as usual but as they were slightly above the landing weight they performed the procedure for landing above

maximum weight. After landing, an incident report was prepared and distributed within the aircrew's company.

Task Decomposition Diagram

A task decomposition diagram of the steps to resolve a bird strike, see figure E.8.

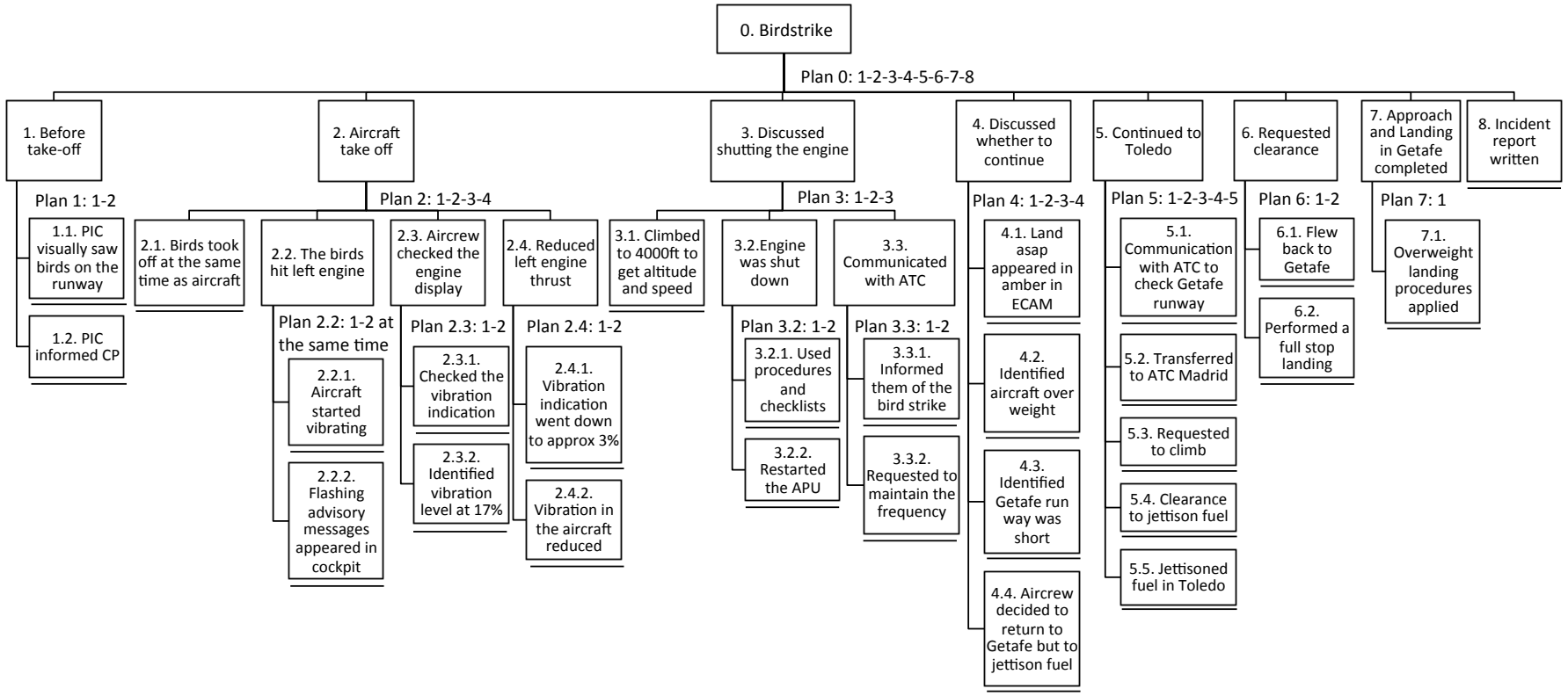


FIGURE E.8: CDM Interview 8: Bird Strike Task Decomposition Diagram

Decision Points

Three main decision points were identified, these are discussed below in tables E.27, E.28 and E.29.

Decision Point 1: Reduce thrust – reduced a little at a time and watching the parameters

CDM Item	Response
Goal Specification	To reduce the level of vibration to reduce any further damage to the engine. The pilot stated that by reducing the vibration "You feel safer and comfortable."
Cue identification	They felt the vibration through the aircraft and the engine display.
Expectancy	No.
Conceptual Model	If the hit happened but the engine parameters were normal. Also, if both engines were affected, you continue with the same thrust or you try to adjust one or both engines slightly.
Uncertainty	No.
Information	The evidence of vibration as well as the engine parameters.
Situation Awareness	Thrust parameters were lower than expected.
Situation Assessment	The pilot would of liked to see the damage to the engine. Also, the pilot stated that it would have been good to know what the consequence of continuing on the remaining engine.
Options	No.
Stress	Stress level increased.
Choice	"If you notice some vibration, think about reducing the thrust, condition permitting"
Analogy	Yes, the pilot had experienced this in another aircraft.

Table E.27: CDM Interview 8: Decision Point 1 - Reduce Thrust

Decision Point 2: Shutdown engine

CDM Item	Response
Goal Specification	Prevent further damage to the engine and the aircraft. The pilot stated that there was no point running the engine, as the APU can provide electricity. Also turning off the engine totally gets rid of the vibration.
Cue identification	The vibration – even 3% of vibration in the aircraft is a lot.
Expectancy	No.

Conceptual Model	If the aircrew had a long flight they would try to keep the engine running for longer. Or if the aircrew did not have APU.
Uncertainty	No, because the aircrew had vibration.
Information	Vibration.
Situation Awareness	Vibration.
Situation Assessment	The aircrew only planned to stay airborne for 15 minutes and all the systems were available.
Options	The pilot stated to keep the engine running. However keeping the engine running would mean the vibration would remain which would impact the aircrew's comfort and possibility of additional damage to the engine.
Stress	Stress stayed the same as decision point one.
Choice	"If there is doubt about the emergency then shut down the engine"

Table E.28: CDM Interview 8: Decision Point 2 - Shutdown Engine

Decision Point 3: To return to Getafe via Toledo to jettison fuel

CDM Item	**Response**
Goal Specification	To reduce the weight the aircraft considering the consequences of a single engine landing.
Cue identification	The pilot said that there were two issues; first that the aircraft was above maximum landing weight and there is a "Land asap" in amber. Weight of the aircraft. The length of the runway suitable for the landing. Single engine remaining in the aircraft. Customer on the flight and certification authority.
Expectancy	No.
Conceptual Model	Longer runway or if there had been different wind conditions.
Uncertainty	No, the aircrew had control of the aircraft parameters.
Information	The weight of the aircraft.
Situation Awareness	All the aircraft parameters, the FCOM, the maximum landing is X amount and that the aircrew needed to get to the point where they can land.
Situation Assessment	The pilot stated he had everything.
Options	Land immediately back in Getafe and not to go to Toledo to jettison fuel.
Stress	The same as the previous decision point, more aware of the fuel falling.
Choice	"If you are overweight reduce the fuel considering the time you have"

Analogy	The pilot had done it several times in both real emergencies and testing.

TABLE E.29: CDM Interview 8: Decision Point 3 - To return to Getafe via Toledo to Jettison Fuel

E.0.0.9 CDM Interview 9: Engine Fire Warning

Description

This interview describes a fire warning in engine number 2, left inboard engine, in the P3 aircraft, which has 4 engines. The inboard engines are the closest to the fuselage and are usually less critical when encountering an emergency. The incident took place a week before the interview date.

The aircrew was made up of three crewmembers, 2 pilots and 1 flight engineer. A inflight technician was also on board the aircraft. The pilot stated that he was the co-pilot on the flight and was carrying out a ferry flight from Nordholz (ETMN) to Ingolstadt (ETSI). No passengers were on the aircraft as it the aircrew simply wanted to get the aircraft to the destination. The pilot said that they had planned to do some "over flights" for test purposes just before landing in Ingolstadt, which would require the pilots to stay airborne for an additional 15-20 minutes, to test the indications in the instrument landing systems.

The aircrew experienced a normal flight until approaching Ingolstadt airport (about 5NM into the final approach) where they were alerted to an emergency when the engine fire warning horn and the four fire warning lights for engine number two went off.

The PIC ordered the flight engineer to pull the E handle to shut off the engine. Pulling the E handle stops various things including the fuel flow, the hydraulics, etc. The warning lights went out and the audio immediately stopped upon pulling E handle. As the warning indication went out immediately the aircrew suspected that they did not have a real fire and did not fire the fire-extinguishing bottle into the engine, which is the usual procedure after pulling the E handle. As the pilots suspected that the warning was not indicating a real engine fire, the pilot stated that they thought "it was due to a technical reason and that they thought it was probably only one of the fire warning detector wires had a short or some humidity in one of the connectors." The inflight technician was asked by the PIC to look out the window and see if they could visually see real signs of a fire in the engine. The inflight technician reported that there were no visual signs of a fire.

The PIC then ordered for the emergency engine shut down checklist. The CP went step by step through the checklist. Each step was read out by the CP and the step was completed and confirmed by the PIC and FTE where appropriate. One of the final steps of the procedure identifies that the aircrew should land immediately. As the aircrew were in Ingolstadt and ready for the landing the aircrew did not need to change the flight plan or their intentions. The PIC then informed ATC that they had to shut down the engine and that they suspected that it was not a real fire, however, they did not declare emergency. ATC then visually checked from the tower for signs of a fire in the engine and confirmed that they could not see any visual signs of an engine fire.

The PIC then ordered for a full emergency landing briefing. The flight engineer retrieved the flight manual, which provided the aircrew with prompts to consider during the briefing. The discussion included confirming that the weather was good in Ingolstadt, the status of the aircraft and confirmation of a standard 3 engine landing which would be completed by the PIC. The aircrew discussed that as there were only 3 engines it was expected that the aircraft would start to yaw and that they would need to counteract this. Furthermore, the CP would take over control during the landing roll.

The pilots completed the actions as stated during the emergency landing briefing and successfully landed without further incident. Whilst the technical reason was not confirmed for the failure, the pilot stated he was certain that it was not an actual fire and was a false alarm. The CP wrote an incident report, which was distributed within the company for follow up.

The pilot stated that for “every step that the aircrew was completing they were constantly monitoring the systems, in this instant the flight engineer was especially monitoring the systems continuously”.

The aircrew quickly did a debriefing. The aircrew filled in an incident report together.

Task Decomposition Diagram

A task decomposition diagram of the steps to resolve engine fire warning, see figure E.9.

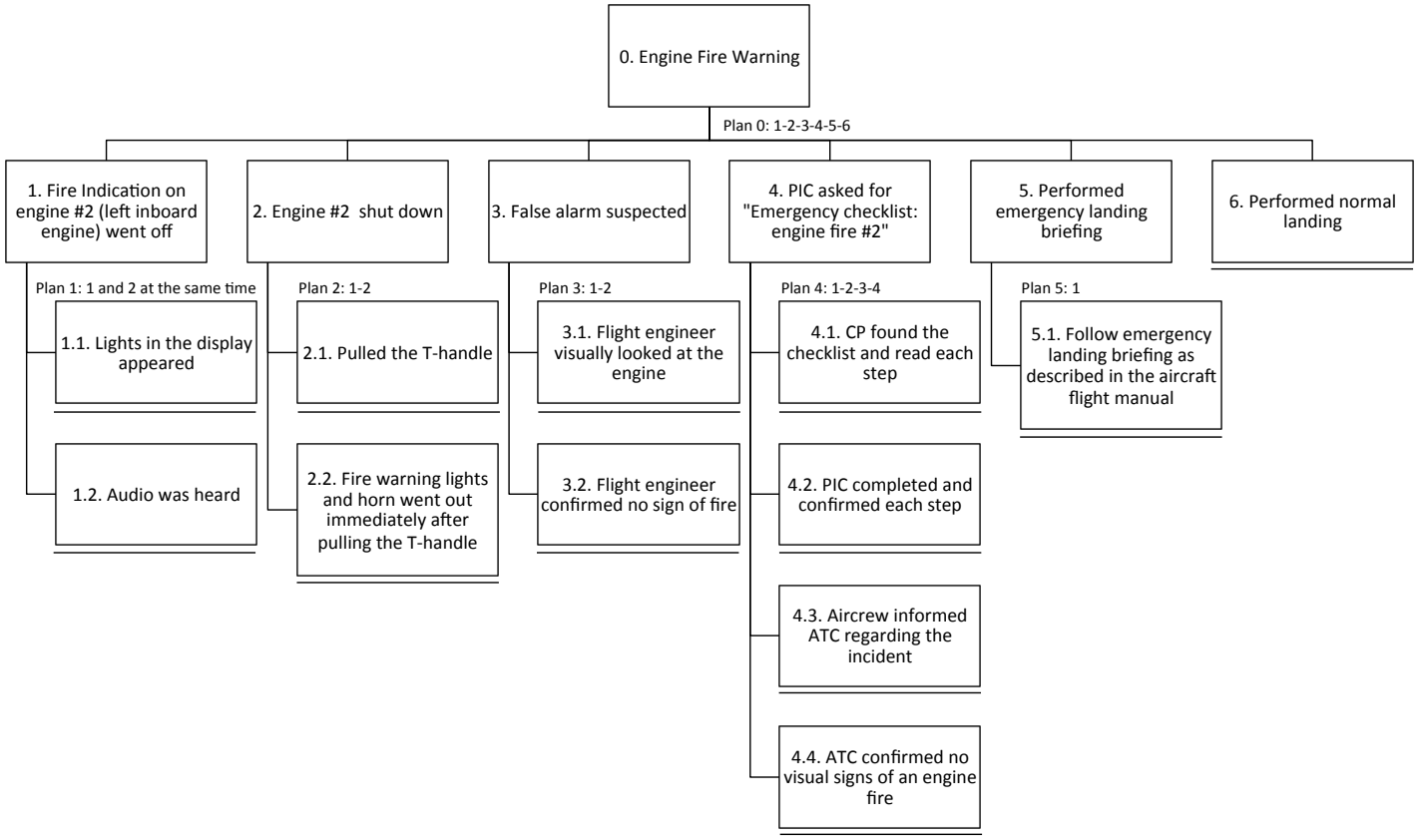


FIGURE E.9: CDM Interview 9: Engine Fire Warning Task Decomposition Diagram

Decision Points

Two main decision points were identified, these are discussed below in tables E.30, E.31.

Decision Point 1: The aircrew did not complete the standard procedure of firing the fire-extinguishing

CDM Item	**Response**
Goal Specification	Not to increase the amount of maintenance for the engine. The pilot stated "if you fire the extinguishing bottle then a lot of additional maintenance work would be required to restore the engine to its normal state."
Cue identification	When pulling the E handle, the warning light and audio went out immediately. For a real fire it was expected that the warning light would stay on for a lot longer.
Expectancy	Not expecting to do this action.
Conceptual Model	If the light had remained on and the bottle would have been fired.
Uncertainty	Yes, because there was uncertainty regarding if the fire was still there. The aircrew thought there was a chance that there could be a really small fire, which could not be seen and was not being detected.
Information	Combination of the lights going out immediately and the report from the in-flight technician and ATC who could not see a fire visually.
Situation Awareness	Fire warning, visual confirmation from flight engineer and ATC that they could not see a fire visually.
Situation Assessment	If you could see the inside the engine and have more reliable and trustable sensors.
Options	The fire-extinguishing bottle could have been released.
Stress	Relatively low, there was nothing problematic. "They could see the field, they had fine weather, no fuel issues and could follow the emergency procedure as outlined in the book."
Choice	"Use the bottle if you think it's a real fire, in exceptional circumstances and it is obvious and indications points to not a real fire, you may consider not to extinguish the bottle".
Analogy	The CP had a couple of fire indications in the past but he had always released the bottle. All fire alarms were false alarms.

Table E.30: CDM Interview 9: Decision Point 1 - The Aircrew Did Not Complete the Standard Procedure of Firing the Fire-Extinguishing

Decision Point 2: Not to continue the testing activities

CDM Item	**Response**
Goal Specification	You never know when the next engine will fail and you don't want to be put under more stress. If you lose an engine you want to land as soon as possible.
Cue identification	As part of the training they are taught not to do it. As the warning lights had come on.
Expectancy	Not expected. The pilot stated that in the moment that the indication came on the decision was made.
Conceptual Model	No. If the mission had been a real search and rescue mission, looking for real people missing and they are going to die but they are flying OK, they might have considered to continue. They would have called for another aircraft and continued searching until the aircraft took over.
Uncertainty	No, the testing was not high priority.
Information	Fire warning. Having a fire on board is one of the most threatening things the pilots can have as there are a lot of flammable fluids on board and a fire can easily destroy the structure of the aircraft.
Situation Awareness	Information in the cockpit systems and the visual from the inflight technician and ATC.
Situation Assessment	Complete information of the aircraft and the status of the fire. Options Yes, to do the test.
Stress	No, the pilot stated that it was not a real fire and they were in a comfortable situation of being close to the airfield.
Choice	"Land as soon as possible, in this special case, we had good luck that it was our destination and we were close" "Which airfield can I reach in the shortest amount of time, considering constraints."
Analogy	Yes, in another test flight for maintenance where they could not restart an engine.

Table E.31: CDM Interview 9: Decision Point 2 - Not to Continue the Testing Activities

E.0.0.10 CDM Interview 10: Cracked Windshield

Description

This CDM interview outlines an incident in the P-3 aircraft where the participant with a co-pilot participant who experienced a cracked front windshield. The incident took place approximately 3 weeks before the interview date.

The flight was planned as a ferry flight from Nordholz (ETMN) to Ingolstadt/Manching (ETSI) with a 4 crewmember aircrew including PIC, CP and flight engineer and an inflight technician who was seated at the back of the aircraft. There were 3 passengers in the aircraft.

The aircrew performed the takeoff in Nordholz, the climb and once in the cruise phase at FL230 (altitude 23000ft) one layer of the front windshield cracked, on the co-pilot side. The pilot stated that there was a loud bang, similar to when you are driving a car on a motorway and a stone hits the windshield. The pilot saw several cracks in the windscreen on his co-pilot side of the cockpit.

The glass in the windshield is made up of three layers, the two outer layers are made of glass and the middle layer is plastic. Once the crack appeared this made the whole aircraft structure weaker and the pilots were afraid that there was a possibility of the glass completely breaking and consequently breaking into the face of the aircrew.

The pilot stated that the probable cause was due to humidity entering in between the layers of the glass which caused a short circuit in the heating filaments. This caused a local overheat which made the windshield crack.

The PIC stated that the windscreen had cracked and all pilots visually investigated the crack. So the CP stated that they should put on the helmets for safety. The crew put their helmets and put down their visors. The PIC initially completed the “off by heart items” also known as the bold face items in the procedures and switched off the heat for the affected panel.

The PIC called for the emergency checklist “cracked front windshield”. The flight engineer took the aircraft flight manual and started reading through the emergency checklist. The CP read each step and the PIC completed the actions and confirmed once he had completed the step. Part of the procedure asked the pilots to check the differential of pressure between inside and outside of the aircraft.

The pilot stated a human could survive up to at 3000m / FL100 without artificial oxygen and masks. As the pressure of the aircraft was higher inside the aircraft than outside,

the aircrew need to ensure the difference of pressure is reduced to reduce the stress on the pressurised part of the aircraft fuselage. One of the procedure steps asked the pilots to reduce differential pressure to below 2inHg, the PIC asked CP to ask ATC for descent to FL120. CP requested descent but the ATC took time to reply because there were a number of other aircraft on the same frequency, which caused a delay of a maximum of 5 minutes, which the pilot stated it felt like "more than 10 minutes". The ATC granted the clearance to the aircrew to drop to FL100.

The pilots descended to FL120 and the aircraft cabin pressure was set to a value which equals to an altitude of FL100 which results in a differential pressure of about 2inHg. Once the descent had been successfully performed and the aircrew felt that the they were safe the PIC then decided to go back to Nordholz because it was an airfield that all the pilots knew, they had just taken off from it, it was only 15-20 minutes away, it was the home base where the aircrew knew there were technical facilities for the P-3 and they knew there was good weather. The pilots flew back to Norholz but there were clouds. The CP asked for a diversion from ATC, and ATC put them on a new path. The CP stated that they followed the standard approach procedure and landed in Nordholz safely.

Once the incident was over the PIC filled out an incident report.

Task Decomposition Diagram

A task decomposition diagram of the steps to resolve a Cracked Wind Shield, see figure E.10.

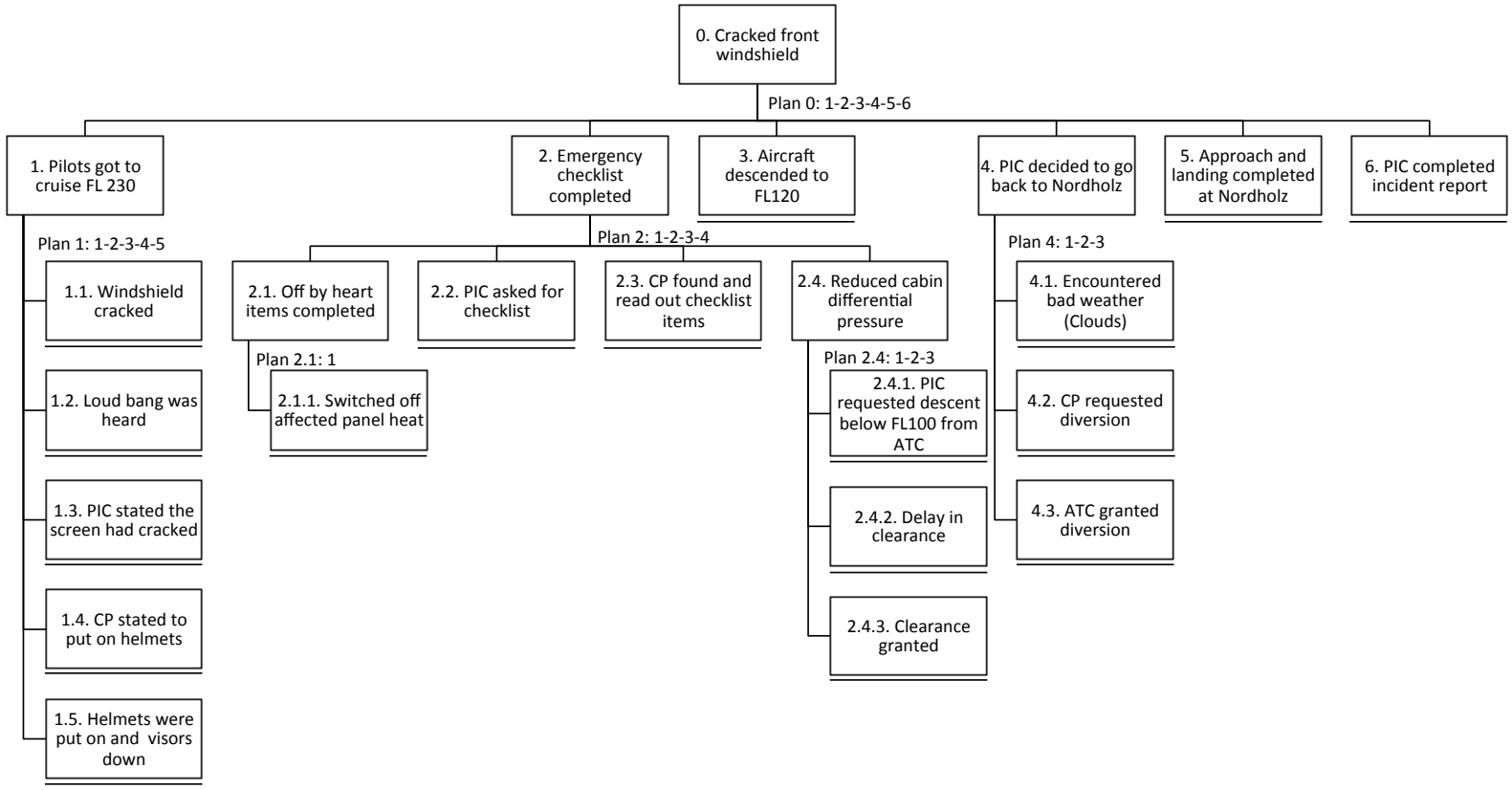


FIGURE E.10: CDM Interview 10: Cracked Wind Shield Task Decomposition Diagram

Decision Points

Two main decision points were identified, these are discussed below in tables E.32 and E.33.

Decision Point 1: Decrease altitude

CDM Item	**Response**
Goal Specification	To reduce the differential pressure and the amount of stress on the aircraft structure.
Cue identification	Cracked front windshield, which means lack of stability of the front windscreen. It may break completely (the other two layers may not be able to withstand the cabin pressure difference between inside and outside pressure) or the air pressure due to the speed of the aircraft. If the windscreen breaks completely the pilot behind may be seriously hurt by the fragments of the window and/or the air blast.
Expectancy	Reduce the stress and avoid any further damage.
Conceptual Model	Yes to increase the cabin altitude, for example, in the event of bad weather, such as ice this would mean the aircrew cannot descend and they would want to stay as high as possible. Another example is if there is high terrain such as the Pyrenees you might not be able to descend that low.
Uncertainty	No, because the aircrew knew what the weather was like and they had a lot of visibility of the ground. However, there was uncertainty about how the glass was going to withstand the rest of the flight.
Information	Based on the weather and the pilots knowing that there wasn't high terrain.
Situation Awareness	Weather information in Nordholz, the visibility of the weather outside the aircraft, information about the area and the pilots' own knowledge of the area.
Situation Assessment	The pilot was unsure how much the glass can actually withstand. The 2inch may only refer to the inner layer being. If the conditions were worse they may need to know the range of it.
Options	Yes, to increase altitude.
Stress	High, as this was a real emergency and they did not how the glass would break and it took time for ATC to give ATC clearance for descent.
Choice	"Follow the checklist initially and then consider how to reduce the differential pressure based on the weather and terrain."
Analogy	Yes, he had done a similar procedure for loss of cabin pressure incident.

Table E.32: CDM Interview 10: Decision Point 1 - Decrease Altitude

Decision Point 2: Land in Nordholz

CDM Item	**Response**
Goal Specification	Safe landing without any harm to any crewmember on board.
Cue identification	The cues that they used included; they had only left Nordholz 15-20 minutes prior, there had been good weather during their take off, Nordholz was the aircrew's homebase and they knew that the location had all the facilities for P-3 maintenance. The pilot also stated that in the back his mind he was aware that some of the aircrew wanted to go back to Nordholz as they had homes, families and cars. He stated that going to another airfield would be an inconvenience.
Expectancy	No.
Conceptual Model	The pilot stated that they based this decision on the fact that they need to land as soon as possible, so the actual position and the closest airport is the trigger where to go. The closest airfield would have been to go to Bremen but the PIC had decided to go back to Nordholz and the CP did not challenge the PIC's decision because he felt comfortable with this decision and also thought this was the most reasonable decision. It could have been different if the aircrew were closer to Manching, which would have resulted in them proceeding to Manching.
Uncertainty	Yes regarding which airport to land, Bremen or Nordholz.
Information	Nordholz was the aircrew's homebase, good weather at Nordholz and P-3 technical support.
Situation Awareness	Weather experience, the homebase and known facilities.
Situation Assessment	Yes all the information was available and no other information was required.
Options	Alternative airports which included landing in Bremen or Hannover.
Stress	Yes, but the pilot stated that he was not the PIC. The pilot stated that none of the aircrew had experienced this emergency before whereas false indications such as a fire can happen often, which means there was more stress than usual.
Choice	"Follow the checklist and consider the best suitable airport with respect to facilities and technical support within the constraints". The pilot stated that they need to consider landing asap vs. landing at a suitable airfield as well as considering the actual weather situation. Weather can be an issue which can have many variances and is often based on personal feelings, experience, etc.
Analogy	No.

Table E.33: CDM Interview 10: Decision Point 2 - Land in Nordholz

Appendix F

Analysis of CDM Interviews

F.1 CDM Interview Results

The CDM interview qualitative data shows five distinct steps; identify an emergency, stabilise situation, determine and analyse the problem, identify and perform course of action to address emergency and confirmation of success of course action and monitor aircraft. Each step has been described below with examples of how they manifest in each of the CDM interviews. It should be noted that the order of the steps; stabilise situation and determine and analyse the problem, may be interchanged.

- **Identify an emergency:** here the pilots are either alerted to a problem in the cockpit or the pilot identifies an issue by monitoring the aircraft and the system. Table F.1 shows every point in the CDM interviews where identification takes place.

CDM Interview	Description
1	The pilots immediately realised that they had a failure as the caution feed highlighted that there is a right engine failure, they had heard a "pop" and a "rumble" and the CP called out that there was an engine failure.
2	Takeoff, climb and cruise had initially been normal until they had started to experience partial loss of radio communication whilst still in Spanish airspace.
3	However, between 15,000-18,000ft, when the aircrew were still climbing approximately 15 minutes into the flight and whilst they were crossing some clouds, the master warning aural sounded, visual cue was presented in the ECAM with a caution warning and the associated checklist. The caution warning indicated that engine 3 had stalled.

4	The pilots initially became aware of the fire indication by an audio alarm and three visual cues: – Red light warning in the condition lever – Master fire warning light in the engine section of the centre panel – Red light in the emergency T-handles.
5	However, approximately an hour before landing, the pilots started to experience a little turbulence. The pilots could see outside the aircraft that there were a lot of clouds and that there was a storm ahead.
6	Upon taxiing on to the runway, the PIC applied thrust, however, the PIC realised that the aircraft was not performing as he expected, as the aircraft did not have the expected thrust.
7	The aircrew took off from Barajas and once reaching 5000ft (approximately 5 minutes) after take off, the wheel of the aircraft started vibrating and there was a hard repetitive alert, which sounded "clack, clack, clack". The pilot stated that "the vibration is normally due to a stall of the aircraft, it's a protection", this indicating to the pilot that the aircraft was about to stall.
8	The pilots felt the birds hit the aircraft and the aircraft began to vibrate. The pilot said that he thought approximately several seagulls hit the left engine, of which two or three entered into the engine. This resulted in engine 1 vibrating when taking off, which indicated that the engine had been damaged. The pilot recalled that there were advisory messages in the cockpit, which were flashing to indicate excessive vibration.
9	The aircrew experienced a normal flight until approaching Ingolstadt airport (about 5NM into the final approach) where they were alerted to an emergency when the engine fire warning horn and the four fire warning lights for engine number two went off.
10	The aircrew performed the takeoff in Nordholz, the climb and once in the cruise phase at FL230 (altitude 23000ft) one layer of the front windshield cracked, on the co-pilot side. The pilot stated that there was a loud bang, similar to when you are driving a car on a motorway and a stone hits the windshield. The pilot saw several cracks in the windscreen on his co-pilot side of the cockpit.

TABLE F.1: Evidence: Identify an Emergency

- **Stabilise situation:** at this point the pilot needs to stabilise the aircraft, which ensures the safety of the aircrew and allows the pilot to have more time. The time might be required to get further understanding of the situation, to make a decision

and/or implement the required steps. Table F.2 presents stabilising the situation in the CDM interviews.

CDM Interview	Description
1	The pilots then completed the immediate action items (one of the pilots called for this – but could not remember if it was PIC or CP). Once the immediate actions are completed, this would return the aircraft to almost normal, stabilised flying. PIC ensured that the aircraft was flying normally and did not go off to one side.
2	The PIC then reduced the aircraft speed to allow herself to have more time to think about what she needed to do.
3	The PIC then ensured that he had the aircraft under control, he checked that the aircraft was still flying and that the autopilot and auto thrust were still engaged.
4	The pilots first maintained aircraft control and then analysed the situation. They analysed the situation by checking which engine had failed by checking the engine indication and the warning system.
5	The pilots could see that there were a lot of clouds outside the aircraft and that there was a storm ahead. The CP stated that they should start to fly around the clouds and try avoid the storm itself. The CP had turned the seat belt sign on to get passengers safely into their seats.
6	No Comment.
7	The pilot investigated the cockpit systems to confirm that the stall warning that he had, was not a real warning. He did this by checking the speed of the aircraft and checked the wing level (1g), which were within the normal parameters and not in stall parameters.
8	The pilots reduced the thrust of the engine slowly to reduce the amount of vibration in the cockpit; by reducing the vibration this reduced the chance of further damaging the engine and also increased the aircrew's comfort level.
9	The PIC ordered the flight engineer to pull the E handle to shut off the engine. Pulling the E handle stops various things including the fuel flow, the hydraulics, etc. The warning lights went out and the audio immediately stopped upon pulling E handle.
10	So the CP stated that they should put on helmets for safety. The crew put on their helmets and put down their visors. The PIC initially completed the "off by heart items" also known as the bold face items in the procedures and switched off the heat for the affected panel.

Table F.2: Evidence: Stabilise Situation

- **Determine and analyse the problem:** here the pilots are identifying what the problem is, often trying to understand the root cause, the severity and the criticality of the problem. This allows the pilot to understand and determine what needs to be done immediately. Table F.3 evidences determine and analyse the problem, in the CDM interviews.

CDM Interview	Description
1	Pilot 1 indicated that both he and the CP were investigating the engine instruments and particularly focusing on the caution feed where it had highlighted that there was an engine failure and the other indicated that the right engine was not running any more. The pilots were evaluating the information to confirm which engine had "died down", even though they knew which one from the beginning. The pilots needed to confirm that the right engine had actually stopped working. The pilot highlighted that in the aircraft there is no cue to which thrust lever needs to be shut down visually.
2	The PIC then asked the CP to turn all the radio equipment to listening, as they were not able to resolve the issue... The PIC then asked the CP to check the mission plan to see if there were any notes regarding what to do in a case of an emergency. However, the mission plan was not helpful as it stated to communicate the emergency to ATC, this with the current radio communication loss was not possible. The aircrew then started to hear some communication from ATC. ATC asked the aircrew to use the radar identifier if they could hear them. ATC asked three times and the PIC only identified two times. On one occasion the PIC did not identify as she felt that they weren't receiving all the communication and she was unsure whether to continue identifying. She was unsure if all the ATC communication was getting through as the communication coming through was of such poor quality.

3	Then the PIC analysed the situation by "trying to understand the problem". The PIC stated that he was trying to understand a lot of information at once, first understanding the location, available fuel, as well as investigating the engine parameters (RPMs, Power, EGT (temperature) and fuel flow). The PIC stated that he wasn't sure why the stall had occurred. He stated that if there had been icy conditions this could of caused the stall, but this was not the case as it was a spring/summer day. The other option could have been that something had come lose in the engine, however, they could not look into the engine itself. The CP also looked out of the window to see if there was any damage to engine but did not identify anything unusual. One of the load masters was asked to also look out of the window at the back of the aircraft to see if he could see anything unusual but he also could not identify anything unusual.
4	They analysed the situation by checking which engine had failed by checking the engine indication and the warning system.
5	The pilots could see that there were a lot of clouds outside the aircraft and that there was a storm ahead... As they were going to hit the storm directly, the aircrew discussed that they need to change their heading. Either to the left which would have taken them to the airport or to the right, which was towards the sea, and the pilots could see that there were good weather conditions.
6	The pilot then began to investigate the systems to identify what was happening. Here the participant stated that he was identifying "why with full levers [he] had lower than expected power". One of the things that the pilot wanted to know was if the engine parameters were lower than expected. The parameters were lower but looked normal considering the known conditions.
7	However, the pilot stated that the aircraft was at "wing level, not pulling, it was [in] autopilot and the speed was 160. There were no conditions for stall, so it was a wrong indication".
8	The pilots initially waited to see what impact they had in the aircraft and investigated the system. The pilot checked the engine parameters to look for an engine stall or an engine shutdown as well as investigating if one or two engines had been impacted. The aircrew also checked the vibration indication, which indicates the percentage of vibration, which showed that the vibration was above the limits, the pilot stated that it had increased from around 4%/5% to 17%. Once they had identified that the vibration was above the maximum level, the PIC reduced the thrust for the affected engine, which reduced the vibration to below the maximum, below 3%.

9	As the warning indication went out immediately, the aircrew suspected that they did not have a real fire and did not fire the fire-extinguishing bottle into the engine, which is the usual procedure after pulling the E handle. As the pilots suspected that the warning was not indicating a real engine fire, the pilot stated that they thought "it was due to a technical reason and that they thought it was probably only one of the fire warning detector wires had a short or some humidity in one of the connectors." The inflight technician was asked by the PIC to look out the window and see if they could visually see real signs of a fire in the engine. The inflight technician reported that there were no visual signs of a fire.
10	The PIC stated that the windscreen had cracked and all pilots visually investigated the crack.

Table F.3: Evidence: Determine and Analyse the Problem

- **Identify and perform course of action to address emergency:** the pilot carried out the steps that are required to solve the problem. These could be actions that the pilot decides on, based on checklists including memory items that they have rehearsed during training. As part of addressing the emergency, the pilot may need to identify a suitable landing. A number of factors are considered including the severity of the emergency, the available fuel, the closest airfield, the available resources at the airfield, etc. Table F.4 shows identify and perform course of action in each of the CDM interviews.

CDM Interview	Description
1	The pilots then completed the immediate action items (one of the pilots called for this – but could not remember if it was PIC or CP).
2	The PIC decided that to abort the mission plan, as there was a real radio communication loss including aborting mission two. Here she said to the CP that they should no longer think about the mission and only of the safety of themselves and the aircraft. The PIC asked the CP to complete some additional tasks such change the transponder, input items into the avionics, however, the CP wasn't able to complete these actions as he was still trying to investigate the radio communication equipment. The PIC stated that she had wanted to hand over the controls to the CP but was not able to as the CP was not able to cope with the stress of the emergency. The PIC decided to follow the French pilots instructions as planned as the French pilot had more "awareness" than she had. The PIC asked the CP to put down the landing gear, which was the planned method for the aircrew to identify with the French pilot that they would be following his direction, however the PIC completed.
3	Once the PIC had an understanding and had identified that they were in a stabilised situation to deal with the checklist, the PIC then said "ECAM actions" which indicates to the CP that he is ready to start the steps of the checklist.
4	Then the pilots used emergency checklists; first completing the memory items, which are highlighted in bold on the checklist, they are the immediate actions that need to be completed from memory.
5	The CP then contacted the radio ATC to request a change of heading, which ATC changed in the direction of the airport for landing. The radio ATC then changed the pilots' frequency and put the CP through to the control CP at the airport for landing clearance.
6	The pilot took the decision to continue with the flight and select both switches to maximum, which gave enough power to take off. As soon as the pilot identified that this step had been missed out from the procedure the participant stated that he "instinctively" switched on the two switches that have been missed off the procedure.
7	This combination of clues indicated to the pilot that it was an incorrect stall warning and no action was required. As there was noise and vibration in the cockpit and the pilot identified that the indication was incorrect, the pilot wanted to increase the comfort by disconnecting the circuit breaker.
8	Once they reached 4000ft, the aircrew started the procedures and checklists to shut down the engine.

9	The PIC then ordered the emergency engine shut down checklist. The CP went through the checklist, step by step. The CP read out each step, which was completed and confirmed by the PIC and FTE where appropriate. One of the final steps of the procedure identifies that the aircrew should land immediately.
10	The PIC called for the emergency checklist "cracked front windshield". The flight engineer took the aircraft flight manual and started reading through the emergency checklist.

TABLE F.4: Evidence: Identify a Course of Action to Address Emergency

- **Confirmation of success of the course of action and monitor aircraft:** Here the pilot spends time monitoring the systems to ensure the course of action has been successful and the emergency has been controlled. Table F.5 presents evidence of confirmation of success in the CDM interviews.

CDM Interview	Description
1	No Comment.
2	No Comment.
3	The aircrew decided to keep the engine at idle and monitor the engine as they were at altitude. They briefly considered shutting down the engine but this was not done as the engine parameters were in the normal range and the aircrew wanted to preserve the engine in case of any other failures that could occur.
4	No Comment.
5	No Comment.
6	The participant stated that at this point he monitored the systems and the thrust had increased and was able to perform the take-off as normal.
7	Once the pilots had gone through the icy conditions, approximately half an hour after turning the circuit breaker off, the pilot turned the circuit breaker back on. Upon turning the circuit breaker on, the pilots did not experience the noise and wheel vibration that they had previously experienced.
8	The aircrew monitored the systems to ensure the engine had shut down.
9	The pilot stated that for "every step that the aircrew was completing they were constantly monitoring the systems, in this instant the flight engineer was especially monitoring the systems continuously".

10	Once the descent had been successfully performed and the aircrew felt that they were safe, the PIC then decided to go back to Nordholz because it was an airfield that all the pilots knew, they had just taken off from it, it was only 15-20 minutes away, and it was the home base where the aircrew knew there were technical facilities for the P-3.

TABLE F.5: Evidence: Confirmation of Success of the Course of Action and Monitor Aircraft

Appendix G

SPAM Questions

G.1 Low Demand – Manual Flight With Fuel Leak

Flight from Ingolstadt Manching to Castle, Northern Germany. The first way point is Bilbao.

Time	**Activity**
	Start activity
	"Maintain flight level 300 and fly s cleared"
3 min	"Are you ready for a question?" Wait for acknowledgement What is your current heading?
3.5 mins	"Are you ready for a question?" Wait for acknowledgement What is the status of your right engine?
4 mins	"Are you ready for a question?" Wait for acknowledgement What is your pitch?
4.5mins	"Are you ready for a question?" Wait for acknowledgement Is there flow through the XFeed Valve?
6 mins	Implement fuel leak
	Wait for the pilot to recognise the leak and deal with it
On recognition	"Are you ready for a question?" Wait for acknowledgement What is your current aircraft state?
30 seconds after	"Are you ready for a question?" Wait for acknowledgement How far can you fly with the current tanks?

	Expect “Mayday” call If “mayday” call given “What are your further intentions?”
End of scenario	“Are you ready for a question?” Wait for acknowledgement “Do you think you have finished the fuel leak problem?” If yes – finish scenario If no – ask “what is left to do?”

Table G.1: SPAM Questions: Low Demand

G.2 Medium Demand – Manual Flying and Engine Fire

Time	**Activity**
	Start scenario
	“Intercept track Bilbao to Upala and maintain FL 300”
2:00	“Are you ready for a question?” Wait for acknowledgement Is the XFeed valve open or closed?
2:30	“Are you ready for a question?” Wait for acknowledgement What is your bank angle?
	After intercept and X nm
3:00	“Fly Hdg 300 to enable further climb”
3:30	“Are you ready for a question?” Wait for acknowledgement What altitude are you flying at?
3.50	“On Hdg 300 climb to FL 320”
4:00	“Are you ready for a question?” Wait for acknowledgement Is there fuel through the right main pump?
	After intercept and X nm
5:30	During climb FL 320 (at 320) – Insert Engine Fire “Turn right to Hdg 030 and climb to FL 340”
5.40	Engine Fire
10 seconds after	“Are you ready for a question?” Wait for acknowledgement Explain the status of the fuel tank

20 seconds after	"Are you ready for a question?" Wait for acknowledgement Explain the status of your aircraft
	Expect "Mayday" call Ask for further intentions if not given with mayday call. Expect request or information for descent and vectors to closest field
End of scenario	"Are you ready for a question?" Wait for acknowledgement "Do you think you have finished the fuel leak problem?" If yes – finish scenario If no – ask "what is left to do?"

Table G.2: SPAM Questions: Medium Demand

G.3 High Demand - Manual Flying With Combined Failures

Time	**Activity**
	Start scenario
	"Direct Barsu to intercept flight plan and maintain FL 300"
2:00	"Fly Hdg 270 to enable further climb" "On Hdg 270 climb to FL 320"
2:10	"Are you ready for a question?" Wait for acknowledgement What is your climb descent rate?
3:00	"Are you ready for a question?" Wait for acknowledgement What is the distance to the next way point?
4.00	"Are you ready for a question?" Wait for acknowledgement What is the status of your left back up pump?
4:30	"Turn right to Hdg 300 and climb to FL 340"
5:00	"Are you ready for a question?" Wait for acknowledgement What is the fuel temperature in the fuel tanks?
5:40	Fuel leak
6:00	Engine fire

6:10	"Are you ready for a question?" Wait for acknowledgement "What is your aircraft status?"
On recognition of the fuel leak	"Are you ready for a question?" Wait for acknowledgement How fast are your fuel tanks depleting? Get the rate
	Expect "Mayday" call Only after engine fire is resolved - Ask for further intentions if not given with mayday call Expect request or information for descent and vectors to closest field a. 30 nm b. 150 heading
End of scenario	"Are you ready for a question?" Wait for acknowledgement "Do you think you have finished the fuel leak problem?" If yes – finish scenario If no – ask "what is left to do?"

Table G.3: SPAM Questions: High Demand

Appendix H

Initial Design Principles

H.1 Decision-Making

H.1.1 Principle 1: Organise Information around the NDM decision points

The Recognition Primed Decision (RPD) model (Klein, 1993a, 1999), which investigates how individuals effectively make decisions in complex situations (Klein, 1993a, 1999). RPD involves non-optimising and non-compensatory strategies, which require minimal conscious deliberation. RPDs do not compare options, but instead involve recognition matching which highlights the most likely action (Klein and Klinger, 1991). Klein et al. (1989) highlight that the decision-maker develops a potential course of action, considers the constraints imposed by the situation and selects the first course of action which is not rejected.

There are three main decision points in the RPD model, which need be considered to support the decision-maker (Klein, 1999):

1. **Situation Recognition:** The decision-maker decides if the situation is typical or novel using critical cues which distinguish the type of situation and casual factors. This explains what is presently happening and what could happen. Based on the above, the decision-maker sets plausible goals and appropriate actions given the goals and expectations. Typical and familiar situations will result in typical actions, which are usually well rehearsed. However, the operator needs support for novel situations, which they have not come across before as they are challenging and unfamiliar.

2. **Serial Option Evaluation:** Evaluates the different course of actions until a valid one is found. Each action is selected from an action queue and arranged according to typicality.

3. **Mental Simulation:** Evaluates if an action is satisfactory, in this phase the decision-maker performs the course of action in his or her imagination; plays out the steps, the potential outcomes and the problems that might occur, and how these problems may be handled.

Information should be organised according to the operator's major tasks and decisions. The system should be organised so that the information needed for a particular goal is co-located and directly answers the major decisions associated with the goal (Endsley and Jones, 2011).

Examples

Aviation: During an emergency, the aircrew's goal is to ensure the safety of the aircraft. The pilots will first investigate the information related to the alerts in the system to determine what is occurring. For example, in the event of an engine failure, the pilots will investigate information related to the engine and fuel, as well as investigating information about the general flying condition of the aircraft. Based on this information, the pilots will make decisions related to which actions need to be performed from memory, which procedures and checklists need to be performed, whether a may day call needs to be made and if an immediate landing is necessary.

F&RS: When an incident commander attends an emergency, he/she will need to understand as much information as possible before arriving on the scene of the incident, and use this to determine what actions may need to be taken immediately. This will help the incident commander understand the decision points which take place on arrival. The incident commander will then need identify the risks, select a course of action, implement the course of action and identify what after care may need to be delivered. This will improve the chance of reaching their goal of safety and reduced destruction of property.

Points to Consider:

- The decision-maker's goals in the emergency situation. For example, is the decision-maker trying to minimise the number of fatalities, reduce the damage to the environment or aviate safely to the closest airfield? Consider the primary goals and secondary goals.
- Prioritise the decision-maker's goals.
- The tasks and decisions that need to be made to achieve the goal(s).

- How will the decision-maker will identify an emergency, determine and analyse the problem, stabilise the situation, identify a course of action to address the emergency, implement the selected course of action and confirm success of resolving the emergency? Identify how the system will support these tasks.
- The information that is needed for each goal. For example, is the first decision to stabilise the situation? What information does the decision-maker need to stabilise the situation? By stabilising the situation, the operator may have more time to make further decisions to resolve the emergency.
- The different types of emergencies the decision-maker could attend to. In addition, consider how these could be similar or different.

H.1.2 Principle 2: Design for Emergency Identification

When an emergency occurs, the decision-maker will either be alerted to a problem by using scan patterns to identify that there are anomalies, or alternatively they may be alerted by a system or person. Support needs to be given to the decision-maker's information needs to understand what the emergency is and why it is occurring. If for example, the system is alerting the decision-maker, consider providing information regarding the anomalies in the system, what impact that has on the system and the time available before the emergency progresses.

Examples

Aviation: There are two methods of identifying an emergency in the cockpit. First, pilots can be made aware of an emergency by the alerting system in the cockpit, which also provides specific information regarding the warning. Secondly, the pilots monitor the cockpit systems and crosscheck the two sets of instrumentation in the cockpit.

F&RS: In F&RS, the IC receives an alarm from the control room. The control room predominately takes emergency calls from the public, recording all the details and passing them onto the IC. The IC receives this information in the form of a tip sheet.

Points to Consider:

- How are decision-makers alerted to the emergency?
- How will the decision-maker identify anomalies in the system?
- If the decision-maker scans the system for anomalies or has he/she been informed by another party?

- The information support required in the initial identification of an emergency.

H.1.3 Principle 3: Design to Determine and Analyse the Emergency

The operator will need to determine and analyse the emergency by developing an understanding of what is happening at the incident. The decision-maker may try to understand the root of the problem, the severity and criticality of the problem. Identifying the root of the problem, may support the identification of the course of action.

The system should allow the decision-maker to determine if the situation they are attending is typical or novel (Klein, 1999). The decision-maker will identify critical cues that mark the type of situation and causal factors that explain what is happening and what is going to happen. These are needed to support the operator in identifying the goals and then to take an appropriate action. Typical and familiar situations will result in typical actions, which are usually well rehearsed. In these situations, there is perhaps less system support needed. For those who may have not attended that particular type of incident or simply those who might like a reminder of the actions that may be needed, may require greater system support. The operator may need support for novel situations, which they have not come across before as the situation may be challenging and unfamiliar (Klein, 1999).

Examples

Aviation: For a suspected engine failure, the aircrew must analyse the situation to understand what failure has occurred. Often pilots experience false positives of an engine failure, which means there usually is uncertainty regarding whether a failure has actually occurred. The pilots will investigate the information to identify that it is really a failure, for example, investigate information on the engine interfaces and also try to visually see if there is smoke or signs of a fire. The pilot will check the engine indication and the warning system.

F&RS: When attending a property fire, analysis takes place on arrival, where the incident commander may send the second in charge to identify access points, gas and electric cut off points. The incident commander will investigate hazards, entrances and identifies what the fire looks like at the back of the property. The incident commander will speak with the occupier of the house to get further information and identify the root cause.

Points to Consider:

- How will the decision-maker determine and analyse an emergency?

- The decision-maker's method of data collection. In addition, consider how the information is recorded and presented to the team.
- The dissemination of information to the team.
- The cues the operator is looking for to identify the type of emergency. This could be in the environment, people, systems, etc.
- The casual factors, which explain what is happening and what is going to happen.
- The anomalies in the situation or system.
- Is this a typical or novel problem? If the situation is typical can you provide the operator with checklists, procedures or information on past similar situations?
- The senses the decision-maker will use to diagnose the emergency. For example, visual, auditory, haptic, etc.
- If the decision-maker will test the problem to determine the cause of the emergency? For example, can the decision-maker test the system to see how different the system behaves from normal procedures?
- Give the operator information about how long the situation can run safely before the emergency progresses.
- Identification of false positives in the system.
- The uncertainty in the information the operator has, for example, what is the reliability of the data? What information may be missing? Is there conflicting information or ambiguous data that they must deal with?

H.1.4 Principle 4: Single or Multiple Decision-Maker(s)

Consider who are the decision-makers. For example, is there one decision-maker with the support of a team, or are there several decision-makers who have to work collaboratively? By identifying who the decision-makers are, the designer can focus the design of the system to focus on their needs.

Examples

Aviation: Two pilot aircrews consist of a pilot in command (PIC) and a co-pilot (CP). The aircrew share the responsibilities of pilot flying (PF) and pilot monitoring (PM) roles. The PF is typically responsible for controlling the vertical flight path, horizontal flight path and energy management through supervision of the autopilot or by manually flying the

aircraft. The PM actively monitors the flight parameters, calling out excessive deviations and assisting the PF. The PM also manages radio communications, supervisors system configuration, monitors aircraft status, performs actions called by electronic/paper checklists and coordinates with the PF throughout the whole flight. The aircrew is supported by ATC who provide additional information, clearances and deviations.

F&RS: The team consists of an incident commander (IC), second in charge (SiC) and firefighters, as well as a supervisory officer for larger incidents. The IC is the main decision-maker and responsible for resolving an emergency, with the support of the SiC who also supports in the decision-making process. Firefighters implement procedures as delegated by the IC and SiC. The supervisory officer will be deployed to incidents, which are more complex and will monitor the incident to ensure that the emergency is resolved successfully and that the firefighters are following good practices.

Points to Consider:

- Who the decision-makers are and their goals.
- Multiple decision-makers, who work and interact together.
- The types of decisions expected to be made by the decision-maker.
- The support required by the decision-maker to support their decision-making process. For example, from other operators or parties to collect information.

H.1.5 Principle 5: Operator's Environment

The design of the system should consider the operator's environment as NDM contexts can be challenging. NDM contexts include the following characteristics (Orasanu and Connolly, 1993a):

- Ill-structured problems
- Uncertain, dynamic environments
- Shifting, ill-defined or competing goals
- Multiple event-feedback loops
- Time constraints
- High stakes
- Multiple players

- Organisational norms and goals

The designer should consider the environment to understand how the system will be used and any constraints that the decision-maker may face. Also, by understanding the characteristics and problem areas the designer may want to support the decision-maker in these areas.

Examples

Aviation: An aircrew experiences an emergency warning mid-flight at 30,000ft. over dangerous terrain. The situation would be more complex and dangerous than an emergency on the ground; where the pilots would have support from other personnel and the flight could be abandon.

F&R Service: When the F&RS is asked to attend a road traffic incident with a trapped passenger, the IC would get key information regarding the incident. This would include location information, type of incident and any details taken during the emergency call. Whilst in the fire engine, the firefighter would usually have between 5-10 minutes to absorb as much information as possible from the their mobile system before arriving at the incident. Viewing and processing this information can be difficult as the fire engine is travelling at high speeds, it's chaotic, bumpy and there are varying amounts of light. In addition, firefighters will usually be wearing Personal Protective Equipment including heavy gloves, visors and so on, which can make the portable devices difficult to use.

Points to Consider:

- The decision-maker's environment. Investigate what makes the environment complex and challenging as well as what makes it difficult for the decision-maker to make decisions.
- The observable features of the setting including complex causal links, interactions between causes, feedback loops.
- The information that the operator will need, including the uncertainties that may arise with this information.
- The environment the decision-maker will be in when trying to absorb information. For example, will the operator be in a fire engine that will be travelling at high speeds? Are there alarms going off?
- Variations in the types of incident that the operator attends.
- The decision-maker's goals; identify if the incident can change and consequently alter their goals.

- The time constraints in the environment and the strategies will be employed by the decision-maker to cope with the time constraints.
- The decision-maker's stake, this could include the number of casualties, damage to environment or property, etc.

H.1.6 Principle 6: Time to Absorb Information

During an emergency the decision-maker has limited time to search for information in often unstable environments with the possibility of fatalities. The decision-maker will want to understand as much information as possible as quickly as possible. The design of the system should support the information retrieval for the operator and present it in a way that is easy to comprehend for the operator. By supporting and understanding when the decision-maker can absorb information this can better support the decision-maker's situation awareness and consequently determining and analysing the situation.

Examples

Aviation: For an engine fire, pilots will first receive warnings visually and aurally, the PIC will then need to implement the memory items to ensure that the aircraft is stable. Once they have control of the aircraft, the pilots will then have time to absorb the information to determine the emergency and identify the procedures and checklists that need to be completed.

F&RS: In the example of a firefighter attending a road traffic collision, the IC will have three opportunities to absorb information.

1. Travelling to the incident: whilst travelling to the incident the IC has a mobile database of information which he explores information about the local environment, the things that could be of risk, where the closest water hydrants are, what kind of property it is, etc.
2. Arriving at the incident: the IC will quickly get an understanding of what is occurring, this could be visually assessing the scene, speaking to other emergency services involved and the public. Here the IC needs to determine if any immediate actions need to be taken.
3. Once the immediate actions are completed, the IC will ensure that there is stabilisation and then gather more information about the incident: investigating the scene further, carrying out a risk assessment, implementing counter measures and then go on to implement the course of action.

Points to consider

- Determine how long will the decision-maker have to absorb information before having to make a decision or action?
- What information is a priority to the decision-maker? Then consider the secondary information that the operator may require.
- Consider how the operator will view or search information in the system. Could this be time consuming? Can a summary of the key information regarding the emergency be automatically generated for the operator?
- Does the operator require the certain information to be absorbed in a single glance? If so, which?

H.1.7 Principle 7: Support the identification of a course of action

The recognition primed decision model identifies that the decision-maker develops a single course of action based on the constraints in the environment. Randel et al. (1996) find that experts base their decisions on the nature of the situation using their expertise; they have a large repertoire of past experiences on which to base the current situation. The decision-maker spends little effort in deciding how to react to a situation, once they have understood the situation; the reaction is often obvious. The decision-maker wants "workable," "timely" and "cost effective" actions (Klein and Klinger, 1991).

Examples

Aviation: Once the aircrew has identified that a real engine failure is occurring, and which engine has been affected, the PIC will implement the immediate action items from memory. This includes putting the thrust lever to idle and shutting down the engine. The co-pilot then implements the associated emergency checklist, which reconfirms the immediate actions and checks the engine fire status.

F&RS: For a property fire, once the incident commander has all the information from all sources, he/she will then make the decision of how to resolve the fire. For an extensive fire, the incident commander may split the crew into two teams. The first team is tasked with to extinguishing the fire from outside the property, whilst the second team is sent into the adjacent property to investigate if that property has been affected by the fire and ensure this does not spread.

Points to Consider:

- Course of actions that are typical for the emergencies.
- The impact of the course of action on the incident.
- The system support required for the generation of courses of actions as well as the rationale behind each action.
- In the event of several courses of actions, highlight how satisfactory each action is, the success rate of completing the action.
- Prioritise the courses of actions based on the available information and constraints.

H.1.8 Principle 8: Mental Simulation

Mental simulation in the RPD model evaluates if an action is satisfactory. When simulating, the decision-maker performs the course of action in his or her imagination; plays out the steps, the potential outcomes, the problems that might occur and how these problems may be handled. The decision-maker either implements the action, or modifies it, or rejects it and goes on to the next action (Klein, 1999). Mental simulation appears in at least three places when decision-making; diagnosing to form situation awareness, generating expectancies to help generate situation awareness, and evaluating a course of action (Klein, 1999).

Examples

Aviation: When an emergency has occurred, the pilot in command may need to simulate a number of things, for example, calculate how much fuel is remaining to identify which airport would be appropriate to land. In addition, when a failure occurs and the pilot is determining and analysing a failure, he/she may use the information to simulate the root cause of the incident.

F&RS: In this extract, the incident commander was asked to attend a casualty who was trapped in a vehicle. The incident commander simulates how to extricate the casualty:

"The paramedics made it understood that the casualty had pre-existing medical conditions and for safety the ambulance crew requested that the F&RS remove the roof of the car. The incident commander was hesitant to remove the roof as the car had no damage to it and the incident commander was trying to reduce the financial loss of the vehicle. There were a number of other options to consider first. The incident commander discussed

if the ambulance crew had considered a splint, an extraction device, which is used by the ambulance service. However, it was decided that the casualty was too heavy for this device. Another option, was removal of the door and the doorposts. However, this was not considered as the crew could not get above the casualty to lift her out."

Points to Consider:

- The operator's mental simulation for possible courses of actions.
- The elements in the course of action that may not successfully resolve the incident.
- The elements in the course of action that could present risks.
- Additional resources that could support the operator's mental simulation including blueprints, images, information from past incidents and system simulations.

H.1.9 Principle 9: Confirm success of the course of action

Once the course of action is performed, the decision-maker will need to identify the success of completing the course of action and identify if further actions are required. Outcomes of performing the course of action include:

- Correct with no errors, which would require the decision-maker to take no further actions;
- Correct with errors, which would mean the actions for the decision are correct but this has resulted in another action which needs to be addressed; or
- Simply incorrect, which would require another decision and set of actions.

Examples

Aviation: Once the pilots have completed the procedures using the checklist, they will continue to monitor the systems to ensure that the course of action has been resolved. In the example, where the pilot is experiencing a stall warning, there would be a lot of vibration and noise in the aircraft where the aircraft is indicating that the aircraft is approach a stall. The pilot will complete the procedures to stop the stall occurring and monitor the system, as well as identify if the vibration and noise in the aircraft has returned to the normal level.

F&RS: The IC will monitor how the emergency is being resolved from a distance and ensure that the correct procedure has been completed. In a road traffic collision where a passenger is trapped, the incident commander will identify success once the passenger

has been retrieved safely out of the vehicle and handed over to the ambulance service for medical care.

Points to Consider:

- Supporting the decision-maker to identify the success of a course of action.
- Errors that could occur after the course of action has been performed.

H.1.10 Principle 10: Support for Individual Situation Awareness

Situation awareness is the foundation for decision-making and performance (Salas and Klein, 2001). In order to match situations, the decision-maker must have an understanding of what is going on. SA is developed through the situation assessment process in the RPD model. Endsley (1988) defines SA as *"the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future"* or simply put *"knowing what is going on."* SA gives the operator an understanding of what is happening around them and an understanding of what that information could mean in the future. SA is dynamic in nature and the repetition of the process continuously updates the decision-maker's understanding of the environment (Parasuraman et al., 2008).

Three levels of SA should be supported in the NDM setting (Endsley, 1995b):

Level 1: Highlight the individual values that are relevant to the status, attributes and dynamics of relevant elements in the emergency environment. Highlight the individual pieces of information that are required to gain an understanding of what is happening

Level 2: Support for the comprehension of the current situation. Perception of the elements in the environment is based on the synthesis of disjointed elements. Comprehension of the current situation includes an understanding of the significance of those elements in light of the operator's goals. The operator will form a holistic picture of the environment based on the Level 1 elements and the patterns that emerge. The operator will get a comprehension of the significance of information and events.

Level 3: Ability to support the projection of future status. The third level looks at the ability to project the future actions of the elements in the environment, at least in the near term. This is achieved through knowledge of the status, the dynamics of the elements and a comprehension of the situation (Both Level 1 and Level 2 SA).

Examples

Aviation: The pilots received and analysed the briefing package, which contains the details of the flight. PIC focuses on the flight plan, whilst the CP focuses on the constraints in the Notice to Airman (NOTAMS). NOTAMs are a written notification which outline issues before a flight, and any circumstances that relate to the state of the flying, this typically advises the pilots regarding potential hazards along a flight route or at a particular location.

Pilots also constantly develop individual SA by monitoring the flight deck systems whilst the aircraft is in autopilot to identify any anomalies in the systems. Pilots are looking for data that does not fit "normal behaviour" that they have been trained to expect.

F&R Service: Usually a single firefighter will scan the available information to build up their knowledge regarding the area of the incident, including the type of building that they might be attending, checking for any harmful substances at the location, the closest water sources in the event of a fire, etc.

Points to Consider:

- Endsley et al. (2003) presents types of questions that need to be asked at each SA level:
  - Perception: What information within the environment does the decision-maker need to attend to in order to address critical task decisions?
  - Comprehension: How are the operator's perceptions of system states and the environment related to their goal? What information does the decision-maker need to integrate to understand the state of the system? What do certain pieces of information mean with respect to the decision-maker's capability to execute a method?
  - Projection: Based on the operator's observations of the system states and the environment, and understanding of what this information means to achieving task goals, what projections can the decision-maker make about future states of the system? What projections should the decision-maker make about future states of the system and environment?
- The appropriate information to support situation awareness as well as presenting it in a manner that supports analysis and projection of future events.
- The information on the missing data, data precision, reliability and credibility on possible errors connected with data processing or information transformation.

H.1.11 Principle 11: Team Situation Awareness

Team situation awareness refers to a shared or distributed awareness or mental representation of the environment between team members. Lipshitz et al. (2001) outlines that team situation awareness is essential for effective decision-making, especially since obtaining and maintaining SA in teams is far more complex than in individuals. Team SA can be acquired when members of the team collect and exchange information and when the members engage in closed-loop communication (Orasanu, 1990). Endsley and Jones (1997) state for a team to successfully function, all team members must possess a high level of the same SA on shared requirements.

Examples

Aviation: Once the pilots have developed their individual SA, they come together in a verbal briefing where they discuss the details and decide on the elements of the flight. ATC are then informed of the flight details. This briefing allows the pilots to discuss their findings, any constraints that could affect the flight and the final flight plan. Briefing allows the pilots highlight any errors that could of occurred in each of the pilot's SA.

F&RS: First IC and SIC work together to develop a shared understanding of the situation. When there are gaps in the SA the firefighter's investigate information that is missing and report back to the IC and SIC.

Points to consider

- The number of operators taking part in sharing their situation awareness picture.
- If there is a phase that the operator must report back to the team. How can the system share the information they deem important? Can they share the information to other devices, or view it on a large display?
- How will the decision-maker filter the information to present to the operators?
- What procedure will take place to make joint situation awareness possible i.e. will there be a briefing activity? What materials will the operators have access to?

H.1.12 Principle 12: Communication

Communication can be considered as the way one mind can affect another, it can be either verbal or non-verbal, intentional or unintentional (Eccles and Gershon, 2004). Hogg and Vaughan (2002) define communication as the "transfer of meaningful information from one person to another", which involves the production and the reception of messages. The

basic concept of communication requires a sender to send a message or information and for a receiver to receive this through a channel of communication. Isaac and Ruitenberg (1999) indicates that communication starts when a sender encodes an idea or message and sends it through one or more channels that can be either verbal or non-verbal. The receiver then decodes this message using long term memory to bring meaning to the message. The receiver may have different characteristics which include experience, culture and expectations which may affect decoding.

Isaac and Ruitenberg (1999) make a distinction between verbal and non-verbal communication. Verbal communication such as speech includes pitch, tone and rhythm have an important role in communicating and supporting the message and consequently the decoding. In contrast, non-verbal communication includes forms such as gaze, gesturing and facial expressions. Non-verbal communication can occur independently or in combination with other forms of communication. Hogg and Vaughan (2002) state "speech rarely occurs in isolation from non-verbal cues".

Examples

Aviation: Communication occurs throughout the flight to develop situation awareness, help make decisions, identify errors, obtain more information, etc. Communication occurs between pilot to pilot, and pilots to air traffic control. For example, pilots discuss the flight plan, make changes to the flight plan and exchange ideas. The aviation industry uses strict phraseology to avoid miscommunication and misunderstanding. This may be particularly important in the event of an emergency as noise may be a factor.

F&RS: Like the aviation domain, the F&RS team communicate to develop and understand the emergency, make decisions, as well as identify risks, place countermeasures, etc. Communication is done face-to-face, or via technology such as radios, involving a number of different parties.

Points to Consider:

- The actions that need to be communicated.
- The verbal and non-verbal communication, direct and indirect communication, as well as addressed and non-addressed communication (Isaac and Ruitenberg, 1999).
- Method of communication, for example, how will the operators communicate with each other? Will it be face-to-face or will they need the support of technology?
- Information sharing with others in the team, for example, is it another pilot who will have the same systems in front of him/her or a firefighter who has to report to the incident commander.

- The third parties the decision-maker needs to communicate with, for example, air traffic control or ambulance service.
- Two-way communications, where not only the decision-maker communicates to the team, but the members of the team report back to the decision-maker. For example, the team may provide the decision-maker with more information about how the incident is unfolding.
- The communication between the operator and system, between system-to-system and operator-to-operator.
- Verbalisation activities where actions and tasks are verbally communicated. For example, in two pilot aircrews the co-pilot will read out the procedures on a checklist and the pilot in command will complete the procedure and acknowledge the items are complete. This allows both pilots to know what the other is doing and to understand what impact that has on the aircraft and/or flight plan.

H.1.13 Principle 13: Verbalisation

Verbalisation is when actions and tasks are verbally communicated. Consider which actions might need to be verbalised to the other operators in the team. For example, in two pilot aircrews the co-pilot will read out the procedures on a checklist and the pilot in command will complete the procedure and acknowledge the items are complete. This allows both pilots to know what the other is doing and to understand what impact that has on the aircraft and/or flight plan. By verbalising their actions both pilots will know what the other is doing and also know what to expect as a result of completing the action. The process also allows both the pilots to check what the pilot is saying and doing is actually correct, therefore ensuring that erroneous manual inputs in to the flight deck are caught. Verbalisation is needed to consolidate the information the pilot has acquired and gathered to further extend their understanding of the situation. It can be considered as a process to help the pilot to slow down his/her thinking process. Verbalisation allows the pilot to consider the pros/cons of a problem which allows more effective evaluation of the problem and consequently come up with better decisions.

Examples

Aviation: The pilots stated as part of the communication training the pilots are encouraged to verbalise their actions. This allows both pilots to know what the other is doing and to understand what impact that has on the aircraft and/or flight plan. By verbalising their actions both pilots know what the other is doing and also know what to expect as a result

of completing the action. The process also allows both the pilots to check what the pilot is saying and doing is actually correct, therefore ensuring that manual inputs in to the flight deck are caught. The pilots outlined that the CP also verbalises each checklist item and then the PIC carries out the item.

F&RS: n/a

Points to consider

- How can verbalisation support the operator's decision-making in an emergency?
- What actions need to be verbalised alongside the actions?

H.1.14 Principle 14: Workload

Parasuraman et al. (2008) definition of workload *"the relation between the function relating the mental resources demanded by a task and those resources available to be supplied by the human operator."* Increased workload reduces the ability of the user to undertake efficient decision-making, thus the decision-maker needs to be supported when completing his/her tasks. These tasks include gathering information and identifying problems; reviewing causal factors with other team members; considering and sharing risks of alternative courses of action.

The NDM environment is a multi-task environment, where the decision-maker uses several different resources for information processing. Wickens (1984) identified four dimensions, these include:

- The stages of processing dimension which describes that perceptual and cognitive (e.g. working memory) tasks use different resources from the selection and execution of action.
- The codes of processing dimension highlights that spatial activity uses different resources than verbal/linguistic activity.
- The modalities dimension outlines that auditory perception uses different resources than visual perception.
- Visual channels dimension outlines between focal and ambient vision, a nested dimension within visual resources.

Two forms of technological intervention are therefore possible; technology that reduces workload by automating tasks that would otherwise consume mental effort (also known

as "offloading") or technology that supports the process of decision-making itself (i.e., decision support) (Rogers and Scaife, 1998).

Examples

Aviation: When an emergency is detected in the cockpit, a pilot's workload increases. The increase in workload is due to the extra tasks of identifying the emergency, stabilising the aircraft and determining what is occurring. Workload could also increase if a take off time slot was missed, which in turn would increase stress. Pilots can rush through system tasks to meet a take off time and this could contribute to a later accident.

F&RS: The IC splits the workload amongst the team. In this scenario, the IC split the tasks between himself and the second in charge: *"The IC sent the second in charge to look at access points and for the gas and electric cut off points. He would also look for hazards, entrances and will inform the IC what the fire looks like at other locations. The IC will speak with the occupier of the building who will hopefully identify potential hazards or possible causes."*

Points to Consider:

- The operator's workload and identify how busy they are.
- Identify tasks that could impact performance.
- The complexity of the tasks that the decision-maker has to perform. Identify if the decision-maker can take on additional tasks (Young et al., 2014).
- The operator is able to respond to unexpected events (Young et al., 2014).
- The operator's additional workload.
- The mental resources and capabilities of the decision-maker's information processing system. Identify the limit and support the decision-maker's performance before it begins to deteriorate.
- Multiple resource theory, the decision-maker uses several different resources simultaneously. Consider the four dimensions; stages of processing, the codes of processing, the modalities and visual channels (Wickens, 1984).
- When the operator has high workload, the strategies they will employ to manage their tasks. Consider the individual characteristics, task characteristics and the workload levels.
- The use of automation to support workload and/or technology that support the process of decision-making itself (Rogers and Scaife, 1998).

H.1.15 Principle 15: Automation

Automation is a method to support operators with workload that they may experience. Automation can differ in type and complexity from simply organising the information sources; to integrating them into a summary format, to suggesting decision options that best match the incoming information, or even carry out the necessary action.

Automation can provide decision support, alleviate the heavy demand and augment system performance to reduce errors. Good automation reduces workload whilst maintaining the operator's situation awareness. Automation can improve precision, process large amounts of data from multiple sources, manage multiple systems as one, provide calculations and precise estimations. Automation frees the operator from monotonous tasks, and this will in turn free attentional resources and allow the operator to concentrate on more rewarding and safety critical elements. The system designer can introduce different levels of automation into systems, Kaber and Endsley (1998) present the levels of taxonomy, which present different levels of automation for monitoring, generating, selecting and implementing tasks.

Examples

Aviation: Cockpits are highly automated systems, with the use of autopilot. The pilot will typically use autopilot and only revert to manual flying when necessary. In the event of an emergency, the crew alerting system identifies errors in the system. For example, the cockpit usually has two sensors to identify altitude. If there is a discrepancy between the two sensors, the pilots will be alerted by the crew alerting system that this discrepancy has occurred.

F&RS: A system in the F&RS identifies the location of the incident and presents the known information to the IC. For consideration an IC's comment: *"When an appliance is mobilised, the appliance receives a mobilising message, which gives the firefighter information about the incident. This includes address information; type of incident (i.e. a house fire, property fire), additional incident information and the corresponding risk card is unlocked for the incident."*

Points to Consider:

- The different levels of automation, for example, the computer decides everything by acting autonomously or the operator must authorise the action.
- Access to raw data, its accuracy, precision and reliability at all stages and levels of automation.

- Provide reasoning of why the action is being completed by the automation.
- The design should keep the user informed of the actions, interpretations, errors, exceptions, changes of state and changes of condition that are relevant and of interest. This should be achieved through clear, concise and unambiguous language.
- Avoid target fixation, this is when the mind focuses on a single thing, which can result in the decision-maker missing other issues/information.
- Avoid out-of-loop syndrome, where automation reduces the operator's excessive workload, to a point of low situation awareness; where in certain cases the operator will not understand what is happening.
- Complexity creep, this is where the designer unwittingly unleashes complexity with the practice of feature escalation. This could lead to increased workload due to the design of the system.
- Use of consistent interaction metaphors for the interaction with devices, i.e. touch screen, switches, etc. This will reduce the learning curve required to use technology.
- Different levels of information for different levels of stress. For example, present an overview and then allow zoom into details only on demand. The system could even intelligently create an overview of the important information. This would reduce the amount of time needed to explore key information points but also gives the operator an option to zoom into the detail when and if they have time.

H.1.16 Principle 16: Monitoring and Crosschecking

Consider the monitoring and crosschecking activities that the operator(s) may require to ensure that errors do not occur.

Examples

Aviation: In the cockpit, the co-pilot will undertake many monitoring and crosschecking activities. For example, the co-pilot will ensure that the items programmed into the systems by the PIC are correct. The co-pilot monitors the values in his/her set of instrumentation as he/she knows the target values (e.g. altitude during cruise or at distinct points during approach, briefed speeds for approach and landing or limit speeds for flaps and gear) and will cross check the PIC's values with his/her instrumentation.

F&RS: In the F&RS there are several actors who are monitoring incident activities. These include:

- The second in charge monitors the incident commander's actions and catches any errors.
- Firefighters monitor the emergency including the fatalities and environment.
- Supervisory officer monitors emergency and team. The supervisory officer monitors the IC and the firefighters.

Points to consider

- Consider if the people, environment or systems need monitoring.
- Can the system support the decision-maker in any of the monitoring and crosschecking activities that that they are required to complete?
- Can the support from the system increase the accuracy and consistency of monitoring and crosschecking information?
- Can the monitoring and crosschecking be completed by automation and a summary given to the decision-maker?

Bibliography

Adams, M. J., Y. J. Tenney, and R. W. Pew (1995). Situation Awareness and the Cognitive Management of Complex Systems. *Human Factors 37*(1), 85–104.

Alexander, M., H. Faulkner, C. Viavattene, and S. A. Priest (2011). A GIS-based flood risk assessment tool: Supporting Flood Incident Management at the local scale.

Allaire, Y. and M. E. Firsirotu (1989). Coping with strategic uncertainty. *MIT Sloan Management Review 30(3)*, 7.

Allen, J. P. and W. L. Rankin (1995). A summary of the use and impact of the Maintenance Error Decision Aid (MEDA) on the commercial aviation industry. *Annual international air safety seminar. Vol. 48.*(Flight Safety Foundation).

Andrienko, N. and G. Andrienko (2007). Intelligent visualization and information presentation for civil crisis management. *Trans. GIS 11*(6), 889–910.

Atoyan, H., J.-M. Robert, and J.-R. Duqet (2011). Uncertainties in Complex Dynamic Environments. *Journal d'Interaction Personne-Systeme 2*(1), 5:1–24.

Bayram, K., E. Fazli, J. Dokic, C. Goodchild, P. Kou, A. P. Gonçalves, N. Mcdonald, S. Peces, N. Senequier, N. Stark, S. Sweeney, U. Teegen, Verhoeven, and F. Zambetti (2013). D1.1 Scope and State of the Art ACROSS. pp. 1–186.

BBC News (2016). Flight 4U 9525: What happened in the final 30 minutes.

Beach, L. R. and T. R. Mitchell (1987). Image theory: Principles, goals, and plans in decision making. *Acta Psychologica 66*(3), 201–220.

Bornstein, G. and Z. Gilula (2003). Between-Group Communication and Conflict Resolution in Assurance and Chicken Games. *Journal of Conflict Resolution 47*(3), 326–339.

Bowers, C. a., F. Jentsch, E. Salas, and C. C. Braun (1998). Analyzing Communication Sequences for Team Training Needs Assessment. *Human Factors: The Journal of the Human Factors and Ergonomics Society 40*(4), 672–679.

Cain, B. (2007). A Review of the Mental Workload Literature. *Defence research and development Toronto (Canada)* (1998), 4–1–4–34.

Cannon-Bowers, J., E. Salas, and S. Converse (1993). Individual and group decision making: Current issues. pp. 221–246.

Cannon-Bowers, J. a. and E. Salas (1998). *Making decisions under stress: Implications for individual and team training.* American Psychological Association.

Cannon-Bowers, J. A., S. I. Tannenbaum, E. Salas, and C. E. Volpe (1995). Defining competencies and establishing team training requirements. *Team effectiveness and decision making in organizations 333*, 380.

Carayon, P. and P. Buckle. (2010). Editorial for special issue of applied ergonomics on patient safety. *Applied ergonomics 41* (no. 5), 643–644.

Carroll, J. M. and J. Olson (1988). *Handbook of Human Computer Interaction.* Helander-North Holland.

Chen-Wing, S. L. N. and E. C. Davey (1998). Designing To Avoid Human Error Consequences. *2nd Workshop on Human Error, Safety, and System Development*, 90–97.

Cole, G. A. (2004). *Management theory and practice.* Cengage Learning EMEA.

Connolly, T. (1982). *On taking action seriously: Cognitive fixation in behavioral decision theory.* Boston: Kent.

Connor, R. O., Z. Roberts, J. Ziccardi, R. Koteskey, J. Lachter, Q. Dao, W. W. Johnson, V. Battiste, and K.-p. L. Vu (2013). Pre-Study Walkthrough with a Commercial Pilot for a Preliminary Single Pilot Operations Experiment. *Human Interface and the Management of Information. Information and Interaction for Health, Safety, Mobility and Complex Environments. 15th International Conference, HCI International 2013. July 21-26. Berlin, Germany.*, 136–142.

Constantine, L. L. and L. A. D. Lockwood (2001). Usage-Centered Engineering for Web Application. *IEEE Software 19*(2), 42–50.

Cooke, N. J., J. C. Gorman, J. L. Duran, and A. R. Taylor (2007). Team cognition in experienced command-and-control teams. *Journal of Experimental Psychology: Applied 13*(3), 146–57.

Crandall, B., G. Klein, and R. Hoffman (2006). *Working Minds: a Practitioner's Guide to Cognitive Task Analysis.*

Croft, J. (2015). NASA Advances Single-Pilot Operations Concepts.

Dane, F. (1990). *Research Methods.* Brooks/Cole Publishing Company.

de Carvalho, P. V. R., J. O. Gomes, G. J. Huber, and M. C. Vidal (2009). Normal people working in normal organizations with normal equipment: System safety and cognition in a mid-air collision. *Applied Ergonomics 40*(3), 325–340.

Degani, A. and E. L. Wiener (1993). Cockpit Checklists : Concepts , Design , and Use. *Human Factors: The Journal of the Human Factors and Ergonomics Society 35*(2), 345–359.

Dekker, S. (2006). The field guide to human error. *Bedford, UK* (August 2000).

Deutsch, S. and R. W. Pew (2005). Single Pilot Commercial Aircraft Operation. (8436).

Dirk Ifenthaler, P. P. and J. M. Specto (2008). *Understanding Models for Learning and Instruction.* Number Ch. Practical Solutions for the Diagnosis of Progressing Mental Models.

Eccles, D. and T. Gershon (2004). Why an expert team is more than a team of experts: A social-cognitive conceptualization of team coordination and communication in sport. *Journal of Sport and Exercise Psychology 26 no. 4*, 542–560.

Eggemeier, F., G. F. Thomas, A. F. Wilson, Kramer, , and D. L. Damos. (1991). Workload assessment in multi-task environments. *Multiple-task performance*, 207–216.

Ellingsen, T. and R. Östling (2010). When does communication improve coordination? *American Economic Review 100*(4), 1695–1724.

Endsley, M. and R. R. Hoffman (2002). The Sacagawea principle. *IEEE Intelligent Systems 17*(6), 80–85.

Endsley, M. and W. M. Jones (1997). Situation Awareness Information Dominance & Information Warfare. *Logicon Technical Services Inc Dayton OH* (January 1996).

Endsley, M. R. (1988). Situation awareness global assessment technique (SAGAT). *Aerospace and Electronics Conference, 1988. NAECON 1988., Proceedings of the IEEE 1988 National*, 789–795.

Endsley, M. R. (1995a). Measurement of Situation Awareness in Dynamic-Systems.

Endsley, M. R. (1995b). Toward a Theory of Situation Awareness in Dynamic Systems. *Human Factors: The Journal of the Human Factors and Ergonomics Society 37*(1), 32–64.

Endsley, M. R. (2000a). Direct measurement of situation awareness: Validity and use of SAGAT. *Situation Awareness Analysis and Measurement*, 1–21.

Endsley, M. R. (2000b). Theoretical Underpinnings of Situation Awareness: A Critical Review Process. *M.R. Endsley and D.J.Garland(Eds) Situation Awareness Analysis and measurement. L.Erlbaum Assoc.Publishers*, 1–24.

Endsley, M. R., B. Bolté, and D. G. Jones (2003). *Designing for Situation Awareness.*

Endsley, M. R. and D. Jones (2011). Designing for Situation Awareness: An Approach to User-Centered Design, Second Edition.

Fireservice.co.uk (2016). The Retained Duty System.

Flach, J. M., S. Dekker, and P. J. Stappers. (2008). Playing twenty questions with nature (the surprise version): Reflections on the dynamics of experience. *Theoretical Issues in Ergonomics Science 9 no. 2*, 125–154.

Golightly, D., B. Ryan, and S. Sharples (2010). COGNITIVE WORK ANALYSIS OF SIGNALLING PROTECTION FOR RAIL ENGINEERING. In *CONTEMPORARY ERGONOMICS AND HUMAN FACTORS 2010*.

Gopher, D. and R. Braune (1984). On the Psychophysics of Workload: Why Bother with Subjective Measures? *Human Factors: The Journal of the Human Factors and Ergonomics Society 26*(5), 519–532.

Gopher, D. and E. Donchin (1986). Workload - An examination of the concept. *Handbook of perception and human performance, Vol. 2, Cognitive processes and performance 2*, 41,1–41,49.

Graham, J., C. Hopkins, A. Loeber, and S. Trivedi (2014). Design of a single pilot cockpit for airline operations. *2014 IEEE Systems and Information Engineering Design Symposium, SIEDS 2014* (April), 210–215.

Griethe, H. and H. Schuhmann (2006). The Visualization of Uncertain Data : Methods and Problems. *SimVis 2006 vi*, 143–156.

Griethe, H. and H. Schumann (2005). Visualizing Uncertainty for Improved Decision Making. *Computer* (June), 3–4.

Gualtieri, J., W. Elm, J. Easter, and J. Naser (2012). Decision-Centered Design Guidelines For The Electric Power Industry's Human Systems Interfaces. (2).

Hammond, K. R., H. M. Hamm, J. Grassia, and T. Pearson (1987). Direct comparison efficacy of intuitive and analytical cognition in expert judgement. *SMC-17(5)*, 753–770.

Harris, D. (2007). A human-centred design agenda for the development of single crew operated commercial aircraft. *Aircraft Engineering and Aerospace Technology 79*, 518–526.

Hart, S. G. and C. Wickens (1990). *Workload assessment and prediction.* Springer Netherlands. Manprint.

Helmreich, R. L. (2000). On error management: lessons from aviation. *BMJ (Clinical research ed.) 320*(7237), 781–785.

Helmreich, R. L. and H. C. Foushee (1993). Why crew resource management? Empirical and theoretical bases of human factors training in aviation. In *Cockpit Resource Management*, pp. 3–45.

Helmreich, R. L., a. C. Merritt, and J. a. Wilhelm (1999). The evolution of Crew Resource Management training in commercial aviation. *The International journal of aviation psychology 9*(1), 19–32.

Hoffman, R. R. (2007). *Expertise out of context: Proceedings of the sixth international conference on naturalistic decision making.* Psychology Press.

Hogg, M. A. and G. Vaughan (2002). *Social psychology: An introduction.* (3rd ed. ed.). London: Pearson Education.

Hunter, G. J. and M. F. Goodchild (1993). Managing uncertainty in spatial databases: Putting theory into practice. *Papers from the annual conference-urban and regional information systems association. Urisa urban and regional information systems.*.

Hutchins, S. G., J. G. Morrison, and R. T. Kelly (1996). Principles for aiding complex military decision making. Proceedings of the Second international command and control research and technology symposium.

Hutton, R. J., T. E. Miller, and M. L. Thordsen (2003). Decision-centered design: Leveraging cognitive task analysis in design. pp. 383–416. Handbook of cognitive task design.

Huttunen, K., H. Keränen, E. Väyrynen, R. Pääkkönen, and T. Leino (2011). Effect of cognitive load on speech prosody in aviation: Evidence from military simulator flights. *Applied Ergonomics 42*(2), 348–357.

Isaac, A. R. and B. Ruitenberg (1999). *Air traffic control: human performance factors.*

Janis, I. L. and L. Mann (1977). *Decision making: A psychological analysis of conflict, choice, and commitment.* Free Press.

Janosky, B., P. J. Smith, and C. Hildreth (1986). Online library catalog systems: An analysis of user errors. *International Journal of Man-Machine Studies 25*(5), 573–592.

Jenkins, D. P., Great Britain, Ministry of Defence, and Human Factors Integration Defence Technology Centre (2009). Cognitive work analysis coping with complexity. (September).

Jenkins, D. P., N. A. Stanton, P. M. Salmon, G. H. Walker, and M. S. Young (2008). Using cognitive work analysis to explore activity allocation within military domains. *Ergonomics*.

Jiang, X., J. I. Hong, L. a. Takayama, and J. a. Landay (2004). Ubiquitous Computing for Firefighters: Field Studies and Prototypes of Large Displays for Incident Command. *SIGCHI Conference on Human Factors in Computing Systems 6*(1), 679–686.

Johnson, A. and R. W. Proctor (2004). *Attention: Theory and practice.* Sage Publications.

Johnson, W., J. Lachter, M. Feary, and D. Comerford (2012). HCI Aero 2012 Task Allocation for Single Pilot Operations: A Role for the Ground. *HCI Aero*.

Johnson-Laird, P. N. (2001). Mental models and deduction. *Trends in Cognitive Sciences 5*(10), 434–442.

Jones, N. a., H. Ross, T. Lynam, P. Perez, and A. Leitch (2011). Mental Model an Interdisciplinary Synthesis of Theory and Methods. *Ecology and Society 16*(1), 46–46.

Kaber, D. B. and M. R. Endsley (1998). Team situation awareness for process control safety and performance. *Process Safety Progress 17*(1), 43–48.

Kaempf, G. L., G. Klein, M. L. Thordsen, and S. Wolf (1996). Decision Making in Complex Naval Command-and-Control Environments. *Human Factors: The Journal of the Human Factors and Ergonomics Society 38*(2), 220–231.

Kahneman, D. (1973). *Attention and Effort*, Volume 88.

Katopol, P. (2004). Cognitive Work Analysis : A Framework for Research in Collaborative Information Seeking. *Journal of the American Society for Information Science*.

Kieras, D. E. (1988). Towards a practical GOMS model methodology for user interface design. *Handbook of human-computer interaction*, 135–158.

Klein, G. (1993a). Naturalistic decision making: Implications for design. *Soar Cseriac 93-01* (April).

Klein, G. (1993b). Sources of Error in Naturalistic Decision Making Tasks. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting 37*(4), 368–371.

Klein, G. (1999). *Sources of Power: How People Make Decisions*, Volume 52.

Klein, G. (2001). *Linking expertise and naturalistic decision making.* Psychology Press.

Klein, G., K. Associates, and D. Ara (2008). Naturalistic Decision Making. *Human Factors 50*(3), 456–460.

Klein, G., R. Calderwood, and D. Macgregor (1989). Critical decision method for eliciting knowledge. *Systems, Man and Cybernetics, IEEE Transactions on 19*(3), 462–472.

Klein, G. and D. Klinger (1991). *Naturalistic decision making.* CSERL4C Gar 31-4.

Klein, G. A. (1989). Recognition-primed decisions. In W. B. Rouse (Ed.), *Advances in man-machine systems research. Volume 5*, pp. 47–92. JAI Press Inc.

Klein, G. a., R. Calderwood, and A. Clinton-cirocco (1986). Rapid decision making on the fire ground. *Proceedings of the Human Factors and Ergonomics Society annual meeting vol. 30*(no. 6), 576–580.

Klein, G. a., R. Calderwood, and a. Clinton-Cirocco (1986). Rapid Decision Making on the Fire Ground. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*.

Klein, G. A. and B. W. Crandall (1995). The role of mental simulation in naturalistic decision-making. In *In P.Hancock, J. Flach, J. Caird,& K. Vincente (Eds.), Local applications of the ecological approach to human-machine systems, (Vol. 2, pp. 324–358). Hillsdale, NJ: Erlbaum.*

Klein, G. A., J. Orasanu, R. Calderwood, and C. E. Zsambok (1993). *Decision making in action: Models and methods.* Ablex Publishing.

Kramer, A. F., E. J. Sirevaag, and R. Braune (1987). A psychophysiological assessment of operator workload during simulated flight missions. *Human Factors: The Journal of the Human Factors and Ergonomics Society 29*(2), 145–60.

Lachter, J., V. Battiste, M. Matessa, Q. V. Dao, R. Koteskey, and W. W. Johnson (2014). Toward single pilot operations: the impact of the loss of non-verbal communication on the flight deck. *Proceedings of the International Conference on Human-Computer Interaction in Aerospace*, 29.

Latorella, K. A. and P. V. Prabhu (2000). A review of human error in aviation maintenance and inspection. *International Journal of Industrial Ergonomics 26*(2), 133–161.

Lawton, R. and N. J. Ward (2005). A systems analysis of the Ladbroke Grove rail crash. *Accident Analysis and Prevention 37*(2), 235–244.

Lee, J. D. and A. Kirlik (2013). *The Oxford handbook of cognitive engineering*. Oxford University Press.

Li, B. (2008). The Classical Model of Decision Making Has Been Accepted as not providing an Accurate Account of How People Typically Make Decisions. *International Journal of Business and Management* (2003), 151–154.

Lighthall, G. K. and C. Vazquez-Guillamet (2015). Understanding Decision Making in Critical Care. *Clinical Medicine & Research 13*(3-4), 156–168.

Lin, C. J., T. C. Yenn, and C. W. Yang (2010). Automation design in advanced control rooms of the modernized nuclear power plants. *Safety Science 48*(1), 63–71.

Lipshitz, R. (1989). Decision making as argument driven action. *Center for Applied Social Science. Boston University.*.

Lipshitz, R. (1993). Decision making as argument-driven action. In G. Klein, J. Orasanu, R. Calderwood, & C. Zsambok (Eds.). Decision making in action: Models and methods (pp. 138-147). Norwood, NJ: Ablex.

Lipshitz, R. (1994). Decision Making in Three Modes. *Journal for the Theory of Social Behaviour 24*(1), 47–65.

Lipshitz, R., G. Klein, J. Orasanu, and E. Salas (2001). Taking stock of naturalistic decision making. *Journal of Behavioral Decision Making 14*(5), 331–352.

Lipshitz, R. and O. Strauss (1997). Coping with Uncertainty: A Naturalistic Decision-Making Analysis. *Organizational Behavior and Human Decision Processes 69*(2), 149–163.

Lyndon, A. (2006). Communication and teamwork in patient care: how much can we learn from aviation? *Journal of obstetric, gynecologic, and neonatal nursing : JOGNN / NAACOG 35*(4), 538–546.

Lysaght, R. J., S. G. Hill, a. O. Dick, B. D. Plamondon, P. M. Linton, W. W. Wierwille, a. L. Zaklad, a. C. Bittner Jr, and R. J. Wherry (1989). Operator workload: Comprehensive review and evaluation of operator workload methodologies. *United States Army Research Institute for the Behavioral Sciences, Technical Report 851*, 903–986.

MacEachren, a. M., A. Robinson, and S. Hopper (2005). Visualizing geospatial information uncertainty: What we know and what we need to know. *Cartography and Geographic Information Science 32*(3), 139–160.

Mathieu, J., T. Heffner, G. Goodwin, E. Salas, and J. Cannon-Bowers (2000). The influence of shared mental models on team process and performance. *The Journal of applied psychology 85*(2), 273–83.

Mayhew, D. J. (1991). *Principles and guidelines in software user interface design* (Prentice-H ed.).

McFadden, K. L. and E. R. Towell (1999). Aviation human factors: A framework for the new millennium. *Journal of Air Transport Management 5*(4), 177–184.

McIlroy, R. C. and N. A. Stanton (2011). Getting past first base: Going all the way with Cognitive Work Analysis. *Applied Ergonomics*.

McIntyre, R. M. and E. Salas. (1995). Measuring and managing for team performance: Emerging principles from complex environments. *Team effectiveness and decision making in organizations*, 9–45.

Mendonça, D. (2007). Decision support for improvisation in response to extreme events: Learning from the response to the 2001 World Trade Center attack. *Decision Support Systems*.

Mesmer-Magnus, J. R. and L. a. Dechurch (2009). Information sharing and team performance: a meta-analysis. *The Journal of Applied Psychology 94*(2), 535–46.

Militello, L. G. and G. Klein. (2013). Decision-centered design. In *The Oxford handbook of cognitive engineering*, pp. 261–271.

Mogford, R. H. (1997). Mental models and situation awareness in air traffic control 65. *International Journal of Aviation Psychology 7*(4), 331–341.

Montgomery, H. (1983). Decision Rules and the Search for a Dominance Structure: Towards a Process Model of Decision Making. *Advances in Psychology 14*(C), 343–369.

Moray, N. (1998). Identifying mental models of complex human–machine systems. *International Journal of Industrial Ergonomics 22*(4), 293–297.

Naikar, N. (2006). An examination of the key concepts of the five phases of cognitive work analysis with examples from a familiar system. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting 50*(3), 447–451.

Naikar, N., R. Hopcroft, and A. Moylan (2005). Work Domain Analysis : Theoretical Concepts and Methodology.

Nancy, S. and A. F. Norcio (1993). Mental Models: concepts for human-computer interaction research. *Int. J. Man-Machine Studies* (38), 587–605.

Nobel, D. (1989). *Application of a theory of cognition to situation assessment.* Vienna: VA: Engineering Research Associates.

Norman, D. (1983a). Some Observations on Mental Models. In *Gentner, D., and A. L. Stevens, eds. 1983. Mental models. Mahwah, NJ: Lawrence Erlbaum & Associates.*, Chapter 2, pp. 7–14.

Norman, D. A. (1983b). Design Rules Based on Analyses of Human Error. *Communications of the ACM 26*(4), 254–258.

O'Hare, D. (1992). The 'artful' decision maker: A framework model for aeronautical decision making. *International Journal of Aviation Psychology 2*(3).

O'Hare, D. and M. Wiggins (2004). Remembrance of Cases Past: Who Remembers What, When Confronting Critical Flight Events? *Human Factors: The Journal of the Human Factors and Ergonomics Society*.

O'Hare, D., M. Wiggins, a. Williams, and W. Wong (1998). Cognitive task analyses for decision centred design and training. *Ergonomics 41*(11), 1698–1718.

Orasanu, J. and T. Connolly (1993a). *The reinvention of decision making.* Ablex Publishing.

Orasanu, J. and T. Connolly (1993b). The reinvention of decision making. In G. Klein, J. Orasanu, R. Calderwood, & C. E. Zsambok (Eds.) Decision making in action: Models and methods. Norwood, NJ: Albex.

Orasanu, J. and L. Martin (1998). Errors in aviation decision making: A factor in accidents and incidents. *Proceedings of the Workshop on Human Error, Safety, and Systems Development*, 100–107.

Orasanu, J. M. (1990). Shared mental models and crew decision making. (46).

Pang, A. T., C. M. Wittenbrink, and S. K. Lodha (1996). Approaches to Uncertainty Visualization. *The Visual Computer*, 1–24.

Parasuraman, R., T. B. Sheridan, and C. D. Wickens (2008). Situation Awareness,Mental Workload,and Trust in Automation:Viable,Empirically Supported Cognitive Engineering Constructs. *Journal of Cognitive Engineering and Decision Making 2*(2), 140–160.

Park, K. S. and K. T. Jung (1996). Considering performance shaping factors in situation-specific human error probabilities. *International Journal of Industrial Ergonomics 18*(4), 325–331.

Patrashkova-Volzdoska, R. R., S. A. McComb, S. G. Green, and W. D. Compton (2003). Examining a curvilinear relationship between communication frequency and team performance in cross-functional project teams. *IEEE Transactions on Engineering Management 50*(3), 262–269.

Patterson, E. S., M. L. Render, and B. A. Chalko (2003). Understanding the Complexity of Registered Nurse Work in Acute Care Settings. *Journal of Nursing Administration*.

Pennington, N. and R. Hastie (1993). Reasoning in explanation-based decision making. *Cognition 49*(1-2), 123–163.

Pennington, N., & Hastie, R. (1986). Evidence evaluation in complex decision making. *Journal of Personality and Social Psychology 51(2)*, 242–258.

Pettigrew, K. E., R. Fidel, and H. Bruce (2001). Conceptual frameworks in information behavior. *Annual Review of Information Science and Technology 35*, 43–78.

Rake, E. L. and O. Njå (2009). Perceptions and performances of experienced incident commanders. *Journal of Risk Research 12*(5), 665–685.

Randel, J., L. Pugh, and B. Wyman (1996). Methods of conducting a cognitive task analysis.pdf.

Rasmussen, J. (1982). Human errors. A taxonomy for describing human malfunction in industrial installations. *Journal of Occupational Accidents 4*(2-4), 311–333.

Rasmussen, J. (1983). Skills, rules, and knowledge; signals, signs, and symbols, and other distinctions in human performance models. *Ieee Trans. Sys. Man Cyber. 13*(3), 257–266.

Rasmussen, J. (1986). *Information processing and human-machine interaction*, Volume 12. North-Holland.

Read, G. J. M., P. M. Salmon, M. G. Lenné, and N. A. Stanton (2016). Walking the line: Understanding pedestrian behaviour and risk at rail level crossings with cognitive work analysis. *Applied Ergonomics*.

Reason, J. (1990). *Human Error*, Volume 1. Cambridge University Press.

Riveiro, M. (2007). Evaluation of uncertainty visualization techniques for information fusion. *10th International Conference on Information Fusion*, 1–8.

Robson, C. (2002). *Real world research.* Blackwell Publishing.

Rogers, Y. and M. Scaife (1998). How can interactive multimedia facilitate learning? *Intelligence 90*(2), 1–25.

Rutherford, A. and J. Wilson (1991a). Searching for the mental model in human-machine systems. In *Models in the Mind: perspectives, theory and application. Y. Rogers, A. Rutherford and P. Bibby (eds.)*, pp. 195–223. London, U.K.: Academic Press.

Rutherford, A. and J. R. Wilson (1991b). Models of Mental Models: An Ergonomist - Psychologist Dialogue. In *Human Factors in Information Technology.*

Salas, E., J. A. Cannon-Bowers, and J. H. Johnston (1997). How can you turn a team of experts into an expert team?: Emerging training strategies. In *Naturalistic decision making*, pp. 359–370.

Salas, E., T. L. Dickinson, S. A. Converse, and S. I. Tannenbaum. (1992). *Toward an understanding of team performance and training.* In: Swezey, R.W., Salas, E. (Eds.), Teams: their training and performance. Ablex, Norwood, NJ, pp. 3-29.

Salas, E. and G. A. Klein (2001). *Linking expertise and naturalistic decision making.* Psychology Press.

Salas, E., C. Prince, D. Baker, and L. Shrestha (1995). Situation awareness in team performance: Implications for measurement and training. *37(1)*, 123–136.

Salas, E., K. C. Stagl, and C. S. Burke (2005). 25 Years of Team Effectiveness in Organizations: Research Themes and Emerging Needs. In *International Review of Industrial and Organizational Psychology, 2004.*

Salmon, P., D. Jenkins, N. Stanton, and G. Walker (2010). Hierarchical task analysis vs. cognitive work analysis: comparison of theory, methodology and contribution to system design. *Theoretical Issues in Ergonomics Science 11*(6), 504–531.

Sanderson, P. M. (2003). Cognitive Work Analysis across the system life-cycle: Achievements, challenges, and prospects in aviation. *Aviation Resource Management 3*, 73–85.

Schellekens, J. M. H., G. J. Sijtsma, E. Vegter, and T. F. Meijman (2000). Immediate and delayed after-effects of long lasting mentally demanding work. *Biological Psychology 53*(1), 37–56.

Schutte, P. C., K. H. Goodrich, D. E. Cox, E. B. Jackson, M. T. Palmer, A. T. Pope, R. W. Schlecht, K. K. Tedjojuwono, A. C. Trujillo, R. A. Williams, J. B. Kinney, and J. S.

Barry (2007). The Naturalistic Flight Deck System : An Integrated System Concept for Improved Single-Pilot Operations. (December), 56.

Schwartz, D. (1990). Coordination and Information Sharing. In *Training for Situation Awareness*. Houston: TX: Flight Safety International.

Senol, M. B., M. Dagdeviren, M. Kurt, and C. Cilingir (2009). Evaluation of cockpit design by using quantitative and qualitative tools. In *IEEM 2009 - IEEE International Conference on Industrial Engineering and Engineering Management*, pp. 847–851.

Shapira, Z. (1995). *Risk taking: A managerial perspective*. Russell Sage Foundation.

Sharples, S. and T. Megaw (2015). Definition and Measurement of Human Workload. In *Wilson, J. R., & Sarah, S. (2015). Evaluation of human work. CRC Press.*, Chapter 18, pp. 515–548.

Shen, S. Y. and M. J. Shaw (2004). Managing coordination in emergency response systems with information technologies. *Proceedings of the Tenth Americas Conferences on Information Systems* (August), 2110–2120.

Smith, W. and J. Dowell (2000). A case study of co-ordinative decision-making in disaster management. *Ergonomics*.

Sperandio, J. C. (1971). Variation of operator's strategies and regulating effects on workload. *Ergonomics 14*(5), 571–7.

Stanton, N., A. Hedge, K. Brookhuis, E. Salas, and H. Hendrick (2004). *Handbook of Human Factors and Ergonomics Methods*. CRC Press.

Stanton, N. A. and K. Bessell (2014). How a submarine returns to periscope depth: Analysing complex socio-technical systems using Cognitive Work Analysis. *Applied Ergonomics 45*(1), 110–125.

Stanton, N. A., D. Harris, and A. Starr (2016). The future flight deck: Modelling dual, single and distributed crewing options. *Applied Ergonomics 53*, 331–342.

Stanton, N. A., R. C. McIlroy, C. Harvey, S. Blainey, A. Hickford, J. M. Preston, and B. Ryan (2013). Following the cognitive work analysis train of thought: exploring the constraints of modal shift to rail transport. *Ergonomics*.

Stout, R. J., J. A. Cannon-Bowers, E. Salas, and D. M. Milanovich (1999a). Planning, Shared Mental Models, and Coordinated Performance: An Empirical Link Is Established. *Human Factors 41*(1), 61–71.

Stout, R. J., J. A. Cannon-Bowers, E. Salas, and D. M. Milanovich (1999b). Planning, shared mental models, and coordinated performance: An empirical link is established. *Human Factors 41*(1), 61–71.

Stout, R. J., E. Salas, and J. E. Fowlkes (1997). Enhancing Teamwork in Complex Environments Through Team Training. *Group Dynamics: Theory, Research, and Practice 1*(2), 169–182.

Strybel, T., K.-P. L. Vu, J. Dwyer, J. Kraft, T. Ngo, V. Chambers, and F. Garcia (2007). Predicting perceived situation awareness of low altitude aircraft in terminal airspace using probe questions. *Human-Computer Interaction. Interaction Design and Usability* (July), 939–948.

Urban, J. M., J. L. Weaver, C. A. Bowers, and L. Rhodenizer (1996). Effects of Workload and Structure on Team Processes and Performance: Implications for Complex Team Decision Making. *Human Factors: The Journal of the Human Factors and Ergonomics Society*.

Vicente, K. (1999). *Cognitive work analysis: Toward safe, productive, and healthy computer-based work.* CRC Press.

Vicente, K. J., J. Rasmussen, and S. Member (1992). Ecological Interface Design : Theoretical Foundations. *IEEE Transactions on Systems, Man, and Cybernetics 22*(4), 589–606.

Vidulich, M. A. (2003). Mental Workload and Situation Awareness: Essential Concepts for Aviation Psychology Practice. In *P. S. Tsang and M. A. Vidulich (Eds.), Principles and practice of aviation psychology. Mahwah, NJ: Erlbaum.*, pp. 115–146.

Volpe, C., J. Cannon-Bowers, E. Salas, and P. Spector (1996a). The Impact of Cross-Training on Team Functioning: An Empirical Investigation. *Human Factors 1*(1), 87–100.

Volpe, C. E., J. A. Cannon-Bowers, E. Salas, and P. E. Spector (1996b). The Impact of Cross-Training on Team Functioning: An Empirical Investigation. *Human Factors: The Journal of the Human Factors and Ergonomics Society*.

Waterson, P. (2015). Sociotechnical Design of Work Systems. In *Wilson, J. R., & Sharples, S. (2015). Evaluation of human work. CRC Press.*, pp. 753–772.

Welford, A. T. (1968). Fundamentals of Skill. *Methuen*.

Weltman, G., J. E. Smith, and G. H. Egstrom (1971). Perceptual narrowing during simulated pressure-chamber exposure. *Human Factors: The Journal of the Human Factors and Ergonomics Society 13* (no. 2), 99–107.

Wickens, C. D. (1984). The structure of attentional resources. In *Attention and Performance VIII*, pp. 239.

Wickens, C. D. (2002). Multiple resources and performance prediction. *Theoretical Issues in Ergonomics Science 3*(2), 159–177.

Wickens, C. D. (2008). Multiple Resources and Mental Workload. *50*(3), 449–455.

Wickens, C. D. and J. G. Hollands (1999). Engineering Psychology and Human Performance.

Wickens, C. D., A. S. Mavor, R. Parasuraman, and J. P. Mcgee (1998). *The Future of Air Traffic Control: Human Operators and Automation.*

Willams, M., J. Hollan, and A. Stevens (1983). Human Reasoning About a Simple Physical System. In *Gentner, D., and A. L. Stevens, eds. 1983. Mental models. Mahwah, NJ: Lawrence Erlbaum & Associates.*, pp. 131–154.

Wilson, J. and A. Rutherford (1989). Mental Models: Theory and Application in Human Factors. *Human Factors : The Journal of the Human Factors and Ergonomics Society 31*(6), 617–634.

Wilson, J. R. (2000). The Place and Value of Mental Models. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting 44*, 49–52.

Wilson, J. R. and S. Sharples (2015). *Evaluation of human work.* CRC Press.

Wong, B. and A. Blandford (2002). Analysing ambulance dispatcher decision making: Trialing emergent themes analysis.

Wong, B. L. W. and A. Blandford (2000). Analysing Ambulance Dispatcher Decision Making : Trialing Emergent Themes Analysis.

Woods, D. D., S. W. A. Dekker, R. I. Cook, L. Johannesen, and N. B. Sarter (2010). Behind human error, second edition. *Behind Human Error, Second Edition*, 1–271.

Young, M. and N. A. Stanton (2001). Mental workload: theory, measurement, and application. In *W. Karwowski (Ed.), International encyclopedia of ergonomics and human factors: Volume 1. London: Taylor & Francis.*, pp. 507–509.

Young, M. S., K. Brookhuis, C. D. Wickens, and P. Hancock (2014). State of science: Mental workload in ergonomics.

Young, M. S., K. A. Brookhuis, C. D. Wickens, and P. A. Hancock. (2015). State of science: mental workload in ergonomics. *Ergonomics 58* (no. 1), 1–17.

Zlatanova, S., S. Zlatanova, D. Holweg, and D. Holweg (2004). 3D Geo-Information in Emergency Responce: a Framework 1. *Proceedings of the Fourth International Symposium on Mobile Mapping Technology (MMT'2004), March*, 29–31.

Zsambok, C. E. (1997). Naturalistic decision making research and improving team decision making. In *Naturalistic decision making.*, pp. 111–120.

Zsambok, C. E. and G. Klein (2009). *Naturalistic decision making*. Psychology Press.