## Abstract

The introduction of highly reliable sensors and remote condition monitoring equipment will change the form and functionality of maintenance and engineering systems within many infrastructure sectors. Process, transport and infrastructure companies are increasingly looking to intelligent infrastructure to increase reliability and decrease costs in the future, but such systems will present many new (and some old) human factor challenges. As the first substantial piece of human factors work examining future railway intelligent infrastructure, this thesis has an overall goal to establish a human factors knowledge base regarding intelligent infrastructure systems, as used in tomorrow's railway but also in many other sectors and industries.

An in-depth interview study with senior railway specialists involved with intelligent infrastructure allowed the development and verification of a framework which explains the functions, activities and data processing stages involved. The framework includes a consideration of future roles and activities involved with intelligent infrastructure, their sequence and the most relevant human factor issues associated with them, especially the provision of the right information in the right quantity and form to the right people.

In a substantial fieldwork study, a combination of qualitative and quantitative methods was employed to facilitate an understanding of alarm handling and fault finding in railway electrical control and maintenance control domains. These functions had been previously determined to be of immediate relevance to work systems in the future intelligent infrastructure. Participants in these studies were real railway operators as it was important to capture users' cognition in their work settings. Methods used included direct observation, debriefs and retrospective protocols and knowledge elicitation.

Analyses of alarm handling and fault finding within real-life work settings facilitated a comprehensive understanding of the use of artefacts, alarm and fault initiated activities, along with sources of difficulty and coping strategies in these complex work settings. The main source of difficulty was found to be information deficiency (excessive or insufficient information).

Each role requires different levels and amounts of information, a key to good design of future intelligent infrastructure.

The findings from the field studies led to hypotheses about the impact of presenting various levels of information on the performance of operators for different stages of alarm handling. A laboratory study subsequently confirmed these hypotheses.

The research findings have led to the development of guidance for developers and the rail industry to create a more effective railway intelligent infrastructure system and have also enhanced human factors understanding of alarm handling activities in electrical control.

## Acknowledgement

This is a small token of gratification to those who have helped me along the way.

First and foremost I would like to thank my supervisors. I'd like to thank Professor John Wilson who helped me throughout the course of my research with his advice and with personally caring for my work. I am also forever indebted to Dr David Golightly and Dr Sarah Sharples who not only encouraged and inspired me, but have also supported me (academically and morally) on a level that was beyond and above their duties. I am truly grateful.

I'd like to thank Theresa Clarke Head of Ergonomics, Network Rail, for her encouragement and understanding.

I am indebted to my participants. Senior managers in Network Rail who were kind enough to spare their precious time to talk to me about intelligent infrastructure. The kind and caring electrical control room operators in Lewisham who welcomed me in their control room, the maintenance technicians in York, Birmingham and Stockport, who walked me through their roles, and finally the students who participated in my laboratory study. A big thank you to all of you!

Thanks are due to my PhD examiners, Professor Erik Hollnagel and Dr Gary Burnett for their insightful comments and their guidance.

I would like to thank Human Factors Research Group at the University of Nottingham and Network Rail Ergonomics team who supported me throughout my research and kept me motivated. Thanks to Sue Cobb, Sally Shalloe, Brendan Ryan, Tamsyn Edwards, Nora Balfe and Grazziela Figueredo for their support and understanding.

Thanks are to my family, my dad, Saba and especially my aunt Sholeh. You were always there for me when I needed you most. Thanks to my sister, Yassi, who corrected my mistakes fiercely and remained humorous about them.

There is one person I need to thank most, my mother. For what I am, today, I cannot thank you enough.

# Publications

## *Journal publications*

Dadashi, N., Wilson, J.R., Sharples.S., Golightly., D (In Press). Practicalities and limitations of cognitive work analysis in complex control systems: a case of alarm handling in railway control room. In: Journal of Rail and Rapid Transit.

Dadashi, N., Wilson, J.R., Sharples.S., Golightly., D (Submitted). Alarm handling strategies identified in work analysis for an electrical control room. Submitted to International Journal of Industrial Ergonomics.

## *Conference publications*:

Dadashi, N., Wilson, J. R., Sharples, S., Golightly, D., & Clarke, T. (2011). A framework of data processing for decision making in railway intelligent infrastructure. *IEEE Conference on Cognitive Methods in Situation Awareness and Decision Support.* Florida.

Dadashi, N., Wilson, J. R., Sharples, S., Golightly, D., & Clarke, T. (2011). Human factors issues in intelligent infrastructure systems . *Ergonomics & Human Factors.*

Dadashi, N., Wilson, J. R., Sharples, S., Golightly, D., & Clarke, T. (2010). Cognitive work analysis practicality and limitations in complex control systems: a case of alarm handling. *11th IFAC/IFIP/IFORS/IEA Symposium on Analysis, Design, and Evaluation of Human-Machine Systems.* Valenciennes.

Dadashi, N., Wilson, J. R., Sharples, S., Golightly, D., & Clarke, T. (2010). Fault analysis in railway maintenance control centres. *International conference of control room design.* Paris.

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# Glossary

This glossary defined the terms and acronyms as they will be used in this thesis.

| | |
|---|---|
| **AC** | Alternating Current |
| **AH** | Abstraction Hierarchy |
| **CCF** | Control Centre of the Future:-a system giving information on train delay |
| **CDM** | Critical Decision Method |
| **CSE** | Cognitive System Engineering |
| **CTA** | Cognitive Task Analysis |
| **CWA** | Cognitive Work Analysis |
| **DC** | Direct Current |
| **DL** | Decision Ladder |
| **DNO** | Distributed Network Operator |
| **DSM** | Dynamic Situation Management |
| **E & P** | Electrification and Plant maintenance |
| **ECO** | Electrical Control Operator |
| **ECR** | Electrical Control Room |
| **ECRO** | Electrical Control Room Operator |
| **ECOM** | Extended Control Model |
| **FOC** | Freight Operating Company |
| **FMS** | Fault Management System |
| **GB** | Great Britain |
| **GPS** | Geographical Positioning System |
| **IECC** | Integrated Electronic Control Centre: a type of signalling system |
| **JCS** | Joint Cognitive System |
| **KE** | Knowledge Elicitation |
| **MCC** | Maintenance Control Centres |
| **MSSCC** | Manchester South Signalling Control Centre |
| **NCC** | National Control Centres |
| **NDM** | Naturalistic Decision Making |

| | |
|---|---|
| **NR** | Network Rail |
| **NX** | Entry-Exit Panel: a type of signalling system |
| **PCM** | Point Condition Monitoring |
| **RCM** | Remote Condition Monitoring |
| **S & T** | Signalling and Telecommunications |
| **SCADA** | Supervisory Control and Data Acquisition |
| **SD** | Standard Deviation |
| **SME** | Subject Matter Expert |
| **TOC** | Train Operating Company |
| **TRUST** | Train Running System on TOPS: A system providing information on train delays |
| **VDU** | Visual Display Unit |
| **WDA** | Work Domain Analysis |
| **WESTCAD** | Westinghouse Control and Display |
| **WMSC** | West Midland Signalling Centre |

# 1. Introduction

## 1.1. Railway control, challenges and potential

The railway industry in the UK plays an important role in Great Britain's economy by providing more than 1.32 billion passenger journeys annually (Network Rail, 2010). Moreover, due to railways being sustainable and environmentally friendly, development targets are in place to double this capacity by the year 2030 (Dft, 2010). An intelligent infrastructure project is one of the projects with the aim of improving the railway service.

Currently, railway infrastructure is managed and maintained by maintenance control centres, which have a wide range of Remote Condition Monitoring (RCM) equipment to check the health state of the assets and to manage the maintenance process if an asset has failed. These control rooms have various RCM and Fault Management Systems (FMS) which are often inconsistent, both in terms of content and form of information presentation. Intelligent infrastructure was mainly introduced to focus on the improvement of the maintenance regime.

Network Rail (NR), which owns and maintains the UK railway infrastructure, launched an intelligent infrastructure project in 2006. Railway intelligent infrastructure aims to use the available technology, including reliable sensors, to collect data about key infrastructure assets. The data then needs to be analysed, using sophisticated algorithms, so that personnel can be informed about the current state of the system as well as potential future asset states.

Recent technological and organisational advances have increased the potential for remote access and monitoring of the infrastructure in various domains and sectors, including water and sewage, oil and gas, and transport. These systems enable accurate and relevant information about the state of the infrastructure to be generated quickly and for safety and efficiency to be enhanced by optimising the use of the infrastructure. The chosen research context for this PhD, however, is not the new technology itself but the challenges it poses for work design.

The challenges for the introduction of intelligent infrastructure need to be considered in light of the fact that railway control is a socio-technical environment and that different control settings with various capabilities and responsibilities have to work alongside each other. Operators' understanding of the health status of an asset depends very much on the knowledge captured from the context as well as the information presented through the systems. Therefore, the development of a human factors understanding is a necessary precursor to the ability to inform the effective design and development of an intelligent infrastructure system.

In order to develop a thorough human factor understanding of a rail intelligent infrastructure it is necessary to know its functionality and its potential users and their needs. However, at the time of starting this PhD, actual intelligent infrastructure applications did not exist in NR. This is despite the fact that they had been launched and examined as part of a long term project over two control periods (each control period is 5 years). Although a number of strategic views were developed, the organisation was unclear about the functionalities, main users and potential interfaces. Therefore, the first objective of this study focused on exploring and understanding railway intelligent infrastructure.

Initial exploratory interviews within NR identified a key challenge in developing an effective railway intelligent infrastructure to be the provision of the right information to the right person at the right time and in the right fashion. Clearly, there is a danger that different groups of personnel using intelligent infrastructure for different functions and purposes could be swamped by the sheer quantity of information provided to them, without it being filtered for relevance. They could be provided with information more suited to another job function with different goals. This was also confirmed through the literature review. Thus, investigation of three areas of challenge was found to be essential to develop an understanding and guide railway intelligent infrastructure systems. These challenges include information overload, multi-agent control and alarm handling.

Railway control is a dynamic setting, with information being collected from a complex and intertwined environment that is monitored by human operators who intervene when necessary. The introduction of supervisory control systems meant that an increasing number of activities could be conducted from the control room and, with the aid of information displays, more information could be presented to the operators (e.g. lever frame vs. VDU signalling). However, it is important to understand that just because the technology is capable of presenting the information does not mean that it will be useful. In this PhD study, various cases of control similar to the future intelligent infrastructure system were used to facilitate an understanding of the relevance and sufficiency of information for those particular tasks.

In the setting of railway control rooms, although each control room is responsible for particular aspects of running and maintaining the railways, all work alongside each other for a safer and more efficient rail service. Moreover, as control environments move towards integration and centralisation, the findings from one control room will be used in others. This is identified as multi-agent control. Within the intelligent infrastructure project, integrating the information collected from various RCM seems to be one of the core characteristics. Therefore, it was important to explore the boundaries and roles associated with it.

Alarms are generated to notify operators of an existing abnormality. In other words, alarms are used to help the operators in monitoring the large amounts of data that are presented to operators. However, presentation of the amount of alarms that an operator can handle and which are also meaningful is one of the most important challenges for the design of any control setting and has been a contributing factor to many accidents and incidents. Therefore, it is important to explore alarm handling in the railway context of relevance to future intelligent infrastructure setting.

To facilitate exploring and informing the challenges mentioned above, extensive interviews were conducted with railway experts involved with the intelligent infrastructure project to provide a more detailed understanding of the concept and to indentify some potential future functions relevant to intelligent infrastructure (these were alarm handling and fault finding). These functions were then used as the basis to investigate the potential challenges (information overload, multi agent control and alarm handling) of intelligent infrastructure. The subsequent deeper study of alarm handling and fault finding helped in developing an understanding of relevant human performance, as well as the associated information and knowledge requirements. These studies led to the generation of hypotheses regarding optimal information and knowledge presentation to support operators. Three follow-up studies (two field studies and one laboratory study) were conducted to investigate these hypotheses.

The interview studies identified the main roles and functions that are going to be involved with intelligent infrastructure. The two field studies were performed in representative domains of intelligent infrastructure and identified the knowledge and information requirements of operators during these activities. This led to the development of a hypothesis regarding the information most suitable for each role. The hypotheses developed were then investigated via assessment of the performance of different roles when presented with different pieces of information in a simulated environment.

The research presented in this thesis takes into account the needs of service users, which clearly requires substantial understanding of human factors. At the start of this research project, little or no previous research into human factors had been carried out with explicit reference to intelligent infrastructure systems. A combination of qualitative and quantitative methods to research human factors was adopted to develop an understanding of the intelligent infrastructure domain and explore its main roles, potential functions and challenges, with a focus on human factors issues.

Thus, gaps have been identified not only in the guidance available to NR regarding the implementation of an intelligent infrastructure to meet the needs of users and company goals, but also in the human factors research base needed to understand and design these central systems of the future.

In the event, technical and organisational developments for Network Rail's intelligent infrastructure have lagged somewhat behind the work of this thesis. Therefore, as well as examining potential human factors from a fundamental point of view, empirical research was carried out on the current types of work system and information handling that would typify work systems for future intelligent infrastructure.

This PhD project was conducted in conjunction with and partially funded by NR, with the researcher based in the Ergonomics Team in NR for long periods. This engagement in the organisation provided the researcher with access to various departments and projects that helped to establish a network of contacts. Strong relationships were also established with various control centres, easing the process of collecting field study data.

Furthermore, by getting involved in other projects, the researcher obtained a thorough understanding of the organisation, the management structure and various departments, as well as the culture of the railway industry. This facilitated the gathering of information concerning developments in ideas and the implementation of intelligent infrastructure systems.

## *1.2. Research aims and objectives*

The overall aim of this thesis is to investigate and to understand the relevant human factors for a future intelligent infrastructure on the GB railway. This involves studies of behaviour, cognitive performance and knowledge requirements for current relevant work functions and, in prospect, for the future intelligent infrastructure.

The objectives of this research project are:

I. Develop a data processing framework that guide and support effective implementation of railway intelligent infrastructure from a human factors perspective

The first objective of this research was to understand the scope and functionality of railway intelligent infrastructure. A review of the literature and the company's (NR) documentation, along with a series of interviews (Chapter 5), facilitated this and led to the identification of human factors associated with the different roles of railway intelligent infrastructure. Moreover, this information was collated within a framework to show the relationship between different activities associated with the process to be supported by the future railway intelligent infrastructure system.

II. Establish an understanding of operators' strategies for human supervisory control tasks in alarm handling and fault finding.

One of the main challenges identified for an effective intelligent infrastructure system is the provision of information relevant to operators in-time. Two functions important in future were identified as intelligent infrastructure systems: alarm handling and fault finding. The second objective was focused on understanding alarm handling and fault finding.

In-depth studies (Chapters 6 and 7) were conducted to understand the operators' behaviour while conducting these tasks. Main outputs included a description of operators' activities, their cognitive processes and artefacts applied (frequency and order). More importantly, operators' strategies when faced with information deficiencies within current control room settings were studied (Chapters 6 and 7). The results of this stage of the research led to initial identification of 'coping strategies'.

III. Produce human factors guidance for the future development and implementation of intelligent infrastructure systems in the railway to match and complement human capabilities and needs.

The findings of the various studies in this PhD programme ultimately informed an effective and successful implementation of railway intelligent infrastructure. This guidance had two purposes: firstly, it assisted NR in designing and developing the intelligent infrastructure and secondly, through the methodological approach adopted and practiced, guidance was provided to human factors specialists in exploring cognitive work in real-life socio-technical systems.

As a result of this, the main contributions are listed below and later on in the thesis will be evaluated (Section 9.1):

- Establishment of a data processing framework that identified the scope and activities within the railway intelligent infrastructure
- Identification of human factors issues of most importance to a successful implementation of railway intelligent infrastructure.
- Understanding of activities, artefacts and coping strategies during railway alarm-handling and fault-finding
- Demonstration of the value of applying a combination of methods in investigating cognition within socio-technical systems
- Guidance for an effective implementation of railway intelligent infrastructure

## *1.3. Thesis synopsis*

Chapter 1 provides a general introduction, background to the research, aims, objectives, and organisation of the thesis.

Chapter 2 reviews the literature on the railway domain and intelligent infrastructure system. Two domains of relevance to future railway intelligent infrastructure (railway maintenance and electrical control) are then reviewed in terms of activities, environments, technologies and current issues. This is followed by a review of intelligent infrastructure systems in the railway and other domains. The issues that can challenge the successful implementation of these systems are identified and there is clarification of the research questions that should be addressed

Chapter 3 presents a literature review of the paradigms that can guide the analysis of control and facilitate the research questions of this PhD. Three paradigms, information processing, supervisory control and cognitive system engineering, are briefly reviewed in this chapter and their relevance to this PhD study is emphasised.

Chapter 4 describes a methodological approach adopted in this research and discusses the various methods applied. Advantages and limitations of each of the methods, in relation to the context of this study, are briefly reported in this chapter and elaborated in the respective chapters.

Chapter 5 presents the results of thematic content analysis of 20 hours of interviews. The interview study was undertaken with key decision makers in NR to identify key concepts of intelligent infrastructure within the railway. This led to the development of a framework for railway intelligent infrastructure, focusing on its information and knowledge requirements and human factors issues. Further card-sorting activities were conducted with railway control operators, in order to confirm the content and sequence of activities suggested in the data processing framework.

Chapter 6 details the work undertaken to understand alarm-handling within a railway control room. Analysis of 18 hours of observational study is presented in this chapter. The main findings include alarm-initiated activities, order and duration of the use of artefacts while alarm-handling, and coping strategies.

Chapter 7 reports on the work undertaken to understand fault-finding within a railway maintenance control centre. 18 hours of field study accompanied by semi-structured interviews with maintenance technicians are reported in this chapter. The main findings include fault-initiated activities, types of information applied and the order of their importance, as well as the strategies adopted by operators to cope with information inefficiencies.

Chapter 8 reports an experimental study conducted to confirm information requirements hypothesised through the findings of the interview study (Chapter 5) and the understanding of problem solving tasks from alarm-handling and fault-finding studies (Chapters 6 and 7).

Chapter 9 presents a discussion of the main findings of this research in relation to its objectives.

Chapter 10 concludes this research, and shows the value of the contributions of this PhD and comments on the future work.

The structure of the chapters of this PhD is shown in Figure 1-1 below, which is accompanied by the objectives pursued in each of these chapters.

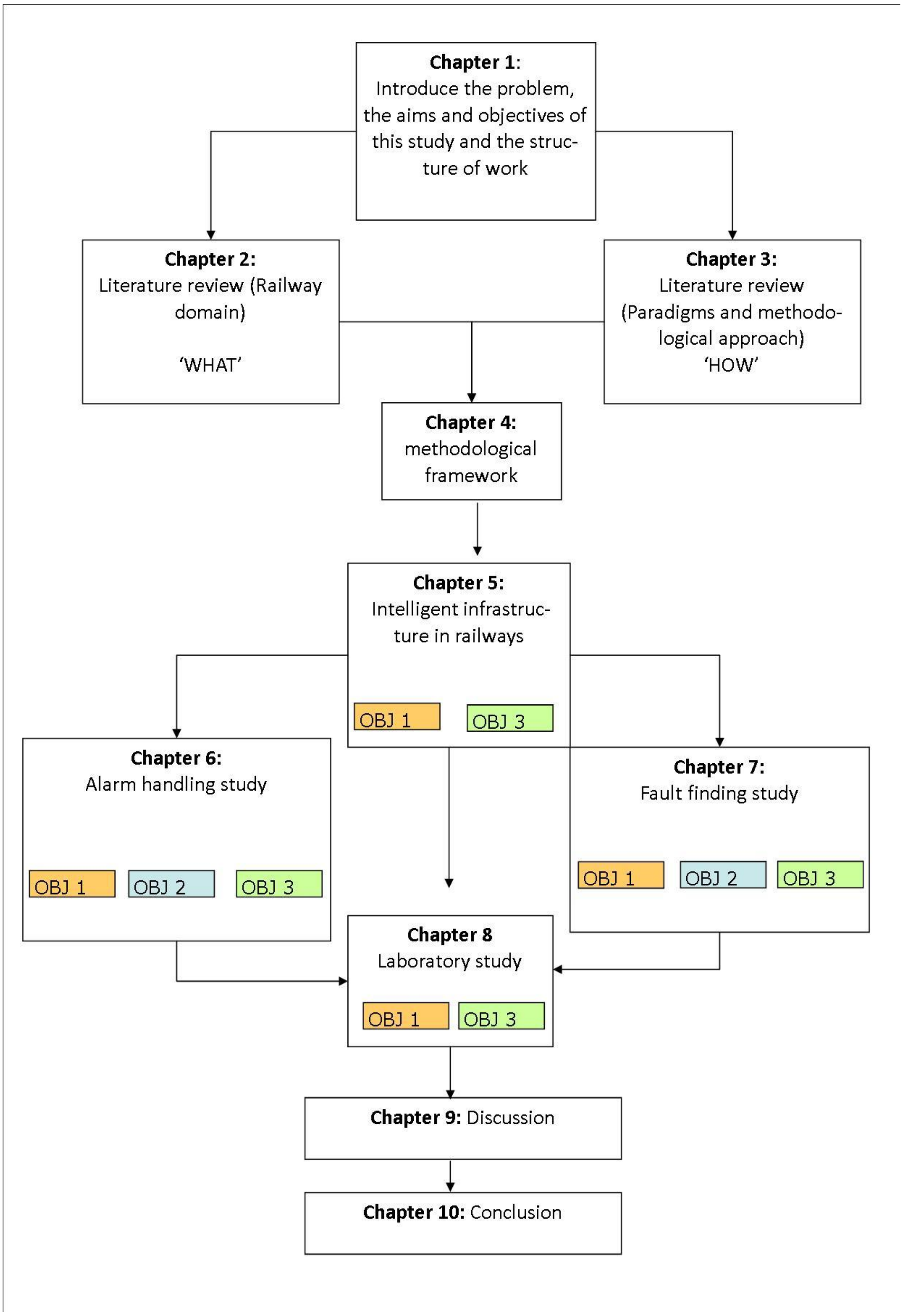



**FIGURE 1-1: THESIS STRUCTURE AND PHD OBJECTIVES**

# 2. Background: The railway domain and intelligent infrastructure

This chapter introduces the rail domain and the role of railway intelligent infrastructure as a facilitator of a safer, more efficient railway. The first section briefly introduces the rail domain in the UK. Two control domains of most relevance to railway intelligent infrastructure-railway maintenance and railway electrical control- are then reviewed in sections two and three. Section four reviews intelligent infrastructure in industries and domains other than the railways, such as aviation, nuclear power plants, manufacturing and health care, followed by a review of Network Rail's approach to railway intelligent infrastructure. Finally, section five use relevant key literature to identify the key challenges of intelligent infrastructure and key human factors research questions to be addressed for successful implementation of intelligent infrastructure systems.

## *2.1. Rail domain*

The railway industry in the UK has an effective and ever increasing role in British economic and commercial growth. For today's cost and energy-aware public, railways offer an easy, accessible, and sustainable mode of transport. Therefore, there is a need to improve the capacity of trains to meet increasing passenger numbers (Dft, 2010).

The railways in Britain comprise a large, complex and intertwined network of rail across nine regional routes. There are nearly 20,000 miles of track, 40,000 bridges and tunnels and 2,500 stations (Network Rail, 2010). Network Rail (NR) owns and maintains the GB railway network in order for Train Operating Companies (TOCs) and Freight Operating Companies (FOCs) to run passenger and freight services.

TOCs rent the track lines to run their trains. If there are problems with the service for which NR is responsible, TOCs are entitled to a fine payable by NR due to the damage to their business. Therefore, it is in the best interest of NR that faults are managed optimally to keep delays to a minimum. Hence, it is critical within NR that all processes work together to ensure safe and efficient running of the service.

There are three main control processes responsible for running and maintaining the railways: signalling control is mainly responsible for running the service, electrical control supplies the electrical resources for the running of the electric track and maintenance control is responsible for maintaining the infrastructure.

Control rooms in today's railway have systems ranging from 19th century lever frames (Figure 2-1) through to Visual Display Units (VDU) systems dating from the mid 1990s (Figure 2-2). Despite their differences in terms of technological advance, the objectives of these systems are effectively the same: 1- to capture information from assets (tracks, signals, electrical supplies, trains, etc.), 2- to monitor the performance of the service safely and efficiently and, 3- to facilitate human intervention if necessary.

**FIGURE 2-1: LEVER FRAME SIGNAL BOX**

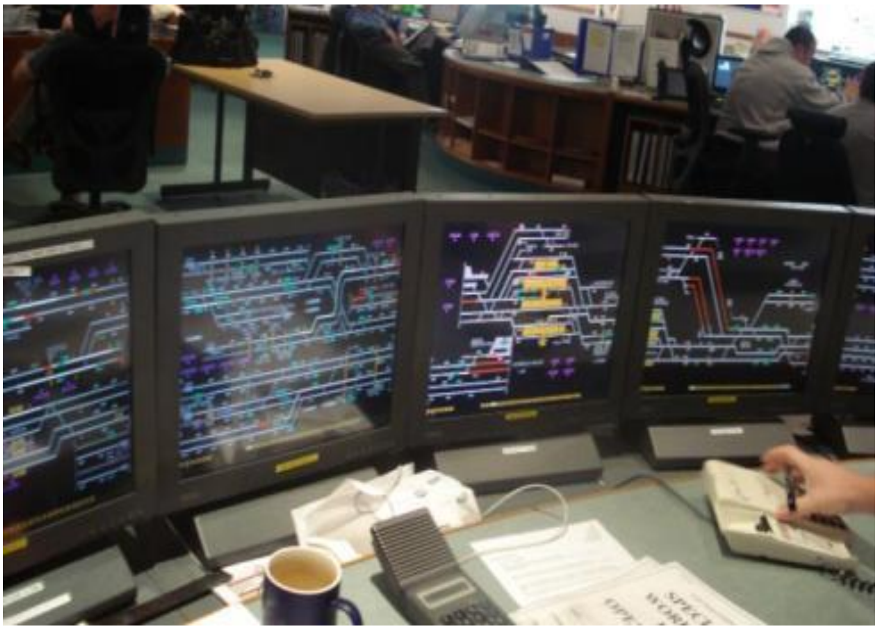


**FIGURE 2-2: VDU SIGNALLING**

Of the three control domains mentioned earlier, maintenance and electrical control show many of the characteristics (monitoring of asset status, maintenance of assets, the need to provide continuous availability of infrastructure) that intelligent infrastructure is intended to provide (This assumption will be elaborated on in section 2.4). It is also likely that at least some of the activities of current maintenance and electrical control will be migrated into any new intelligent infrastructure-based control environment. With that in mind, the next two sections provide a detailed illustration of the nature of both maintenance and electrical control. Each control environment is reviewed in terms of the roles of the operators, their main activities and the technologies available to them.

## *2.2. Railway maintenance control*

Maintenance control is responsible for managing and maintaining the wellbeing of the railway infrastructure to ensure the safe and efficient running of the service. Today, railway maintenance is managed through three sub-groups in the maintenance department: Signalling and Telecommunication (S&T), Track Maintenance, and Electrification and Plant (E & P).

Maintenance operators are responsible for maintaining the railway infrastructure in a safe way to facilitate the punctual and efficient running of the service. There are generally three different roles within maintenance control. In most maintenance control centres, one operator is responsible for all of these roles.

The first role of the maintenance operator is to observe the state of assets in the infrastructure (e.g. a failed point machine on the track). When he/she notices the failure of an asset, he/she then will plan the rectifying procedure and inform respective operational teams.

The second role is to guide the maintenance team on the rail track to diagnose and fix a fault. Maintenance technicians have access to the live status of assets via remote condition monitoring systems. Therefore, when track workers are testing equipment, they can be informed whether their actions have been effective or not.

The third role is to record the performance of assets and inform policy makers so that they can adjust the maintenance regime accordingly. For example if a certain point machine keeps failing, then the maintenance technician reports it to a route controller so that a wider investigation will be carried out.

### *2.2.1. Activities*

In order to meet the responsibilities associated with their roles, maintenance control operators conduct a number of activities. This is not specific to any one of the roles and is spread across all three. According to Network Rail’s job specification (Network Rail, 2006) the role of maintenance technician control is generally to monitor, handle alarms, plan the rectifying procedure and communicate with different railway stakeholders.

Maintenance control operators have a wide range of information displays available to them, providing information on the status of the assets in their area of coverage. Operators have to monitor these displays on a regular basis to check the performance of the assets.

Because it is not possible to monitor the status of assets constantly, alarms are used. When there is an abnormality, Remote Condition Monitoring (RCM) systems identify the failure and notify the maintenance control operator via an audible siren. The operators will then have to handle the alarms and plan the clearance procedure.

For example, when a point machine is failed on the track, the maintenance operator will notice the fault through an audible alarm generated by the RCM system (e.g. Point Condition Monitoring). Moreover, if the maintenance workstation is located in the signal box, the signaller orally informs the maintenance operators about the fault.

The maintenance operator uses condition monitoring systems to play back and simulate the condition of the point machine to the moment of its failure. This helps the operator to diagnose the causes of the failure. Often, this is not sufficient for diagnosing the failure and the operator sends a track maintenance team to investigate. In the meantime, he informs the signaller of potential delays that will affect the operation of the service.

The railway is a socio-technical environment; communicating between different control rooms and operators is a core part of any role. Maintenance control operators tend to communicate with signallers, train drivers, track workers, TOC representative and members of public.

### *2.2.2. Environments*

There are generally two types of maintenance control rooms in the UK railways and each is equipped with a wide and varied range of technologies, from a workstation located in the signal box (i.e. signalling maintenance) to a control room dedicated to managing and directing the overall maintenance activity (i.e. National Control Centres). These two types of control rooms are briefly described below.

National Control Centres (NCC) (Figure 2-3) are responsible for monitoring and maintaining the railway within specified geographical routes in the UK railway network. They are equipped with advanced systems, such as RCM systems, timetable schedules, etc. and are responsible for supporting different control processes: signallers, electrical control room operators, train drivers, TOCs, and outside agencies, such as transport police.

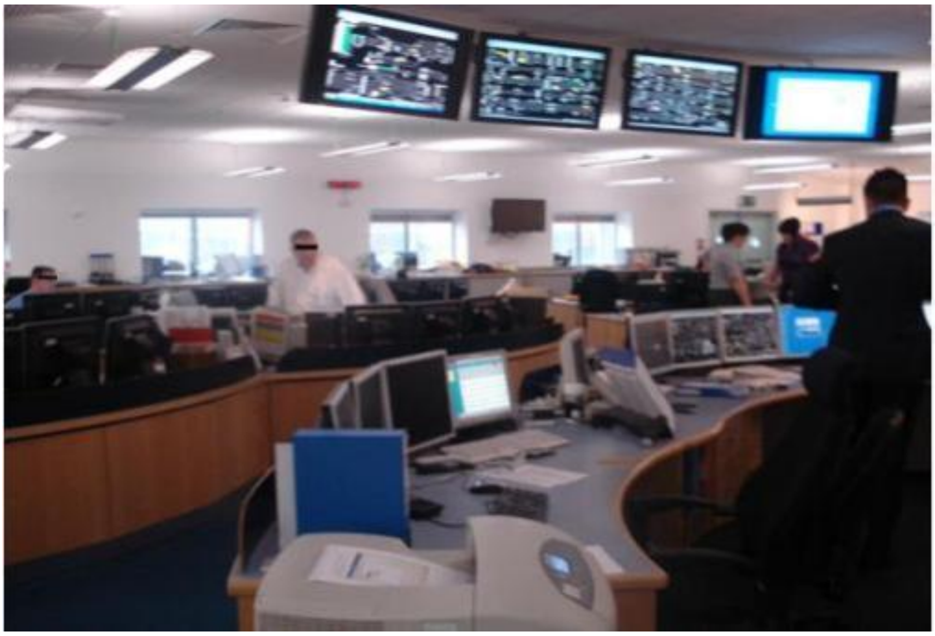


**FIGURE 2-3: LONDON NORTH EAST NATIONAL CONTROL CENTRE**

The second type of maintenance is more local: it focuses on maintaining the operational railways (i.e. signals, points, etc.) and manages the faults that affect the running of the service (Figure 2-4). These control rooms are usually adjacent to signal boxes or consist of one workstation in a signal box. They use a variety of equipment and RCM systems as well as signalling video panels that present a schematic indication of the location of a train. In the present thesis, operators residing in these control rooms will be referred to as '*maintenance technicians'*.

**FIGURE 2-4: MANCHESTER SOUTH MAINTENANCE CONTROL CENTRE**

### *2.2.3. Technologies*

RCM systems have been used in the rail network for many years. By 2006, NR had 3000 RCM systems across its infrastructure, monitoring 30 asset types (Ollier, 2006). RCM systems in NR are divided into two groups: train-borne RCMs and trackside RCMs. A train-borne RCM is facilitated by sensors that are installed on a train, while a trackside RCM has been made possible by the help of sensors directly installed on the infrastructure (Bint, 2008). Examples of trackside RCMs include Points Condition Monitoring (PCM), Earth Leakage Detection, Weather Station and Relay Room Temperature Monitoring.

The most common interfaces used in these two types of maintenance control rooms are summarised in Table 2-1

**TABLE 2-1: EXAMPLE OF THE INTERFACES COMMONLY USED IN SIGNALLING MAINTENANCE AND NATIONAL CONTROL CENTRES**

| Asset monitored | Control system | Description | Location |
| --- | --- | --- | --- |
| Signal, point machines, buildings | WestLock™ Technician Workstation | Developed by Westinghouse Rail Systems™ for use by signalling technicians for monitoring, control and fault diagnosis. | Signal box & NCC |
| Signals, point machines, | WestCad™ | Developed by Westighouse Rail Systems™, it also generates information about power, fire, intruders and HVAC regarding the remote building with sensitive assets within. Although it provides detailed logged data it does not facilitate much diagnosis. | Track circuits |
| Point machines | Ansaldo (Asset watch and Track watch) | Two web-based interfaces developed by Ansaldo™ to provide event logs to describe assets' behaviour. Ansaldo™ provides information regarding swing times of points, voltage and current in individual circuits. | Signal box & NCC |
| Rail | POSS™ | Developed by Strukton System™ for online condition monitoring system of point machines. It facilitates access to historical data, analysis, logbook and setting performance indicators. | NCC |
| Track, weather condition | Wheelchex™ | Developed by AEA technology™ and monitors the load produced in the rail by the wheels of each passing train and measures the size and impact of forces from damaged wheels. | NCC |

| | | | |
|---|---|---|---|
| Signals, track circuit | Rail weather systems | Developed by Vaisala™ to use weather forecasts and predict the future state of assets and adjust train speeds accordingly. | Signal box & NCC |
| Signals, track circuit | TRUST | It provides information regarding timetables of trains and checks whether they are running according to the planned schedule. | Signal box & NCC |

### *2.2.4. Current issues*

The technical facilities used in maintenance control are developed by different companies, have various capabilities and have been used alongside each other. Therefore, there are duplicated and, in some cases, inconsistent pieces of information available to the operators. For example, in the York NCC there are both POSS™ and ANSALDO™ systems that provide information regarding the condition of the point machines.

Moreover, these systems are not perfect and there are uncertainties involved with them. For example, the loss of connection between the logger and the interface can prevent operators from accessing online track data. Therefore, the operator cannot diagnose the fault remotely and will have to send an investigation team onto the track.

One of the main problems faced by the maintenance operators is the volume of alarms and alerts that are presented to the operators. This is due to the huge number of assets being monitored and also due to duplications involved with various RCM systems.

## *2.3. Electrical control*

Rail Electrical Control Rooms (ECRs) in the UK were originally integrated from a number of adjacent railway traction power supply systems. Since 1932, Electrical Control Room Operators (ECROs) have been responsible for remotely opening and closing electrical equipment, instructing staff on the operation of manual switches, and leading the maintenance and fault-finding of electrification distribution and Direct Current (DC) traction equipment. To do so, they have two main roles.

The first role is to monitor the status of the electrical supply. If there is loss of power on the railway tracks, the operator is notified by the SCADA (Supervisory Control and Data Acquisition Systems), and proceeds with the appropriate rectifying procedure.

The second role is to manage and plan the isolation of the tracks when a maintenance team needs to work on the track. This also involves programming the isolations and switching circuit breakers, informing the maintenance team, as well as the signaller controlling that area, about the state of the track.

### *2.3.1. Activities*

In order to meet the responsibilities associated with their roles, ECROs carry out a number of activities. These include monitoring, alarm handling, isolating and communicating.

Similar to the railway maintenance control, monitoring is one of the core activities in electrical control. Operators have to monitor the SCADA displays in order to get an overview of the state of the power supply on different railway tractions.

Since continuous monitoring of various infrastructural assets is not possible, alarms are used to notify operators when there is a problem with the safe provision of electrical supplies. Operators notice the alarms through an audible siren and handle them depending on their type and priority.

When there is maintenance work scheduled on the tracks, the ECROs have to isolate the tractions from the rest of the power supply network so that track workers can work on and around the railway track safely. At the beginning of each week, a schedule of the planned maintenance work is presented to the ECRO. They have to assess and programme these isolation requests and prepare them for the ECRO who is going to be on shift on the night of the maintenance work. (Most maintenance work is conducted during the night shift to avoid service disruptions). Furthermore, there are certain situations (e.g. trespass) where the ECRO has to perform an emergency isolation.

Communication is one of the key activities within the electrical control: operators have to get the information from railway track workers and maintenance teams to ensure that the tracks are safe to work on. They need to inform the signallers whether the tracks are ready and safe for the trains to run and, on some occasions, they communicate with members of the public when they have to handle an emergency situation.

### *2.3.2. Environment*

ECRs are placed separately from signal boxes and maintenance control centres. At present, there are 13 electrical control centres under the control of NR: five Alternating Current (AC) ECRs (Cathcart, Crewe, Rugby, Romford and York) and eight DC ECRs (Lewisham, Brighton, Eastleigh, Selhurst, Raynes Park, Canterbury, Paddock Wood and Sandhills).

### *2.3.3. Technologies*

According to NR's "Specification for remote control equipment for electrical distribution systems" handbook (Network Rail, 2008), control displays in ECR are human machine interfaces, which display either a mimic diagram operated through physical keys and push buttons (Figure 2-5), or full graphic VDUs operated through keyboard and mice (Figure 2-6). Supervisory control systems in electrical control rooms are in the form of SCADA systems.

As an example, the workstation specification of Lewisham ECR is briefly described. Lewisham ECR (Figure 2-6) has three workstations with similar information available to all of them. Two ECROs are actively responsible for monitoring and operating the systems simultaneously and the third workstation is used for emergency situations. Apart from dynamic information displays on their desks, there is a static board covering one wall of the ECR. This board illustrates an outline of the electrical system laid out on the rail network within the area under control. Although the board is no longer up to date, some of the less experienced operators use this to familiarise themselves with the area. The screen layout of the high resolution graphic VDU displays contains the following: alarm banner, menu bar/area, system information bar (including date, time, operator log-in identity), command/error message bar, picture display area, system overview and detailed operating/outstation page or general/system-wide pages (e.g. index pages, lists, event logs, trend displays, data communication network and status page, current alarm log or AC system overview).

There are three displays on each of the workstations, which are normally arranged in the following order (Figure 2-6):

- Left hand screen→ supply system overview
- Central screen→ operational display
- Right hand screen→ alarm information or AC overview (where supply system is DC)

The operational display, as its name suggests, is used to apply operating procedures. The other two displays are used to identify and interpret problems.

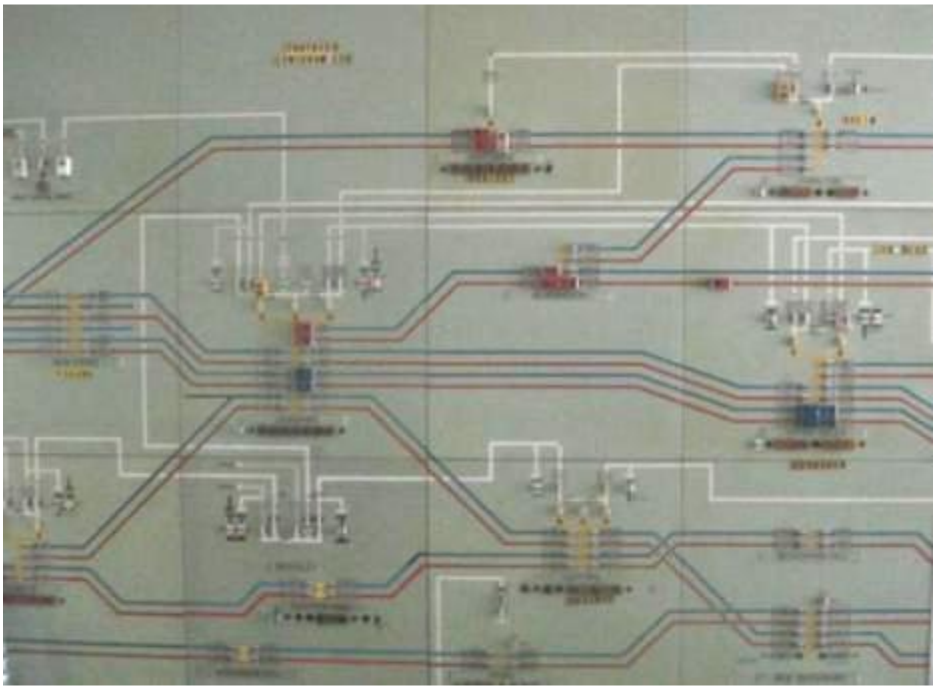


**FIGURE 2-5: ELECTRICAL CONTROL ROOM CONTROL PANEL**

**FIGURE 2-6: ELECTRICAL CONTROL ROOM SCADA**

### 2.3.4. Current Issues

One of the main problems faced with ECROs is the volume of alarms generated by the SCADA. This is especially the case when one abnormality triggers other problems and an alarm avalanche occurs. Alarms generated in Lewisham ECR in one week from 29/01/2009 to 05/02/2009 were totalled to 1884 alarms. Although operators do not have to respond immediately to all of these alarms, the number of alarms is a considerable issue.

Furthermore, communication as the key part of ECROs' activities is not very efficient. The ECRO is often 2nd or 3rd in line for receiving information. For example, in the case of unplanned maintenance work (e.g. due to a failed signal), the ECRO would not know until the person in charge of the maintenance team needs to get access to the track, whereas the signaller would know immediately since the signals in his/her area of coverage have failed. However, there are no regulated procedures that would enhance this communication.

## 2.4. Intelligent infrastructure systems

Railway development projects were put in place to respond to the shortage in infrastructural resources, in order to meet growing demand for capacity (Dft, 2010). Crainic et al., (2009) have pointed out that building new infrastructure to fulfil these demands is no longer an option. A more optimal approach to infrastructure maintenance is therefore necessary and that is to move from breakdown maintenance (fixing after failure) and time-based preventive maintenance (fixing following a periodical inspection) to predictive maintenance (fixing before failure).

Reliable sensors, sophisticated algorithms and advanced surveillance systems have enabled live monitoring of the infrastructure in complex work environments. This architecture has different names in various industries, such as Condition Monitoring Systems in power plants (Hameed et al., 2009): Condition Based Maintenance in mechanical systems (Jardine et al., 2006), Structural Health Monitoring in aviation (Buderath & Neumair, 2007) Pervasive Healthcare in medical systems (Drew & Westenskow, 2006).

Integrated information systems to support maintenance and monitoring have long been used in different industries and domains. Some examples include: manufacturing (Lau, 2002; Jardine et al., 2006), undersea and petro-chemical (Strasunskas, 2006), space exploration (Park et al., 2006), civil infrastructure (Aktan et al., 1998; Aktan et al., 2000), water and sewage (Adriaens, et al., 2003), defence (Jones et al., 1998) and transportation (King, 2006; Lyons and Urry , 2006; Ollier, 2006; Khan, 2007; Blythe and Bryan, 2008).

NR is planning to develop an intelligent infrastructure system as a key part of its future development. It is mainly considered as a means of centralising and integrating the support that is currently provided to infrastructure maintenance by monitoring the condition of assets remotely. Potential failure or unnecessary fixed-term replacements will then be prevented by providing relevant information to the maintenance function. Another main use of intelligent infrastructure in the railway is to facilitate optimal asset maintenance. Currently, maintaining assets is performed through fixed schedules. This time consuming, costly and risky approach can be replaced by analysing real-time asset information and attending to track-side equipment only when necessary. Therefore, intelligent infrastructure in rail will be introduced to move the railway, and especially its maintenance and engineering activities, from a 'find and fix' mentality to 'predict and prevent', and potentially to 'design and prevent' (Bint, 2008).

Figure 2-7 below shows a visualisation of intelligent infrastructure on the rail network. This is a simplified version of the model that NR applied to guide the implementation of a pilot intelligent infrastructure system (Network Rail, 2009). The oval on the left hand side of the figure shows some of the infrastructural assets (e.g. embankment, point, signal, level crossing, and track) that can potentially benefit from a more optimal maintenance regime. Loggers or other data acquisition devices collect information regarding these assets (i.e. remote condition measuring). Data presented in current systems, such as RCM systems, are presented in an integrated database. A strategic infrastructure solution is then required to extract the optimum information and present it to the appropriate operators. In other words, '*Network Rail is aiming to centralise all data derived from all RCM systems*' (Bint, 2008, pp.3).

At the time of writing this thesis, NR successfully piloted the intelligent infrastructure system between Edinburgh and Glasgow. Over 5000 points and 700 signalling power supplies were monitored, leading to over 400 positive interventions (Network Rail, 2011). Details of the pilot and various phases of the project are discussed in Chapter 5 of this thesis.

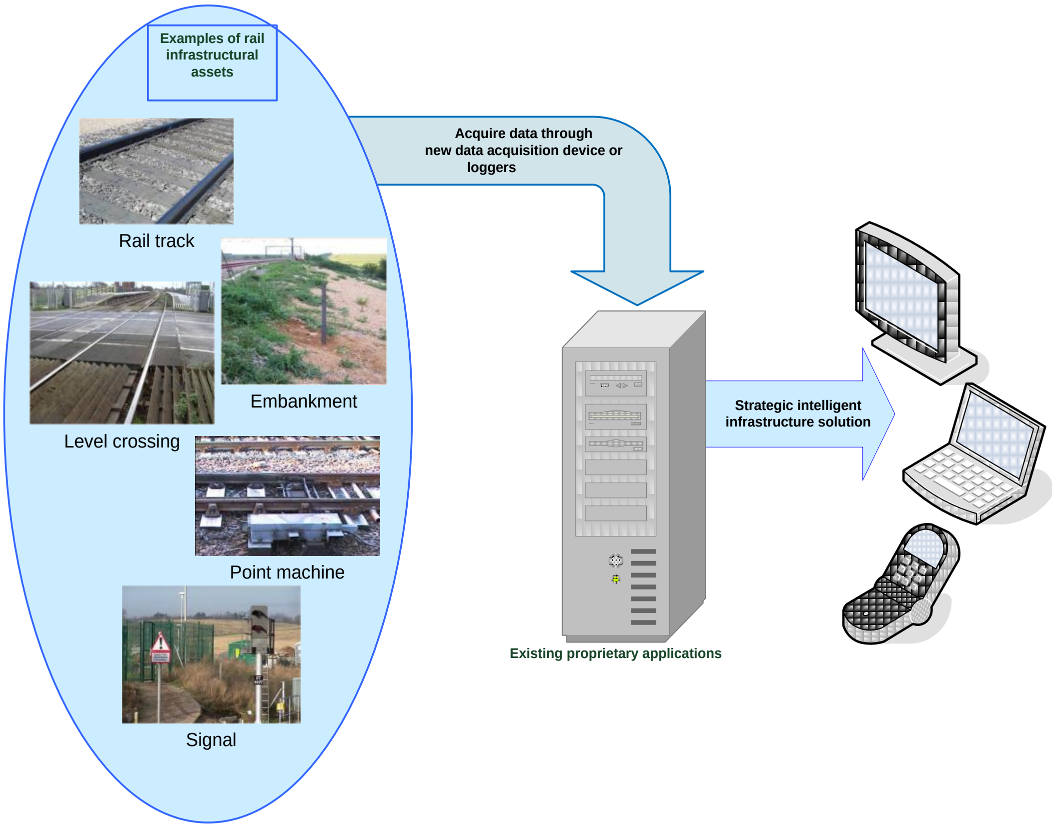



**FIGURE 2-7: SIMPLIFIED HIGH LEVEL MODELLING OF INTELLIGENT INFRASTRUCTURE IN NETWORK RAIL**

Previous research studies have mainly focused on developing more sophisticated and advanced RCM systems for the railway (Marquez & Schmid, 2007; Hull, Roberts, & Hillmansen, 2010). The existing proprietary applications in Figure 2-7 mainly refer to RCM systems. After prioritising failures according to their criticality, RCM enables a human operator to programme the maintenance process in order to mitigate the risk of those failures (Carretero et al., 2003). Since these systems are very costly to implement, only a number of assets in the railway are being monitored with RCM equipment. These are selected on the basis of their safety criticality and the effect of their failure on the efficiency of the service (i.e. delays and track availability).

Fararooy (1998) and Clark (2005) investigated RCM systems in railways, and pointed to the following limitations for developing an effective RCM system:

- RCM systems applied in railways are usually standalone systems with their own dedicated user interface
- Lack of standardisation across applications as well as maintenance practices
- Technological issues in developing railway specialised RCM systems
- Wide scope of coverage
- Diversity of equipment that needs to be monitored
- Conflict of interests between various departments, diversity of benefits
- Diversity of responsibilities, with users being responsible for a number of tasks

Carretero et al., (2003) investigated the large-scale application of RCM equipment for railway infrastructure to facilitate a 'preventive maintenance' regime. The need to engage users throughout the development process was taken into account and the following was pointed out: '*even the best methodology in the world will fail if management, staff and workers do not support it (Carretero et al., 2003,pp.259)*'.

Despite detailed and on-going work, conducted to understand and improve RCM systems in the railway (Garcia Marquez, Roberts, & Tobias, 2007; Lagnebäck, 2007; McHutchon, Staszewski, & Schmid, 2005), almost all of the limitations apart from the technical issues still persist. These problems have nearly caused RCM systems to lose their business case in railways (Bell, 2008). It seems that, in designing these systems, human factor issues have not been considered at the early stages.

Review of the literature of intelligent infrastructure systems in various domains (Jardine et al., 2006; Adriaens et al., 2003; Aktan et al., 1998; Blythe & Bryan, 2008; King, 2006) confirms that, although these systems differ in terms of components and complexity, the main process consists of five stages:

- Capturing data and attributes from domain components; attributes can refer to the environment in which the component is located, its age, type, etc.

Jardine et al., (2006) pointed out that, in the first stage (data acquisition), two types of data should be considered: event data and condition monitoring data. The former looks into what happened (e.g. breakdown, overhaul) and the latter measures the health status of the infrastructure. However, they suggest that, despite the importance of collecting event data, it is often neglected by developers who wrongly assume that the recording of only condition monitoring data will suffice.

- Patterns of component behaviour are produced. This can be achieved through studying historical data or experimental findings.

This stage includes data cleaning, to ensure that the data is relevant and error free, along with data analysis. The data analysis is usually conducted through algorithms and mainly includes signal processing, image analysis, time-domain analysis and frequency domain analysis (Jardine et al., 2006).

- Generate system diagnostics and prognostics, followed by the analysis of recognised patterns.

In this stage, sophisticated algorithms are used to assist operators in diagnosing faults and suggest rectifying procedures. Although much has been done in developing and analysing diagnostics information (Hameed et al., 2009), it is more difficult to develop rectifying procedures and present operators with a number of options. This can be related to the difficulty in understanding the behaviour of assets and, in particular, lack of appropriate understanding of the situational information associated with the failure.

- Transfer diagnostics and prognostics to relevant operators.

In order to ensure effective implementation of an intelligent infrastructure system, data obtained from the infrastructure must be transformed into useful information, as well as being exploited in the optimal way (Crainic, 2009). Failure to define the correct purpose for the data may result in the system presenting too little information or overloading the operator with inappropriate information. Hence, it is important to realise what level of detail is required. For instance, does the operator require a simple binary (working / failed) assessment of the status of an asset, or a sufficiently detailed measurement? Moreover, the operator should know the effect of the measured condition on the overall run of the service in order to predict potential failures and behaviours of the asset in the future.

- Update the pattern log with new conditions.

This is the stage where information and knowledge captured in earlier stages are now fed back to the system (e.g. using artificial intelligence, artificial neural networks, or simply operator's feedback). However, eliciting knowledge from real-world maintenance practice is not very straightforward and it is not easy to document it digitally for future use (Jardine et al., 2006). One solution to facilitate and support this feature is to develop a robust understanding of problem solving and fault finding practice as well as operators' knowledge and information requirements.

Aktan et al., (1998) conducted exploratory research to investigate the issues associated with remote sensing of the asset conditions during live operations while developing highway bridges. They confirm that, in doing so, a wide knowledge of advanced sensors, communication and information technology, state parameters, environment, deterioration mechanism and performance measures is required. Such intelligent infrastructure systems should be able to:

- Sense the definitive features on the piece of infrastructure
- Assess the condition by analysing the information captured and performance criteria
- Communicate the findings through appropriate interfaces
- Learn from infrastructure condition patterns
- Decide the optimum course of action

From this, they suggested three main factors to be considered in order to develop an effective intelligent infrastructure system:

1. The knowledge required for diagnosing problems
2. The technology necessary for transmitting the knowledge
3. The people who will work with the technology

Similarly, Adriaens et al. (2003) noted the stages required for the development of intelligent infrastructure for sustaining water resources as: specifying boundaries of the system, providing adequate quantifications that enable trend analysis, identifying quality indicators and methods for interpretation of data and integration of use (Adriaens et al., 2003). These stages reflect the need for reliable and accurate sensors that enable the acquisition of useful data.

From the three factors identified by Adriaens, et al., (2003), technology is the least problematic one, especially with the advent of highly sophisticated algorithms, artificial intelligence applications, neural network algorithms, etc (Adeli & Jiang, 2009). The other two factors (i.e. knowledge and people) are more difficult to tackle and usually system developers wrongly assume that they can overcome this lack of understanding with additional technical functionality, which in practice may lead to more problems.

Crainic et al., (2009) have explained that we are back to where we started 15 years ago; the main reason for the introduction of intelligent systems was to deal with the exhausted resources at a time when it was not possible to build any more infrastructures to cope with the capacity demand. Today the problem remains, as we have exhausted our resources again. This time, the resources concern the capacity for operators to comprehend and act on the volume of information they are presented with (it is hardly possible to present any more information to operators in control rooms). Therefore, one of the most important challenges facing the success of an intelligent infrastructure system is the management of information within the system.

As mentioned in the previous sections, railway control systems have enabled the control of large areas with complex intertwined components and have revolutionised the look and functionality of control systems. It seems that intelligent infrastructure aims to improve this functionality by managing and integrating the existing technologies, thereby assisting operators to make more informed decisions. However, the review of the potential domains of intelligent infrastructure (Section 2.2 and Section 2.3) suggests a number of challenges that will be potentially even more problematic with the introduction of intelligent infrastructure systems. These include:

- Information overload
- Multi-agent control
- Alarm handling

### *2.4.1. Information overload*

One of the recurring questions in designing dynamic control environments such as a railway control is whether more is better. Process and transport control systems collect data remotely from complex environments, enabling operators to monitor and intervene if necessary (Sheridan, 1992).

Within railways, advanced technologies, such as the switch from manual control to automation, the introduction of highly reliable sensors and the application of sophisticated algorithms, have increased the volume of data available to operators in their decision making. While this creates opportunities for more efficient control, it also places an increasing cognitive demand on the operator.

For example, in Manchester South maintenance signalling centre, Ansaldo™ systems are being used with POSS™ signalling panels, TRUST and CCF. It is important to understand how operators manage the information that is presented to them and how they direct their attention towards the most useful pieces of information.

Similar research in complex environments has shown that operators are disadvantaged by the provision of multiple sources of information as well as multiple opportunities for actions (Omodei et al., 2005; Seagull et al., 2001). Two examples of information overload include:

- There is too much information to handle. For example in the Three Mile Island incident, operators were bombarded with too many alarms with no diagnostic information. In the first few minutes alone, more than 500 alarms were generated (Campbell, 1988).

- Getting lost in complex sources of information, where the operator finds it difficult to make decisions, was evident in the case of the USS Vincent shooting down a civilian Iran Air plane because it was mistakenly identified as military aircraft on the system (Mitchell et al., 2004).

In an experimental study conducted by Omodei et al., (2005) the average performance of fire-fighters was significantly better when they were presented with incomplete information compared to situations in which they were presented with complete information. The reason suggested for this degraded performance was that, in the case of the complete information, operators could not optimally prioritise the information in the time provided. In other words, the problem of precedence of the information inspection over action generation reduced their overall performance.

Understanding and assessing the relevant and sufficient information have been mainly the focus of control domains with high time pressures, associated with activities such as fire-fighting (Omodei et al., 2005), health care (Seagull et al., 2001) and the military (Thunholm, 2005), to name but a few. Despite the alignment of control systems with these standards, optimal information presentation is highly dependent on the task that is being performed (Speier, 2006). Therefore, there should be a balance between the number of tasks for which operators are responsible and the amount of information made available to them. Cummings and Mitchell (2007) noted that there are limits to how much information operators can keep track of before they demonstrate degraded performance.

In order to facilitate an understanding of these issues in the domain of the present study, the following research questions are relevant to this thesis:

1. What is the optimal hierarchy of information presentation that is going to be required within an intelligent infrastructure task?
2. What is the optimum level of information for a particular problem solving task?
3. How do operators deal with the problem of multiple sources of information in railway problem solving?

### *2.4.2. Multi-agent control*

Control environments are moving more and more towards integration and centralisation. Therefore, the information generated in one control room will be used in another. For example, in railway maintenance, the information presented to the maintenance operator in the national control centre will be used by track workers. Moreover, different operators are responsible for different aspects of a decision making task. The cooperation between personnel with different roles within the control environment is a key aspect of the success of these control processes.

Two aspects of the work that should be analysed in order to understand and inform these multi agent control systems are:

1. What are the roles involved with these systems?
2. What are the goals and objectives of each of those roles?

There are multiple operators within an intelligent infrastructure system, any of whom at any one time might assume a different role and therefore require a level of support appropriate to this role. For example, in railway intelligent infrastructure, if we assume that asset failure prevention is the ultimate goal, the information provided by the system will be used differently by different people (from the track worker on a railway site to the operator in a control room and ultimately by the policy maker).

Hoc (2001) looked into the concept of cooperation between different agents in the dynamic environment (e.g. interface, operators, etc.). Depending on the situation and the level of autonomy of the agents, they have different levels of cooperation with each other and their own particular activities to perform. He has recommended that one way of developing an understanding of levels of coordination is to decompose one goal (i.e. solving a problem) into its sub-goals and look into the activities of different agents during each sub-goal. The important point that needs to be considered here is that the study has focused on goals rather than tasks.

Johansson and Hollnagel (2007) confirm the incremental change that is imposed on human operators within today’s complex control room and also the challenge that is created by changes in their control boundaries. The ECOM (Extended Control Model), which describes different stages of the control process for a single controller, can also relate to the activities distributed amongst multiple operators. Therefore, it is important to understand the boundaries between the different roles of intelligent infrastructure and to support each role accordingly.

Johanssen (1997) conducted a study in control environments in the cement industry, where several roles from different domains (i.e. control room operators, field operators, maintenance personnel, operational engineers, laboratory personnel, etc.) need to cooperate in order to make an operational decision. He has developed an information flow from a series of expert knowledge elicitation studies to inform the effective implementation of these systems. Among the main findings, he recommends that the visual and mental coherence of information presented to the operators should be considered in order to support effective data acquisition. Operators have a sequential approach towards certain sources of information when they want to collect information regarding a particular problem. Presenting this information in a cohesive way that matches their mental model and cognitive processing is necessary for effective decision making.

Thus, the following research questions are relevant to this thesis:

1. What are the different roles involved in railway intelligent infrastructure?
2. Thinking about potential functions of a railway intelligent infrastructure, what is the sequence of activities?

### *2.4.3. Alarm handling*

Technical advances in designing complex control settings allow huge amounts of data to be collected from various remote sensors. Presenting all of these data seems to be both impossible and unreasonable. Alarms are then introduced to assist human operators in managing these numerous sources of data.

According to the Health and Safety Executive in the UK, poor alarm handling continues to be a major safety issue (Wilkinson & Lucas, 2002). It was reported as a contributing factor in many major accidents, such as Three Mile Island in 1979 (Campbell, 1988) and the Texaco refinery explosion in 1994 (Wilkinson & Lucas, 2002; Timms, 2009). In transportation, aircraft hazard reports confirm that problems with alarms have contributed to about 50% of all incidents recorded between the years of 1984-1994 (Gilson et al., 2001).

In the Ladbroke Grove enquiry report, alarm handling was noted as a contributing factor (Cullen, 2000). Similarly, poor alarm handling is suggested to have had an assisting role in the Channel Tunnel Fire (Brown, 1999). Major problems associated with alarms include alarm flooding, poor system state indication, poor priority management and nuisance alarms (Wilkinson & Lucas, 2002; Gilson et al., 2001; Seagull & Sanderson, 2001).

Woods (1995) conducted a study to understand alarm handling in various domains and to explore the cognitive activities associated with it. He suggested that the alarm problem can be addressed from two viewpoints: perceptual functions and how informative the alarms are. The former focuses on perceptual signals used to identify abnormal conditions, as well as their alerting potential, whereas the latter relates to alarm semantics and how informative they are (Woods, 1995).

Many key research projects have focused on alarm handling response times (Stanton, 2006), direction of attention (Woods, 1995; Gilson et al., 2001), modelling the operators' diagnostic procedures (Woods, 1995; Stanton & Baber, 2006), information load (Woods et al., 2002) and how informative alarms are (Seagull & Sanderson, 2001). It seems that early research studies were mainly focused on improving alarm perception. Understanding what makes an alarm meaningful became much more important later on.

Robinson et al., (2006) introduced various factors affecting the usability of auditory displays, alarms and warnings. Design factors that need to be considered in relation to auditory displays include: appropriate level of sensitivity, contrast between the audible siren and background noise, perceived urgency of the task and the alarm respectively as well as multiple alarms (Robinson et al., 2006). These factors, in their wider sense, refer to the two perspectives introduced by Woods (1995): how informative the alarm is and alarm perception. Many researchers have approached alarm problems from either of these viewpoints. These studies have their basis in field observations that are then further investigated within controlled laboratory environments. In the majority of these studies, non-expert volunteers or a combination of expert and novice volunteers participated. The measures used to evaluate the suggested improvement usually included: time to diagnose, mental workload, number of controlled actions and quality of response (Stanton, 2006; Gilson et al., 2001).

Based on this, the following research question is relevant to the thesis:

1. What are the railway alarm handling activities and artefacts?

## *2.5. Chapter summary*

This chapter reviewed the railway control domains that are going to be of high importance to the railway intelligent infrastructure project. The roles, activities, environments and technologies available in the existing control domains are initiated. This has led to the introduction of intelligent infrastructure, which potentially is going to be of assistance to the domains mentioned in this chapter (maintenance control and electrical control). Intelligent infrastructure aims to facilitate integration and centralisation of existing systems that are currently available to the operators in maintenance control rooms. This is to enhance safety and efficiency, two main priorities of Network Rail (Network Rail, 2010).

For example, safety is promoted because if the remote sensing technologies are used to their potential then this can enable maintenance technicians to get a better understanding of the track without sending track workers on site and reduce the associated safety risks. Furthermore, notifying maintenance operators of a future failure based on data collected from the remote sensors can reduce the delay minutes, increase the service capacity and increase the efficiency of the service.

Despite the need to understand the roles of operators in complex control settings such as railway control rooms, the socio-technical nature of these domains imposes challenges on researchers to explore them. The research questions investigated within this PhD study aim to understand and guide these challenges. Furthermore, these challenges will focus on different objectives of this PhD study. Table 2-2 below summarises these questions, their corresponding objectives and the relevant chapters were these studies have been performed. These challenges are categorised in three groups and include:

- Information overload
    1. What is the optimal hierarchy of information presentation that is going to be required within an intelligent infrastructure task?
    2. What is the optimum level of information for a particular problem solving task?
    3. How do operators deal with the problem of multiple sources of information in railway problem solving?
- Multi-agent control
    1. What are the different roles involved with railway intelligent infrastructure?
    2. Thinking about the potential functions of a railway intelligent infrastructure, what is the sequence of activities?
- Alarm handling
    1. What are the railway alarm handling activities and artefacts?

**TABLE 2-2: RESEARCH QUESTIONS AND THEIR RESPECTIVE OBJECTIVES AND STUDIES**

| Research questions | Objectives | Chapters |
|---|---|---|
| What is the optimal hierarchy of information presentation that is going to be required within an intelligent infrastructure task? | I-Develop a data processing framework that guide and support effective implementation of railway intelligent infrastructure from a human factors perspective<br><br>III-Produce human factors guidance for future development and implementation of intelligent infrastructure systems in the railway, which will match and complement human capabilities and needs. | Chapter 5: interview study<br><br>Chapter 5: card sorting study<br><br>Chapter 6 and 7: explore particular problem solving tasks that will be most relevant to railway intelligent infrastructure tasks |

| | | |
|---|---|---|
| What is the optimum level of information for a particular problem solving task? | I-Develop a data processing framework that guide and support effective implementation of railway intelligent infrastructure from a human factors perspective<br><br>III-Produce human factors guidance for future development and implementation of intelligent infrastructure systems in the railway, which will match and complement human capabilities and needs. | Chapter 6 and 7: investigate particular problem solving tasks<br><br>Chapter 8: investigate the hypothesis associated with the optimum level of information |
| How operators deal with the problem of multiple sources of information in railway problem solving? | II- Establish an in-depth understanding of operators' strategies for alarm handling and fault finding.<br>Produce guidance for future development and implementation of intelligent infrastructure systems in the railway, which will match and complement human capabilities and needs.<br><br>III- Produce human factors guidance for future development and implementation of intelligent infrastructure systems in the railway, which will match and complement human capabilities and needs. | Chapter 6 and 7: investigate the case of multiple source of information in railway maintenance control |
| What are the different roles involved with railway intelligent infrastructure? | I- Develop a data processing framework that guide and support effective implementation of railway intelligent infrastructure from a human factors perspective<br><br>III- Produce human factors guidance for future development and implementation of intelligent infrastructure systems in the railway, which will match and complement human capabilities and needs. | Chapter 5: The interview study that led to identification of the roles |

| | | |
|---|---|---|
| Thinking about potential functions of a railway intelligent infrastructure what are the sequence of activities? | II-Establish an in-depth understanding of operators' strategies for alarm handling and fault finding.<br>Produce guidance for future development and implementation of intelligent infrastructure systems in the railway, which will match and complement human capabilities and needs.<br><br>III- Produce human factors guidance for future development and implementation of intelligent infrastructure systems in the railway, which will match and complement human capabilities and needs. | Chapter 6 and 7: alarm handling and fault finding study |
| What are the railway alarm handling activities and artefacts? | II-Establish an in-depth understanding of operators' strategies for alarm handling and fault finding.<br>Produce guidance for future development and implementation of intelligent infrastructure systems in the railway, which will match and complement human capabilities and needs.<br><br>III- Produce human factors guidance for future development and implementation of intelligent infrastructure systems in the railway, which will match and complement human capabilities and needs. | Chapter 6 : in-depth analysis of railway alarm handling |

In order to explore these research questions a comprehensive approach to the understanding of control domains should be used. A selection of paradigms of analysis of control is reviewed in the next chapter. These guide the selection of research methodologies adopted within this PhD programme.

# 3. Paradigms to the analysis of control

The previous chapter reviewed railway control domains and introduced intelligent infrastructure as a new system that aims to improve the safety and efficiency of the railway service. From this, a number of research questions were identified; if not investigated these could impose serious challenges for the successful implementation of railway intelligent infrastructure. As mentioned in chapter two, the research questions are relevant to three groups of challenges and are listed below:

- Information overload
  1. What is the optimal hierarchy of information presentation that is going to be required within an intelligent infrastructure task?
  2. What is the optimum level of information for a particular problem solving task?
  3. How do operators deal with the problem of multiple sources of information in railway problem solving?
- Multi-agent control
  4. What are the different roles involved with railway intelligent infrastructure?
  5. Thinking about the potential functions of a railway intelligent infrastructure, what is the sequence of activities?
- Alarm handling
  6. What are the railway alarm handling activities and artefacts?

This chapter introduces and reviews paradigms that can facilitate investigation of these research questions. The first section reviews the information processing paradigm which investigates control settings via an understanding of linear interactions between human operators and control settings. The second section explores a supervisory control paradigm, in which operators' roles during interactions with the system is explored; section three reviews a cognitive system engineering paradigm, in which the co-agency between operator and system is explored. Section four states the relevance of these paradigms to the research questions of this PhD.

## *3.1. Information processing paradigm*

Early studies designed to understand human-machine interactions were mainly limited to the analysis of human interactions with physical artefacts, along with other observable activities in the control room (Cacciabue, 1997). Neisser (1967) and Newell and Simon (1972) were among the first to theorise about the need to understand the operators' cognitive activities and formulate human operators as information processors. More sophisticated models became necessary to explain the operators' reasoning and decision making process, with the increasingly complex and automated technologies in control rooms (Cacciabue, 1998).

Understanding human behaviour has long been of interest to system designers; among the very first and most pervasive models is the S-O-R model (Stimulus, Organism, and Response) (Rassmussen, 1986). Although the idea was to associate human functions with their cognitive processing, the notion was mainly based on the engineering concept of the black box. Therefore, human functions are mostly considered as separable rather than parallel procedures. However, due to its simplistic approach of associating stimuli with responses, it is still being used as a common means to explore control settings.

In other words, the information processing paradigm is the outcome of a linear and fragmented view of human-computer interaction, in which humans are seen as information processors and it is possible to explore their activities through investigating the information inputs (stimulus) and outputs (response) (Rasmussen, 1986).

This paradigm has long been used to guide an understanding of the components of control processing (e.g. Rasmussen, 1986; Pendergrass et al., 1987; Ruterburg, 1995; Cacciabue, 1998). The aim is to model cognitive activities in control rooms by associating human cognition with the sequence of tasks. For example to '*identify the specific attention devoted to the stages or mental operations that occur between the stimuli and responses* (Cacciabue, 1998), p.18'.

One example of such models is presented in Cacciabue (1998) (Figure 3-1), and is briefly reviewed here. Four cognitive functions responsible for converting stimuli into a response are: perception, interpretation, planning, and execution. The feeders and effectors of these cognitive functions are memory/knowledge base as well as allocation of resources.

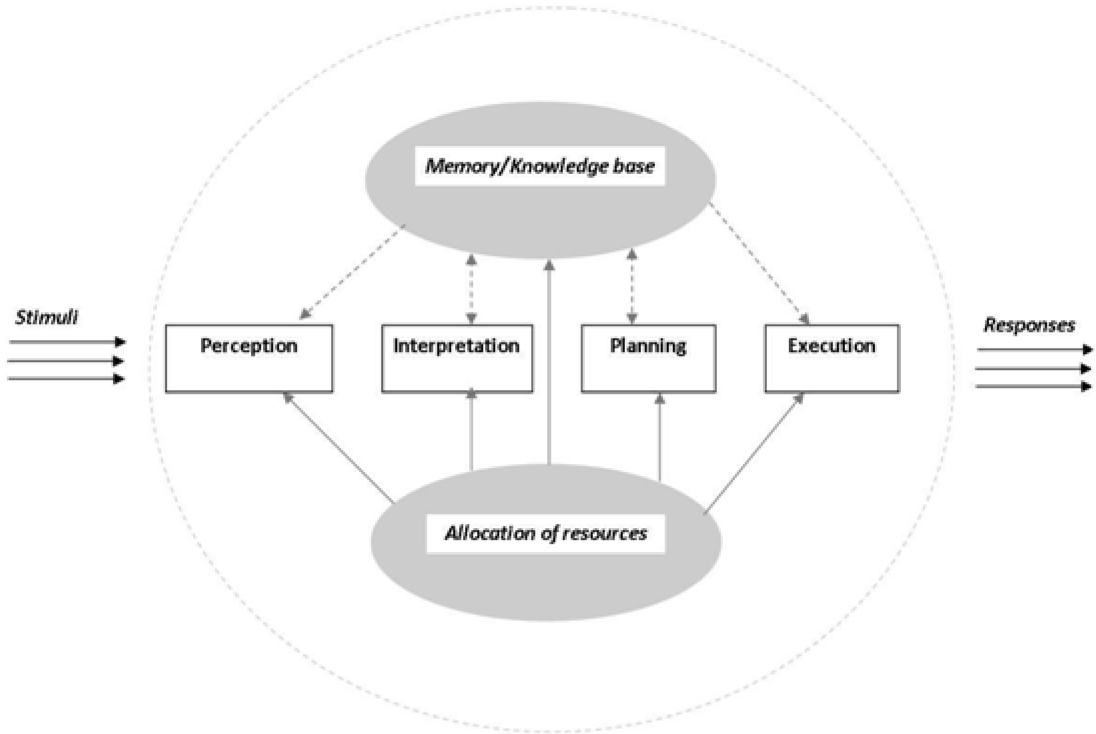



**FIGURE 3-1: A MODEL OF INFORMATION PROCESSING TAKEN FROM CACCIABUE (1998, P.20)**

'Perception' refers to the reception of a sensory stimulus that activates information seeking for further processing. 'Interpretation' refers to a detailed elaboration of the perceived information to form an understanding of the problem. 'Planning' is the stage at which decisions are being made to support the optimum course of action and 'execution' refers to the implementation of that action. 'Memory/knowledge base' refers to the operator's experience and individual differences. Finally, 'allocation of resources' is the availability of useful resources to the operators (Cacciabue, 1998).

Ezzedin and Kolski (2005) have proposed a model (Figure 3-2) to represent the cognitive activity of railway controllers. In order to represent the operators' information processing, they divided situations into the categories of normal and abnormal. This model consists of two main processing units: operational and cognitive. Moreover, static and dynamic descriptions were defined to enable adaptations of human behaviour in real life situations. This model does not factor in the dynamic nature of the control task and is limited to the activities anticipated by the designer.

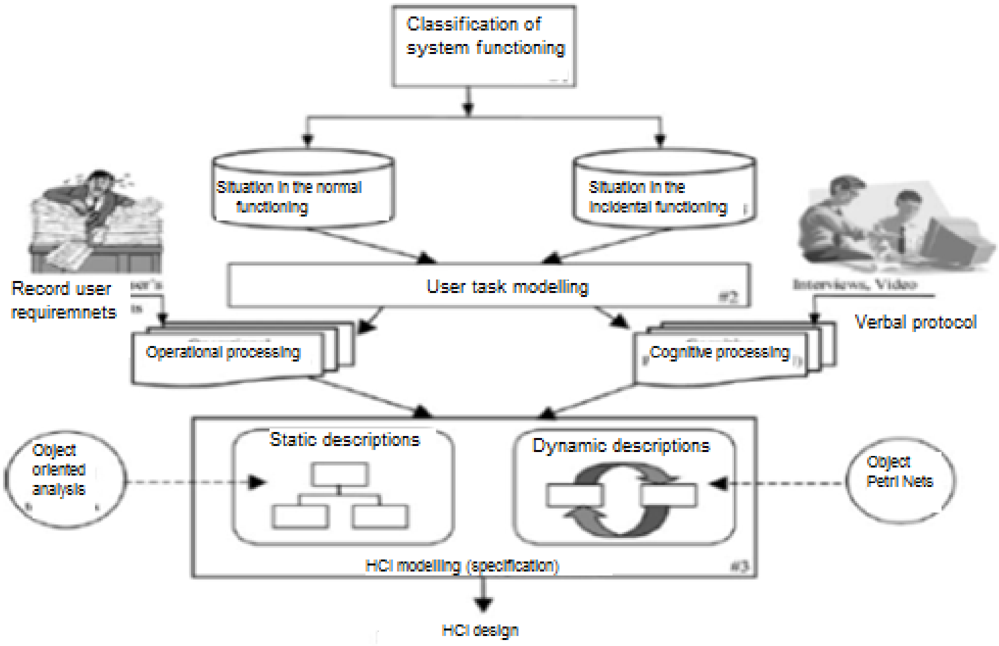



**FIGURE 3-2: MODEL OF COGNITIVE ACTIVITIES OF RAILWAY SUPERVISORY CONTROLLERS, TAKEN FROM EZZEDIN & KOLSKI (2005)**

Information processing paradigms have been widely used to facilitate studies associated with decision making, problem solving, as well as alarm handling. Models of alarm handling were introduced to guide the exploration of the various stages conducted by operators when handling alarms; very early ones include that of Lees (1983), which has three stages: detection, diagnosis and correction. A model suggested by Rouse (1983) also has three stages: detection, diagnosis and compensation. Although other models are available, as noted by Stanton (2006), there is little evidence that these models reflect a real life alarm handling environment. To overcome this uncertainty, Stanton et al (1998) identified a sequence of activities that are initiated by the generation of an alarm (Figure 3-3).

This model includes two sets of events: routine and critical. When an alarm is generated, operators observe the reported warning and accept if it is genuine. Based on their understanding of a failure, operators might analyse, correct, monitor, or reset the alarm. If the cause of the failure is unknown, then the operator will conduct a series of investigations to diagnose the problem. Finally, they monitor the situation to ensure that the abnormality is dealt with (Stanton, 2006).

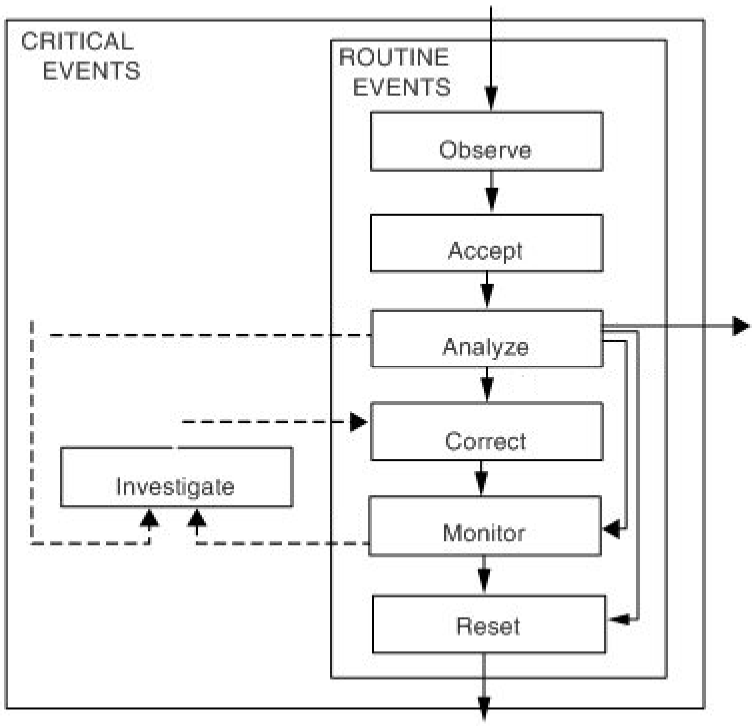



**FIGURE 3-3: ALARM-INITIATED ACTIVITIES, TAKEN FROM STANTON, (2006) P. 1008**

Examination of these examples shows that information processing as a paradigm has facilitated the exploration of control settings on the basis of a sequence of conceptual activities that occur in the control room. Despite being very useful, this approach focuses only on the information that is processed and does not include the contextual characteristics that have led to that form of information processing (Kerstholt & Raaijmakers, 1997).

Moreover, cognition is not bound to an individual human operator; understanding the information processing in increasingly complex and multi-agent environments needs to include constraints and affordances of the context (Hollnagel, 2002). Hutchins (1995) argues that early cognitive studies attempted to understand the human individual, leaving issues such as context, culture and even history for later. This would not lead to an accurate understanding of the domain, since those marginalised issues (context, culture, etc.) are at the core of human cognition.

Thunholm (2005) also confirms the dynamic nature of decision making in the battlefield. He claims that the nature of military decision making is not an independent process, but the state of the problem evolves on the basis of the expertise and the actions of the decision maker. The model suggested by Thunholm (2005) aims to model the planning process under time pressure. The focus of this model is to plan, modify, and refine one course of action, instead of understanding how one action is chosen from a series of alternatives.

In search of a way to apply realistic settings to modelling decision making, Ranyard and Williamson (2005) applied a conversation-based process tracing method to uncover information requirements during planning. Two methods were joined together to capture information resources in the real life environment: an active information search combined with limited information techniques were adapted to capture the knowledge utilised by decision makers in real life settings. Finally, the information was organised through content analysis techniques and presented within a matrix to elaborate on the decision makers' search patterns. These techniques guided the data collection methods adopted in the present PhD study.

Hoc and Amalberti (2005) suggested a Dynamic Situation Management (DSM) model, focusing on how operators make compromises for optimal planning. This model suggests that, apart from the time and resources required for the short term control of the system, it is equally important to consider unexpected events, which might pile up and affect the long term control of the system. This emphasises the need to include context early on in the process.

Reason (1987), pointed out that, despite their great potential, complex control systems have failed in emergencies. This is partially due to inconsistency between the system and human operators' information processing and the fact that, during problematic situations, operators are more likely to use their knowledge-based heuristics rather than the pre-programmed instructions. Reason suggested that it is necessary to design a new generation of systems that incorporates basic human cognition at the outset. Hence, in these dynamic situations, merely looking at the stand alone functionality of the system would not be sufficient; a more cognitive approach is required (Hoc, 2001). The supervisory control paradigm reviewed in the next section is one step towards such a transition.

## *3.2. Supervisory control paradigm*

The advances in technical equipment in control rooms have changed the role of operator to that of supervisor. Rouse (1976) noted this and predicts that, with technological advances, machines will become more and more involved in the control process, to a point where there will be intersecting and overlapping areas of responsibilities (Rouse, 1976). This change has inspired the supervisory control paradigm.

Sheridan (2002) lists six levels of control that show the historical trend from manual to supervisory control. These stages are 1- direct human control, 2- indirect human control, 3- computer aided indirect control, 4- supervisory control, 5- remote supervisory control and 6- remote multi-task supervisory control.

Sheridan and Hennessy (1984, p.8) defined supervisory control as: '*activities of the human supervisor who interacts via a computer with a complex and semiautonomous process*.' They simply assign machines to transfer sensed and modified information of an on-going physical process to a human operator. In other words, the system acts as a mediator between the two (Sheridan, 1997).

Automation is a distinct feature of supervisory control models, as noted by Miller and Prasuraman (2007), who state that there should be flexible delegation of automation to various tasks within the control environment. They have therefore argued that the most important aspect of supervisory control is task delegation and, in order to conduct a successful delegation, detailed task decomposition is necessary.

User interaction with automatic systems has received much research attention. Endsley and Kaber (1999) conducted a study to assess the effects of automation on performance, situation awareness and workload. Semi-automated systems (intermediate levels of automation) were introduced to overcome the 'out of the loop' performance problem through joint human-system interaction. Parasuraman and Riley (1997) confirmed that over-reliance on automated systems occurs through a lack of understanding of the automated procedure, choosing not to use them at all or when there are too many false alarms, and a lack of focus on the human operators' needs when designing the system.

Identifying the activities involved in the supervisory control system seems to be a reasonable way of exploring and investigating these systems. According to Sheridan (1992), supervisory control behaviour consists of five basic elements: plan, teach, monitor, intervene and learn (Figure 3-4). These elements are briefly explained below.

Plan: the human operator has to understand how the process works and what the system's objectives and constraints are, enabling them to decide on a control strategy (e.g. decide on alarm priorities).

Teach: to instruct the computer, based on the planned programme (e.g. define alarm priorities in colour coding or setting a threshold level on the machine)

Monitor: Systems taught or instructed, as in the previous stage, will work automatically; the human operator needs to ensure that the system and these automated features are working properly. A problem arises when there are too many variables to monitor, which is almost always the case in today's complex socio-technical environments. A potential solution to assist operators in monitoring is notifying them of any abnormalities through alarms (Chapter 2).

Intervene: the operator needs to intervene when they find anomalies or if any abnormalities are observed. Problems arise when the operators are uncertain as to whether they should intervene, due to lack of information or lack of transparency between the human operator and the automated component. Furthermore, when operators are faced with a high workload or stress, they might fail to detect the need for intervention (Sheridan, 2002).

Learn: Operators learn from their experience and apply their knowledge in future supervisory control roles.

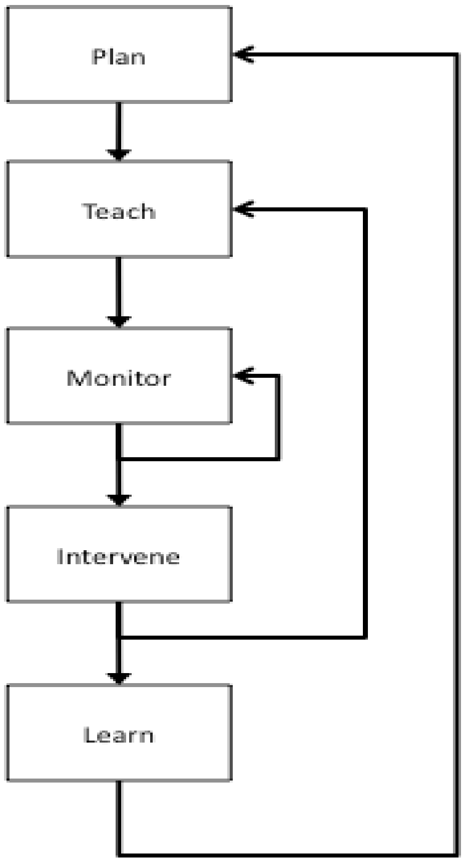



**FIGURE 3-4: SHERIDAN'S (1992) SUPERVISORY CONTROL MODEL**

Brandin and Charbonnier (1994) identified the tasks within the supervisory control systems associated with an automated manufacturing system as:

1- monitoring of the work cell behaviour via sensory feedback
2- evaluating the control
3- enforcing corrective procedures when necessary.

Brandin and Charbonnier (1994) also suggested that, in order to develop such systems, it is important to understand the domain's physical characteristics and other behavioural specifications.

Cummings et al. (2010), explored human supervisory control within nuclear power plants and associated the five elements of human supervisory control (Figure 3-4) with various features of the system, the human operator being one of them (Figure 3-5). For example, monitoring is a process that includes observing the interface to learn from it or to plan a course of action. The planned action is conveyed to the system when the operator feels the need to intervene on the basis of what they have monitored.

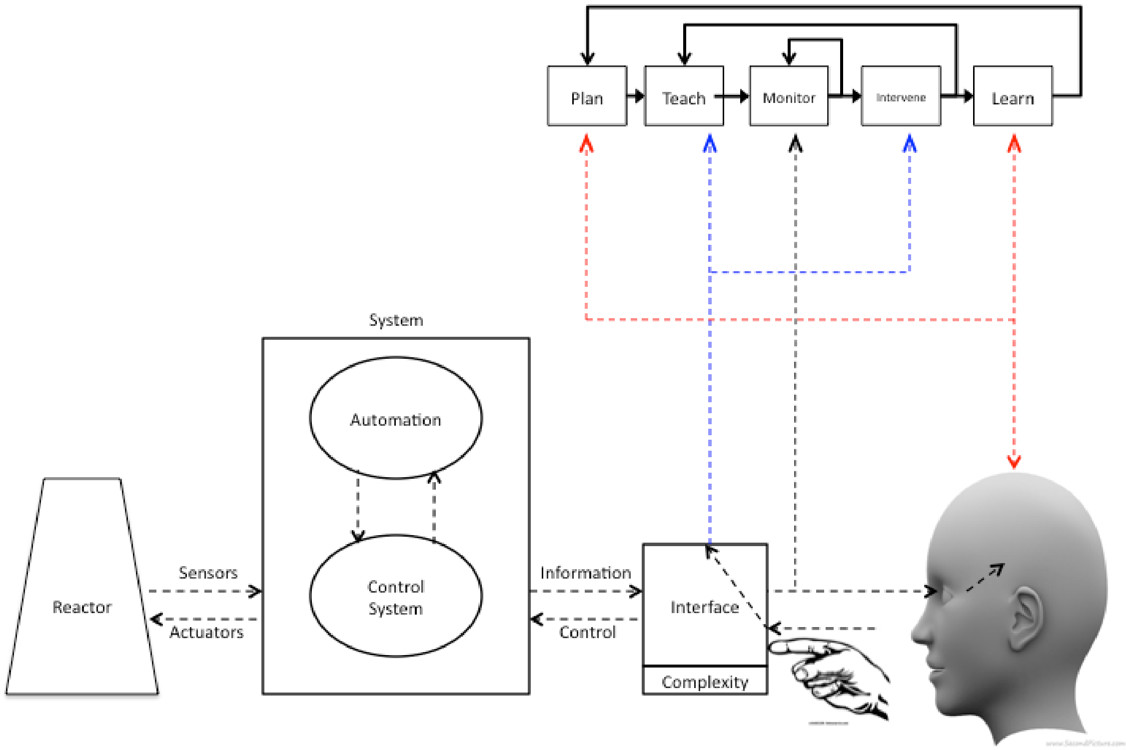



**FIGURE 3-5: HUMAN SUPERVISORY CONTROL IN THE NPP CONTEXT ( CUMMINGS ET AL. 2010)**

A supervisory control paradigm has guided many research studies in understanding the features in complex control settings: aviation (Endsley & Kriss, 1995; Wickens, Mavor, & McGee, 1997; Morphew & Wickens, 1998; Sarter & Amalberti, 2000; Metzger & Parasuraman, 2005), nuclear and process control (Moray, 1997; Mumaw et al., 2000; Guerlain, 2002) health care (Leape, 1994;Helmreich & Musson, 2000; Guerlain et al., 2005), automobiles (Sheridan, 1992; Fong & Thorpe, 2001), and military (Amalberti & Deblon, 1992; Cummings & Mitchell 2006; Crandall & Cummings, 2007; Cummings & Mitchell, 2007). However, the supervisory control paradigm focuses mainly on physical or mechanical functions, rather than cognitive and mental functions.

Looking into the studies mentioned above and from the work of Sheridan and Henassy (1984), Kirlik et al., (1996), Xiao et al., (1997) and Hollnagel

(2000), it seems that two major themes can be used to explore control environments from a supervisory control point of view. These are listed below and explained in the present section.

1. Understanding operators' strategies while interacting with these complex systems
2. Understanding the optimum resource and function allocation for the control demands

### *3.2.1. Understanding operators' strategies*

Human operators tend to adopt strategies and shortcuts to overcome the limitations imposed by technical systems, including those of inefficient information presentation in supervisory control systems.

Systems should support operators while they are bombarded with information from various sources and have to make decisions quickly and accurately. This implies a strong need to understand the strategies used by control room operators for troubleshooting and decision making. A review conducted to understand problem solving strategies in battle decision making, defined cognitive strategies as:

…"*regularities in reasoning that can be crafted to guide decision making in a particular set of circumstances for doing an action in the most effective manner*" (Pounds & Fallesen, 1994,p.1).

Kim and Seong (2007) conducted a study to provide recommendations for the information types presented to nuclear power plant operators and the use of operators' diagnostic strategies. They defined strategies as:

"*A sequence of mental effectors that operators used to transform an initial state of knowledge into a final goal state of knowledge*'' (Kim & Seong, 2007, p.171)

Another study, which analysed decision makers' behaviours in dynamic systems, was conducted by Kerstholt (1996). He analysed operators' strategies (judgment-oriented vs. action-oriented strategies) when making decisions, depending on various information costs (e.g. how time consuming it is to collect that information). This study suggested that operators had different problem-solving strategies, depending on the cost of the information presented to them. If the cost was high, decision makers selected an action-based strategy and, if the information cost was low, decision makers chose a judgment-based strategy (Kerstholt, 1996). This shows a link between operator's strategies and the type of information presented to them. It is to be noted that the type of information in this case refers to the level and nature of information, rather than its format.

Patrick et al., (2006) analysed human control process strategies within control room teams. Findings suggest that operators within various teams and various control rooms selected different goals and strategies to detect, diagnose and conduct problem solving. These were found to be very much dependent on their contextual and situational differences. Moreover, this conclusion suggests that, in order to understand the operators' strategies and derive general design recommendations, it is important to consider various situational conditions.

Schriver et al., (2008) examined pilots' decision making strategies while presented with different cues. They found that, depending on the cue, the level of attention among operators will vary and that affects their potential strategy and consequently affects their decision making performance. It is, therefore, safe to assume that the cues selected for attention by operators can be used as an indication of their particular strategies.

Dynamic decision behaviour infers that human operators constantly adapt their actions to the situation, depending on their strategies. Various factors can affect the strategies adopted by decision makers. These include information cost (Kerstholt, 1996), information type (Kim & Seong, 2007), cognitive feedback (Seong & Bisantz 2008) and information processing modes (Rasmussen & Lind, 1982).

Within an intelligent infrastructure system, as mentioned in the previous chapter, information overload will be a recurring dilemma. As with the technological advancements, there will be selection of information available to the operators. Knowledge of the strategies they use can guide designers in presenting operators with information congruent with their strategies.

### *3.2.2. Resource and function allocation within a supervisory control*

Technology was initially introduced in control rooms to assist operators with physical tasks; gradually it became sufficiently advanced to assist operators with cognitive processing as well as physical tasks (Hollnagel & Woods, 1983). Whilst this creates opportunities for more efficient and proactive control, it also places an increasing cognitive demand on the operator (Roth et al., 2002; Woods, 1985;Woods et al., 2002).

Within supervisory control, resources refer to both cognitive abilities (memory, attention, workload, etc.) and physical artefacts (phone, information display, memory pads, automated features of the supervisory control systems, etc.). Moreover, operators' knowledge and competence to solve a problem, as well as the time available to complete control tasks has to be considered for both design and evaluation of supervisory control systems. Therefore, it is important to understand the resources available within a control room, along with their effect on the control.

Nilsson and Johansson, (2006) studied the use of artefacts in a mixed reality environment in terms of support given to the functions of the system. This study investigated the artefacts from the users' viewpoint. It recommended a new approach for assessing the usability of the mixed reality system, since these artefacts encouraged new methods of interaction and the users' perceptions of these systems were different from other human-machine ones.

Furthermore, although supervisory control paradigms have enabled the work environment to be described in terms of operators' roles while interacting with the control systems, it does not provide the means for understanding the effect of situational changes on supervisors' roles. Both strategic analysis and function allocation within a supervisory control paradigm are necessary features; however, they still focus on the routine situations an operator has to attend to in sequence (Thistle, 1996). As the work on strategies has illustrated, interaction with supervisory control is highly dependent not just on the design of the technology, but on a range of individual and contextual factors.

Woods and Roth (1988) specified that operators needing the most support during emergency situations are let down by technology design that is incompatible with the demands of the operator or the operational context. Therefore, more holistic paradigms are required to guide design in these situations. Cognitive system engineering, described in the following section, is one example of such a paradigm.

## *3.3. Cognitive system engineering paradigm*

Earlier in this chapter, two paradigms for understanding control environments were described, whereby physical and mechanical characteristics (response to a stimuli or the reaction to a supervisory system) were analysed. Woods and Roth (1988) argue that this is not sufficient to explain control complexities. Cognitive System Engineering (CSE) is a paradigm that attempts to address this challenge.

CSE refers to the need for an understanding of mental processes in complex control settings in order to develop efficient design within these systems. In other words, CSE is a paradigm that facilitates an in-depth understanding of the control environment. Various features in the control setting affect operators' and designers' understanding of the system, consequently affecting their information processing (Hollnagel, 2002). Hoffman and Militello (2009, p.95) defined CSE as:

*"A type of applied cognitive science, trying to apply what is known from science to the design and construction of machines."*

In a paper by Hollnagel and Woods (1983), CSE was re-emphasised as the paradigm that can facilitate better design of control systems that support human limitations and cognitive challenges. Many researchers have used or been inspired by this paradigm (e.g. Norman, 1988; Woods & Sarter, 2000; Hoffman & Militello, 2009; Norros & Salo, 2009; Dalal & Kasper, 1994; Paradis et al., 2002; Ryder et al., 1998).

Roth et al., (2002) listed three interconnecting elements in every cognitive system as a 'cognitive system triad', consisting of artefacts, world, and agents (Figure 3-6).

'Agents' refers to either a human or a machine that processes information and performs tasks within cognitive systems. 'World' is the environment in which agents are active; this defines the social, organisational and contextual constraints. 'Artefacts' refers to any objects and resources that assist agents to conduct their tasks.

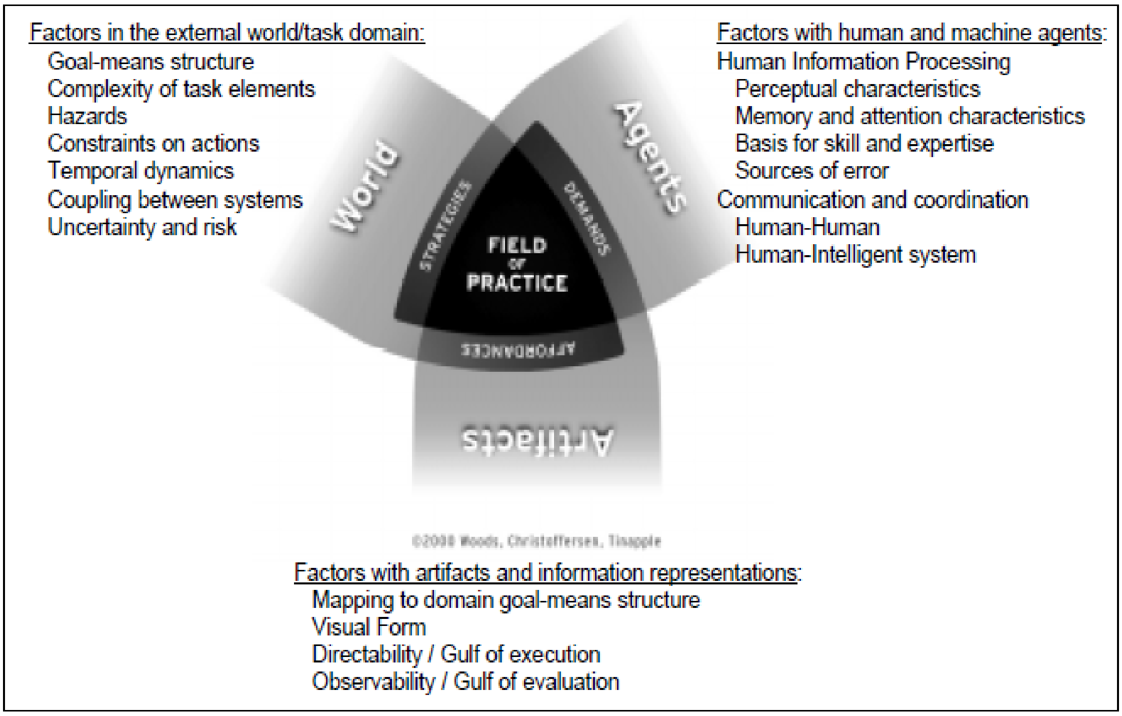



**FIGURE 3-6: COGNITIVE SYSTEM TRIAD TAKEN FROM ROTH ET AL. (2002)**

Figure 3-7, taken from Hollnagel and Woods (1983), shows the stages required for developing a cognitive system understanding to guide the design of man-machine systems. It must be noted that this diagram highlights both the top-down and bottom-up nature of CSE. At the top end, it is important to understand the technical demands and, at the bottom, it is necessary to assess the applied cognition within the control room.

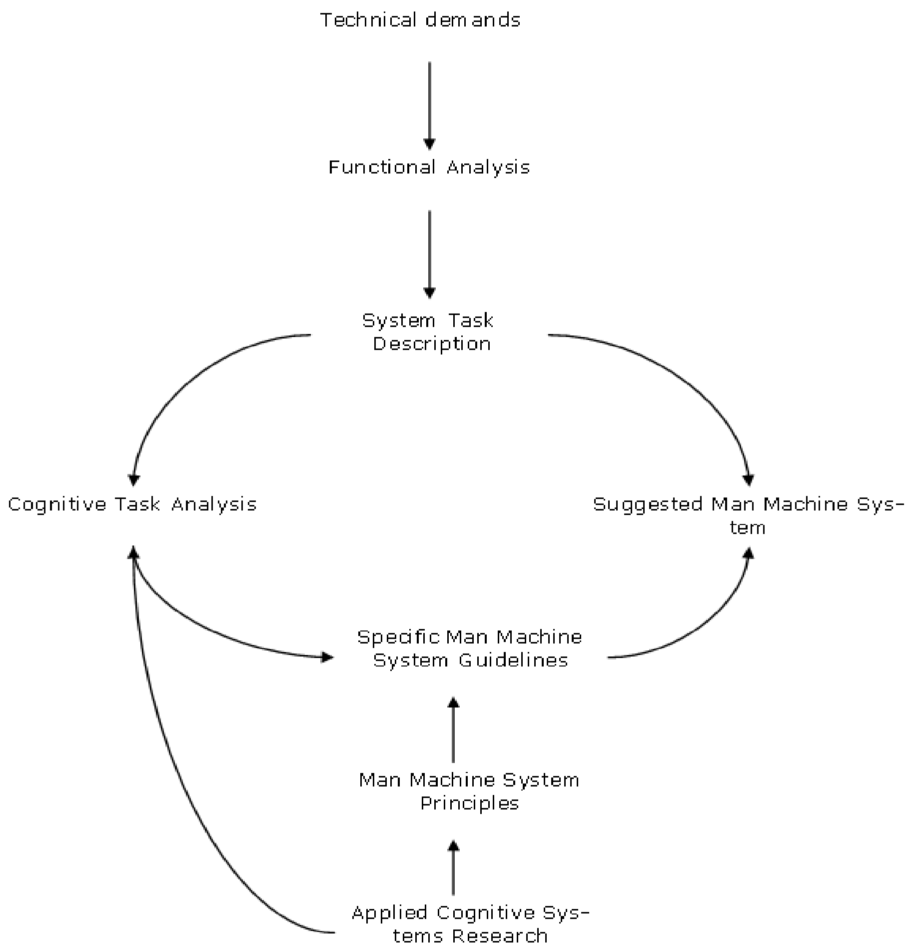



**FIGURE 3-7: COGNITIVE SYSTEMS ENGINEERING IN THE DESIGN PROCESS TAKEN FROM HOLLNAGEL & WOODS (1983, P. 592)**

In order to facilitate this understanding, CSE focuses on understanding three threads within the work setting: use of artefacts, coping with complexity and joint cognitive systems. These are briefly described below.

### *3.3.1. Use of artefacts*

Artefacts will affect the way human operators work and collaborate in the control environment and therefore have an effect on the operators' cognition (Woods & Hollnagel, 2006). As Woods (1998) pointed out, new design is developed with the hypothesis that artefacts can improve the performance and quality of the interaction. Therefore, it is important to understand how operators' ways of thinking change with the introduction of new artefacts; this will not be possible without understanding how operators conduct their tasks with their current artefacts.

"*An artefact is a device used to carry out or facilitate a specific function that is part of work* (Hollnagel & Woods 2005, p.66)".

The reason for understanding cognitive processing in control rooms is even more important when it comes to introducing new technologies. New artefacts introduce new levels of complexity for operators, causing new forms of errors (Hoffman & Militello, 2009).

Exploration of the artefacts in control room settings has been widely used to inform current best practice within the control room or to develop an understanding with regard to future settings. Furniss and Blandford (2006) explored the artefacts available to medical dispatch units in lieu of understanding the distributed cognition within the context of the study.

Ryder et al., (1998) focused on the procedures associated with decision making tasks and modelled the interaction of artefacts in the form of a task analysis. This was to guide the design of a new telephone operator workstation. Paradis et al., (2002) conducted a form of Cognitive Work Analysis for designing decision support systems in defence and, in the first steps of this analysis, identified the relevant artefacts.

### *3.3.2. Coping with complexity*

Complexity is caused when operators are faced with multiple channels of information and control lines dividing their attention. This is the case in today's complex control rooms, where the amount of data presented on the systems has dramatically increased (Cumming et al., 2006; Harper, Michailidou, & Stevens, 2009; Woods et al., 2002).

Cummings et al., (2006) listed the sources of information complexity as:

- Volume of information
- Ambiguous sources of information
- Unclear relationship between different information sources

When faced with these complexities, heuristics are being used to reduce the cognitive load in order to overcome the shortcomings and make the optimum decision (Cummings & Mitchell, 2006). These are, in other words, shortcuts applied by operators that consequently make their decisions somewhat biased. These decision biases should be identified and managed to avoid risky operations. Under time pressure, these heuristic biases might be misleading and result in a wrong decision. Assimilation bias and automation bias are two of the best known and most researched biases (Cummings et al., 2010).

Paradis et al., (2002) applied CSE to guide the design of intelligent decision supports in defence. One advantage of using CSE was noted to be its ability to indentify cognitive demands and to consider ways in which technology could be exploited to deal with these demands. They adopted a pragmatic approach by breaking down the activities into small engineering steps and conducting an analysis of each step.

Hollnagel and Woods,(2005) have identified the strategies potentially applied by operators to cope with complexities due to information inefficiencies. These are listed in Table 3-1 below.

**TABLE 3-1: COPING STRATEGIES FOR INFORMATION INPUT OVERLOAD AND INFORMATION INPUT UNDERLOAD (TAKEN FROM HOLLNAGEL & WOODS 2005, P. 80-81)**

| Strategy | Definition |
|---|---|
| Omission | Temporary, arbitrary non-processing of information; information is lost |
| Reduced precision | Trading precision for speed and time, all input is considered, but only superficially; reasoning is shallower |
| Queuing | Delaying response during high load, on the assumption that it will be possible to catch-up later (stacking input) |
| Filtering | Neglecting to process certain categories; non-processed information is lost |
| Cutting categories | Reducing the level of discrimination; using fewer grades or categories to describe input |
| Decentralisation | Distributing processing if possible; calling in assistance |
| Escape | Abandoning the task; giving up completely; leaving the field |
| Extrapolation | Existing evidence is 'stretched' to fit a new situation; extrapolation is usually linear, and is often based on fallacious causal reasoning |

| | |
|---|---|
| Frequency gambling | The frequency of occurrence of past items/ events are used as a basis for recognition/ selection |
| Similarity matching | The subjective similarity of past to present items/event is used as a basis for recognition/selection |
| Trial-and-error (random selection) | Interpretations and/ or selection do not follow any systematic principle |
| Laissez-faire | An independent strategy is given up in place of just doing what others do |

### *3.3.3. Joint Cognitive Systems*

Joint Cognitive System (JCS) views the cognitive system as a result of human-computer co-agency rather than human-computer interaction. What matters is the performance of the whole unit, rather than the individual. In other words, it is not defined by what it is but it focuses on what it does.

The main objective of a JCS is to achieve the goal, i.e., the intelligent outcome of the system. Any restrictions, such as lack of time, resources or even operators' competence, which prevent the JCS from achieving the goal, are considered as a complexity and need to be managed.

Although it is feasible to investigate the first two threads of CSE (use of artefacts and coping with complexity) the third thread (JCS) is not easy to explore (Norros and Salo, 2009) and it therefore lead to an incomplete CSE. Understanding JCS requires the researcher to identify the characteristics of the system that has to be in place in order to maintain control in its dynamic environment.

To achieve a JCS understanding of a control system, three entities should be explored. The two obvious ones are human and system and the third one, which is quite difficult to investigate, is their cognitive coupling, Relationship between cognitive characteristics of the user and cognitive characteristics of the system (Dalal & Kasper, 1994).

According to Dalal and Kasper (1994) the characteristics of these entities (user and system) are related to the goals, knowledge, problem solving strategies and cognitive styles. The relationship between user and system will determine how successful their joint behaviour will be and how flexible the joint system is in complex situations. Furthermore, what defines this relationship is the problem or situation in which the coupling takes place. The characteristics of the problem solving task will lead to the selection of goals by the user, who adopts certain cognitive styles and problem solving strategies. Therefore, contextual understanding is very important in the study of JCSs.

Although CSE is a well-known and widely used concept, its application and successful implementation can be quite challenging (Lind, 2009). One of the challenges to an understanding of the relationship between user and system is identification of the boundaries between their cognitive characteristics.

It is equally important to realise that a new approach requires new ways of collection and data analysis. Lind (2009) argues that a lack of theoretical understanding of the relationships between automatic systems, their process controls and human machine design explains the lack of industrial impact of such systems.

It seems that CSE is often mistakenly viewed as a method or framework, rather than a paradigm. It is important to remember that CSE is a 'way' to solve the problem, rather than a solution on its own. Woods et al. (1996) noted that CSE investigates the cognitive work when people (or group of people) pursue goals and how their behaviours and strategies are adopted to optimise these goals.

## *3.4. Relevance of the Paradigms in this PhD study*

Earlier in this chapter, three paradigms that have been used to explore and understand control environments were reviewed. This section will revisit the research questions associated with this PhD study and discuss the paradigms that can guide them. Moreover, in order to facilitate to guide the selection of these paradigms, their potential and limitations are briefly described here.

From the literature reviewed in this section, it seems that although information processing models lack the contextual characteristics of the control environment, they are very useful in developing an understanding of specific aspects of decision making activities, as in the studies reviewed earlier. Moreover, in order to understand human operators as information processors, observing and analysing individuals in a structured way can be sufficient.

The supervisory control paradigm explores two main themes and focuses on the roles of operators while interacting with the system. These themes include investigating operators' strategies and understanding the resource and function allocations associated with each role. This paradigm also investigates the domain in procedural form. However, instead of focusing on one cognitive activity and an individual's information processing associated with it, the supervisory control paradigm looks at a range of activities involved in one role.

The cognitive system engineering paradigm focuses on performance in the work environment. Therefore, an understanding of the domain and the roles within it is required to facilitate this. In order to develop such an understanding it is important to have access to detailed situational knowledge of operators' cognition in the world.

These paradigms were used to facilitate the investigation of different research questions in this PhD study. These paradigms have been selected on the basis of the outcomes of the research questions as well as the feasibility of collecting data to inform the relevant studies. It must be noted that these research questions are not limited to any one paradigm and often various aspects of one research question are explored through a number of paradigms.

- *Questions 1 & 2: What is the optimal hierarchy of information presentation that is going to be required within an intelligent infrastructure task? What is the optimum level of information for a particular problem solving task?*

When thinking about the different tasks of the intelligent infrastructure system (e.g. alarm handling), operators' procedures while performing these tasks should be analysed. Therefore, an information processing paradigm is required at the beginning to develop an understanding of these procedures (Chapters 5, 6 and 7). The word 'hierarchy', especially in the context of intelligent infrastructure systems, refers to various levels of roles and responsibilities and requires a supervisory control paradigm to develop an understanding of resource and function allocations associated with different roles (Chapter 5). As the word ‘optimal’ directly links with ‘performance’ a CSE paradigm is required to facilitate investigation of the optimal hierarchy of information presentation.

- *Question 3 & 6: How do operators deal with the problem of multiple sources of information in railway problem solving?*

Dealing with a problem and managing a complex situation correspond to performance and it seems that the best way to develop such an understanding is through a CSE paradigm in which operators’ coping strategies are explored. In so doing, detailed understanding of the artefacts and their uses in different situations is necessary (Chapters 6 and 7)

- *Question 4: What are the different roles involved in railway intelligent infrastructure?*

Understanding the roles of operators while interacting with intelligent infrastructure, in terms of their specific requirements, is similar to the supervisory control paradigm in which different elements are activated during various activities. Therefore, the activities and functions associated with the intelligent infrastructure system were explored (Chapter 5).

- *Question 5: Thinking about the potential functions of a railway intelligent infrastructure, what is the sequence of activities?*

The sequence of activities refers to an understanding of two things: the activities and the procedures the operator performs in order to complete tasks. Therefore, a supervisory control paradigm is adopted to explore and investigate the activities, functions and resource allocations. Moreover, selecting specific aspects of the activity, it is possible to apply an information processing paradigm to investigate the sequence of activities in terms of operators’ information flow (Chapters 6 and 7).

## *3.5. Chapter Summary*

This chapter has reviewed the paradigms that can be used to understand control environments. The three paradigms reviewed were information processing, supervisory control and CSE. It seemed that these and more specifically the CSE paradigm provided the means to explore and investigate the research questions of this PhD study. Moreover, the threads associated with these paradigms such as use of artefacts and coping strategies in the CSE paradigm as well as resource allocation and operators' strategies in supervisory control paradigm acknowledges the need to investigate the research questions of this PhD study in order to develop a thorough understanding of intelligent infrastructure systems.

Exploration of these issues within complex and dynamic control environments, such as railways, needs a combination of methodological approaches that are cohesive, feasible and ecologically valid. In the next chapter the methods that facilitated this PhD study have been reviewed.

# 4. Research framework and study methods

Previous chapters have introduced intelligent infrastructure systems and described potential challenges in the rail domain. This is followed by specific research questions along with paradigms that can guide the explorations of these questions. This chapter presents and reviews the methodological approaches that can guide the objectives of the research. Each method is reviewed in turn to assess feasibility and relevance to the domain of intelligent infrastructure. Details of the use and implementation of each of these methods are discussed in subsequent chapters.

## *4.1. Research Methods*

Field studies are no longer purely anthropological, with the researcher immersed in the domain without interruption, nor are laboratory studies just about measuring variables (Hoffman & Woods, 2000). It is very difficult to mark the boundaries between qualitative and quantitative methods when the aim is to understand the context. This was certainly the case in this PhD study. Therefore, throughout this research, a combination of methods was adopted to explore the context, systems and human operators. Structured data collection techniques, e.g. verbal protocol, video recording were used to provide a comprehensive overview of the task under study and within its context. Furthermore, laboratory studies were developed to facilitate a targeted analysis of selected aspects, such as information presentation for alarm handling. Details of the methods and their subsequent chapters are summarised in Table 4-1. Different methods informed the selection of the later studies. Figure 4-1 shows the flow of the methods used in this PhD programme, as well as how they have facilitated each other.

**TABLE 4-1: OVERVIEW OF RESEARCH OBJECTIVES, METHODS AND OUTPUTS**

| Objective | Methods | Output | Chapter |
|---|---|---|---|
| Develop a data processing framework that guide and support effective implementation of railway intelligent infrastructure from a human factors perspective | Workshop<br>Interview study<br>Field study | Data processing framework<br><br>General understanding of intelligent infrastructure<br><br>Human factors issues associated with intelligent infrastructure | 2 & 5 |
| Establish an in-depth understanding of operators' strategies for human supervisory control tasks in alarm handling and fault finding. | Field study<br>Interview study | Understanding problem solving | 6 & 7 |
| Produce human guidance for future development and implementation of intelligent infrastructure systems in the railway, which will match and complement human capabilities and needs. | Field study<br>Interview study<br>User trials | Inform knowledge and information requirement of intelligent infrastructure (general guidance) | 5,6,7& 8 |

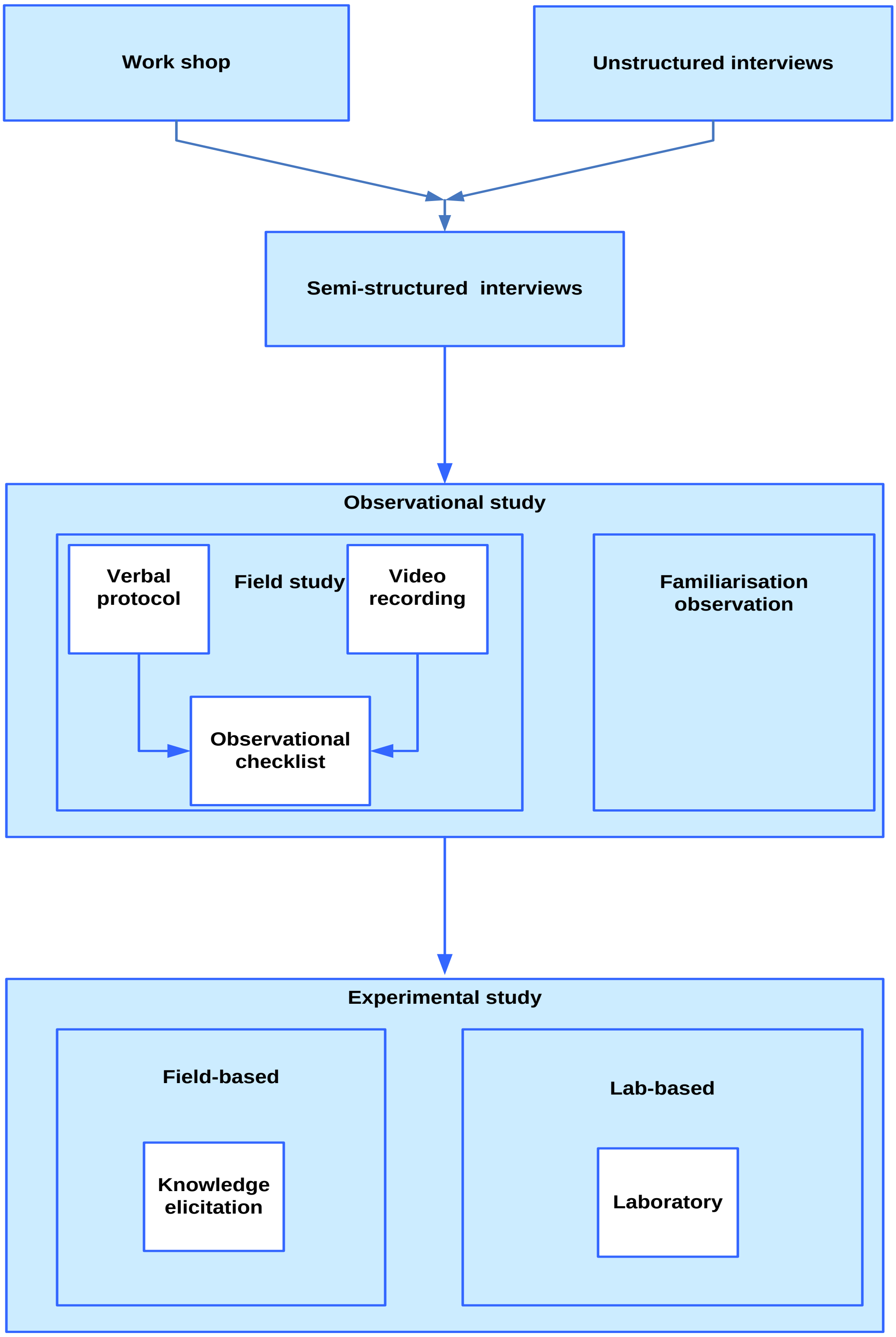



**FIGURE 4-1: METHODS USED IN THIS PHD AND HOW THEY HAVE INFORMED EACH OTHER**

## 4.2. Workshop and interviews

### 4.2.1. Workshop

Workshops enable the collection of the opinions of Subject Matter Experts (SMEs) on various aspects of a topic. It is useful to initiate an understanding of a domain by validating and verifying the findings, brainstorming a problem or getting a general feeling about a particular issue (Robson, 2011)

The railway has many intertwined components and it is not feasible to investigate all aspects of a future project in detail. Network Rail (NR) uses workshops to engage potential users of a future system in the design and development phases of its projects. It is particularly useful since designers can narrow down the scope of the system and possible functionalities required by the users.

In this study, the researcher attended a one day workshop held by NR in November 2008. This was the researcher's very first exposure to the intelligent infrastructure project. The attendees were senior managers in the company who were deeply involved with the project.

### 4.2.2. Interviews

Interviewing is one of the most commonly used tools for eliciting knowledge and structuring empirical findings (Fontana & James, 2000). Many studies use interviews to understand the socio-technical nature of work; some of the examples of their use in the railway include studies by Farrington-Darby et al.(2006); Pickup et al. (2003); Wilson & Murphy, (2002).

Robson (2011) categorised interviews into three main forms: unstructured, semi-structured and structured. In this study two of these forms, unstructured and semi-structured, have been applied at various stages and are briefly discussed below. Figure 4-2 lists the various forms of interviews used in this PhD study.

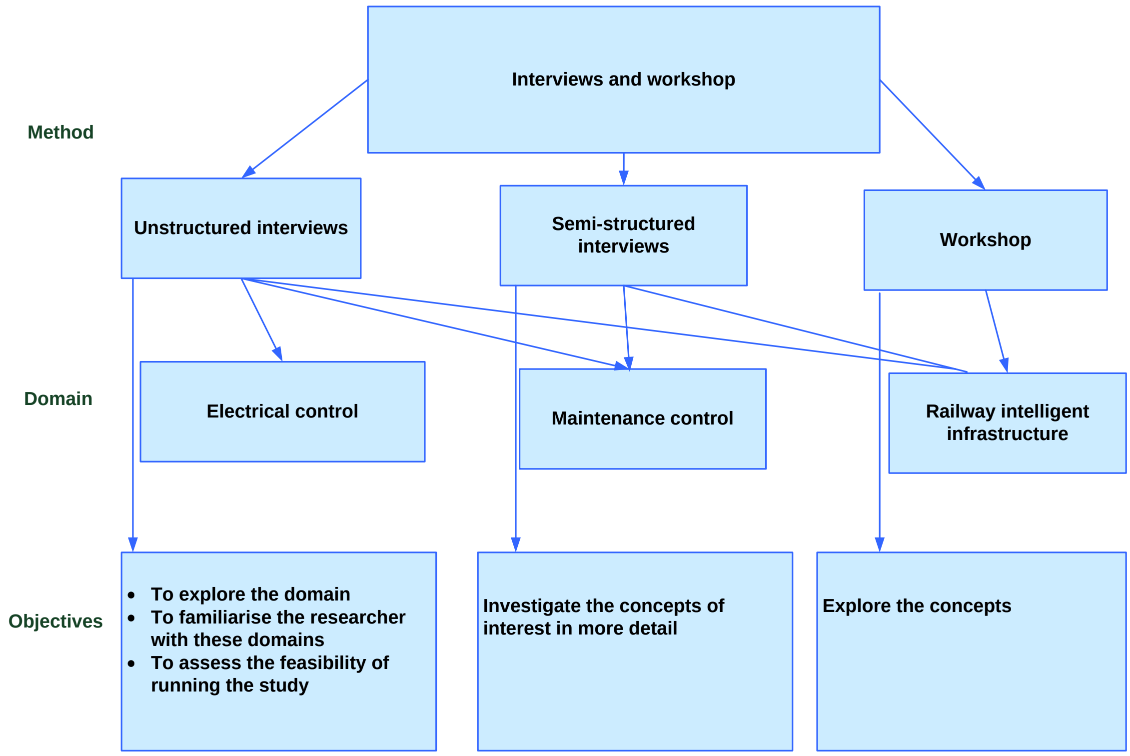



**FIGURE 4-2: VARIOUS FORMS OF INTERVIEWS AND WORKSHOPS USED IN THIS PHD STUDY AND THEIR OBJECTIVES**

#### 4.2.2.1. Unstructured interviews

The unstructured interviews utilised in this PhD programme were performed to achieve two purposes: 1- to facilitate an exploration of the domain (exploratory interviews), and 2- to become familiar with a specific aspect of the domain (familiarisation interviews). The researcher then used other methods to investigate these domains in more detail.

A number of familiarisation interviews were conducted in this PhD programme. The aim of these interviews was to briefly introduce the domain of study to the researcher and to assess the feasibility of carrying out the study within various contexts. For instance, it would be important to establish whether conducting the study in a railway Electrical Control Room (ECR) during peak time would interfere with the safe and efficient operation of the control room and how the researcher could manage and mitigate such risks. Moreover, these interviews helped the researcher to obtain a general understanding and appreciation for the context of the study; for example, the observational checklist (Section 4.3.2.3) was designed after a series of familiarisation interviews.

These interviews were unstructured, and the interviewees (railway operators in all of the cases) were asked to describe their main responsibilities and provide a high level outline of the work in the control rooms, along with the available resources and challenges they have while conducting various problem solving tasks. Overall, nine interviews were conducted (a total of 17 hours) in four different control rooms (one electrical and three maintenance control centres).

Table 4-2 below summarises the familiarisation interviews conducted throughout this research.

**TABLE 4-2: INTERVIEWS**

| Location /Area of study/interest | Number of interviewees | Role of interviewees | Duration (per interviewee) | Relevant chapter |
|---|---|---|---|---|
| Supervisory control systems in railway | 1 | Senior system developer | 2Xhours | 2 |
| Intelligent infrastructure project | 2 | Senior ergonomist | 1Xhour | 2 & 5 |
| Electrical control room | 1 | Head of electrical control | 1Xhour | 6 |
| Electrical control room | 2 | Electrical control room operator | 3Xhours | 6 |
| Maintenance control centre | 3 | Maintenance control centre | 2Xhours | 7 |

#### 4.2.2.2. Semi-structured interviews

Semi-structured interviewing is a method that enables qualitative data to be captured and guides the researcher towards an understanding by exploring various aspects of the complex work setting (Robson, 2011). Semi-structured interviewing is different from unstructured interviewing in the sense that there are a number of predefined questions to guide the study. However, since the domain is not fully known, the structure of the questions addressed in this study can only be partially designed (Schmidth, 2004).

In this PhD study, semi-structured interviews were informed by the cognitive task analysis approach.

##### *4.2.2.2.1. Cognitive Task Analysis (CTA)*

Task analysis forms an envelope of procedures and contextual facts which can elaborate human behaviour in working environments (Shephard & Stammers, 2005). The change in the role of human operators, from actors to thinkers, led to the development of a framework capable of capturing both physical activities as well as mental processes in complex control settings. Therefore, the concept of CTA was formed (Hoffman & Militello, 2009).

CTA aims to cover three aspects of human-machine interaction: technical skill, context, and mental model (Cacciabue, 1998). It can therefore provide researchers with information regarding the working environment, structure of cognitive plans, and links between tasks and goals. To achieve this level of understanding of tasks, different forms of data collection and analysis are employed. These methods have to be more focused on internal processes and mental operations than mere observation of physical interactions. Various techniques have been adopted to engage with this level of detail.

O'Hare et al., (1998) confirmed that CTA is an appropriate approach to the exploration of complex cognitive tasks. However, the effectiveness of the approach is highly dependent on the researcher's knowledge of the domain, as well as the extent and quality of resources available to the study.

Hollangel (1993) introduced Goals-Means Task Analysis (GMTA). The idea of this approach was to break the task into its goals and sub-tasks, followed by defining elementary actions, pre-conditions and post-conditions linked to the task. Pre-conditions are the goals of previous tasks that activate the current task; post-conditions are the output of the successful execution of the task and will be considered as the pre-conditions for other tasks in the sequence.

More qualitative data collection techniques seem essential to the delivery of the level of detail required, as well as the provision of insights from working environments. These techniques include interviews, field observations and verbal protocols (Corbett, Koedinger, & Anderson, 1997; Crandall, Klein, & Hoffman, 2006).

Hoffman et al., (2009) used CTA to explore issues in the procurement of an intelligent decision support system. In doing so, they conducted a thematic analysis of a series of documentations relevant to the topic of study and performed structured interviews with experts.

One form of CTA, which has widespread use in various studies as an explanation of decision making activities, is the Critical Decision Method (CDM) developed by Klein (1989).

CDM is a retrospective interview technique with a focus on exploring decision making in its natural setting. These environments enforce various challenges on the decision maker, including time pressure, high information content and dynamic conditions (Klein et al., 1989).

O'Hare et al., (1998), describe CDM as a knowledge elicitation strategy, based on the critical incident technique.  It elicits knowledge from both interviews and protocol analysis with talk aloud, aiming to assess human problem solving skills in naturalistic decision making contexts (Shadbolt, 2005).

In CDM, the researcher asks questions from expert operators regarding a certain incident. The questions used in this technique are called 'probes', which focus on various aspects of decision making. Figure 4-3 shows an example of the interview 'probes', suggested by Klein et al., (1989).

| Probe type | Probe content |
|---|---|
| Cues | What were you seeing, hearing, smelling...? |
| Knowledge | What information did you use in making the decision , and how was it obtained? |
| Analogous | Were you reminded of any previous experience? |
| Goals | What were your specific goals at this time? |
| Options | What other courses of actions were considered by or available to you? |
| Basis | How was this option selected/other options rejected? What rule was being followed? |
| Experience | What specific training or experience was necessary or helpful in making this decision? |
| Aiding | If the decision was not the best, what training, knowledge or information could have helped? |
| Time pressure | How much time pressure was involved in making the decision? ( Scales varied) |
| Situation Assessment | Imagine that you were asked to describe the situation to a re life officer at this point, how would you summarise the situate ion? |
| Hypothetical | If a key feature of the situation had been different, what differ ence would it have made in your decision? |

**FIGURE 4-3: CRITICAL DECISION INTERVIEW PROBES TAKEN FROM KLEIN ET AL. (1989 P. 466)**

Crandall (1989) conducted a CDM study with twenty fire commanders to explore their tactical and strategic decisions at the scene of a fire. This method enabled her to identify the commanders' perceptual cues and gave an indication of how their decision making changes with the dynamics of the situation.

Wong and Blanford (2002) used the CDM technique to understand the decision making of ambulance dispatchers. Thirteen dispatchers were interviewed and the timeline of the incidents they believed to be memorable led to an in-depth understanding of their roles as well as their constraints.

The first series of semi-structured interviews were conducted to inform the researcher's understanding of railway intelligent infrastructure. The second series of semi-structured interviews were conducted in the maintenance control room, in order to facilitate a detailed understanding of fault finding (Chapter 7). The questions of this study were formed in a similar manner to the probes in the CDM suggested by O'Hare et al., (1998). The last series of semi-structured interviews was performed to facilitate the selection of an alarm scenario. This alarm scenario was used to further investigate the data processing framework (Chapter 5).

## *4.3. Observation*

Observational studies are at the core of understanding any socio-technical environment. In this project, they were conducted for two purposes: 1- to become familiar with the domain of the study (familiarisation study), and 2- to explore a specific research question (field study).

### *4.3.1. Familiarisation observation*

'Familiarisation observations' were conducted as a fact finding and exploratory activity, which consisted of visits to signal boxes, maintenance control centres and electrical control rooms.

The familiarisation observations were designed to assist the researcher in obtaining an understanding of the study's domain, mainly railway control rooms and remote condition monitoring equipment. These observational studies were conducted for two purposes: 1- fact finding and exploratory understanding of the domain, e.g. observing various types of signalling control: lever frames, NX panels, VDU and IECC, and 2- to familiarise the researcher with the details regarding a specific study, e.g. pre-study observation in Lewisham ECR. A total of 31 hours of observations were performed in 11 railway control rooms, which are summarised in Table 4-3 below.

**TABLE 4-3: FAMILIARISATION OBSERVATIONS**

| Date | Location | Duration (hours) | Relevant chapter |
|---|---|---|---|
| October 2008 | Rugby signal box (VDU) | 2 | 2 |
| October-November 2008 | Lewisham ECR (VDU-SCADA) | 4 | 2 & 6 |
| October 2008 | York signal box (IECC) | 4 | 2 |
| October-March 2008 | London North East route control-York | 4 | 2 |
| November 2008 | Wembley signal box (NX) | 2 | 2 |
| December 2008 | Manchester signal box (Lever frame) | 1 | 2 |
| December 2008 | Liverpool signal box (lever frame) | 1 | 2 |
| February 2009 | London Bridge signal box (NX) | 2 | 2 |
| April 2009 | Rugby ECR (VDU-SCADA) | 3 | 2 & 6 |
| May 2009 | Manchester South MCCS | 4 | 2&7 |
| May 2009 | West Midlands signalling centre | 4 | 2 & 7 |

### *4.3.2. Field study*

The second piece of observational research was an investigation into the main functions of a potential intelligent infrastructure that has analogues within existing systems, i.e. alarm handling in a railway electrical control room. These studies are referred to as 'field studies' in this thesis.

Field studies are useful for developing an understanding of the domain in a comprehensive way (Bisantz & Drury, 2005); they enable researchers to identify significant issues in complex socio-technical settings. Sundstrom and Salvador (1995) have noted that structured field studies can interconnect with exploratory observational studies to produce an understanding of user needs.

The field studies conducted as part of this research are designed to investigate potential intelligent infrastructure functions within existing control settings. Since SCADA systems are the closest to an intelligent infrastructure system and centralised RCM within the railway industry, SCADA-based ECRs were selected for the field studies. Moreover, the interview studies identified alarm handling as one of the essential functions of the future intelligent infrastructure system. Therefore, a total of 18 hours of field studies were conducted in one railway ECR. It is common to use a combination of methods to capture complex control domains, such as the use of a combination of observational checklists and field visits to understand signalling and automation (Balfe, 2010). In this PhD, a combination of video recording, verbal protocol and observational checklists were used to facilitate observations.

#### 4.3.2.1. Video recording

Data from video recordings is a useful tool that enables the researcher to review and analyse the activities during the field studies with more accuracy (Robson, 2011). This method is of specific relevance to the exploration of socio-technical environments since it facilitates the capture of a number of sources of information, such as the operators' interactions with the technical system and their conversations with other team members.

Video recording was used in this PhD to capture detailed information, such as the artefacts used, the screen the operator was attending to, time spent thinking without clicking on any of the buttons, etc. Furthermore, the operators' comments regarding the alarm, during and after handling, were recorded.

#### 4.3.2.2. Verbal protocol

When operators are conducting cognitive activities (i.e. remembering, monitoring, etc), it is often the case that their thinking is not visible and observation of the responses alone is not sufficient to get a clear understanding of the activity. In other words, human behaviours, while interacting with cognitive systems, are not usually in the form of observable actions. Verbal protocol analysis facilitates the capture of these mental processes whereby the operator explains their actions, either while performing the tasks or following the completion of the activity (Bainbridge & Sanderson, 2005).

Throughout the alarm handling study conducted in the ECRs, operators were asked to explain their actions and their reasoning, either while handling or after they had cleared the alarms. Approximately two hours of the operators' talk-aloud was audio recorded. This data also informed the completion of the observational checklist, discussed below (Chapter 6).

#### 4.3.2.3. Observational checklist

An observational checklist is a technique that enables the findings from the observational studies to be structured. Many researchers have benefitted from the use of observational checklists in order to organise their understanding of the domains. More specifically, observational checklists are useful for informing the design and development of socio-technical systems. Some of these domains include virtual reality (Neale, Cobb, & Wilson, 2000), nuclear power plants (Mumaw  et al., 2000) and Railways (Balfe, 2010; Dadashi.Y, 2009).

An observational checklist was designed on the basis of a familiarisation observation session conducted in an ECR. The observational checklist developed for the objectives of this PhD was time-stamped. It recorded the artefacts adopted by operators while alarm handling. One column in the checklist recorded the operators' comments regarding their sources of difficulty (Chapter 6).

## *4.4. Experimental studies*

Experimental studies enable a hypothesis to be explored and investigated in an isolated environment. These studies are very popular among human factors researchers. The core reason for using experimental studies in human factors studies is twofold: 1- to facilitate the quantification of an improvement in the human-machine interaction, and 2- to perform a structured comparison between a set of pre-defined design recommendations (Role & Diaz-Cabrera, 2005).

The aims and objectives of this PhD programme have been driven mainly by qualitative studies and studies of real-life situations. However, there were certain circumstances in which the use of qualitative assessment alone was not sufficient to meet the objectives of this study.

The levels of information obtained from the interview studies reflected information content as well as a hierarchy associated with it. Although the observational studies conducted as part of the field studies in electrical control did qualitatively confirm the framework, the need for a more direct and robust method of assessment was greatly felt. Therefore a knowledge elicitation exercise was designed.

Furthermore, following the identification of the problem solving stages and its association with the data processing framework, it was hypothesised that different information is targeted at improving the performance at different stages. Since it was not possible to isolate the stages of problem solving in a real-life situation, this had to be simulated in a laboratory study. More specifically, as it would have been impossible for expert operators to isolate their cognitive processing stages, students were used as participants.

The difference between experimental studies and observational studies in this PhD is that, in the observational studies, the researcher is observing the research environment (e.g. ECR) as events occur in it. In the experimental studies, the researcher defines and controls the events that are occurring in the research environment. Depending on the type of the research environment, two forms of experimental studies are utilised in this PhD programme: field and lab-based.

### *4.4.1. Field-based study*

A knowledge elicitation study was designed to underpin the optimal type and order of information required for the alarm management problem solving task. In a review conducted by Hoffman (2008), knowledge elicitation (KE) was recognised as one of the methods of cognitive task analysis and one that facilitates an in-depth understanding of the operators' cognitive processing while decision making. Various techniques can be used for KE, such as interviews, task analysis, unobtrusive observation, verbal protocol, rating and sorting tasks, limited information problems, etc.

In this study, an alarm scenario was developed in which railway operators were asked to rate pieces of information potentially required for the problem solving task in terms of importance. They were then asked to place this information within the three categories (sets of information) identified in Chapter 5.

### *4.4.2. Lab-based study*

Interest in laboratory studies and simulated environments increased with researchers' need to investigate isolated and particular aspects of human behaviour. However, the hypotheses explored through laboratory studies in complex socio-technical environment are often derived from field-based and observational studies (Wilson, 2000).

Findings from the qualitative methods undertaken in this PhD study classified various stages of decision making and identified their optimal level of knowledge and information presentation. These recommendations were investigated within a laboratory study. Details of this study are reported in chapter 8 of this PhD thesis.

## *4.5. Cognitive work analysis*

Cognitive Work Analysis (CWA) is used in this PhD to capture the data from all of the methods above in a coherent way to represent the domain. CWA is a conceptual and system-based approach for analysing human information interactions in highly dynamic socio-technical work places (Sanderson et al.,1999; Fidel & Pejtersen, 2004). It was initially proposed by Rasmussen et al, (1994), and subsequently modified by Vicente (1999) and Lintern (2009). Table 4-4 below lists the CWA stages in each of the three approaches.

**TABLE 4-4: COGNITIVE WORK ANALYSIS STAGES**

| Rasmussen et al. (1994) | Vicente (1999) | Lintern (2009) |
|---|---|---|
| Work domain analysis<br>Activity analysis in work domain terms<br>Activity analysis in decision making terms<br>Activity analysis in terms of mental strategies<br>Analysis of work organisation<br>Analysis of system users | Work domain analysis<br>Control task analysis<br>Strategies analysis<br>Social organisation and cooperation analysis<br>Worker competencies analysis | Work domain analysis<br>Work organisation analysis<br>Cognitive transformation analysis<br>Strategies analysis<br>Cognitive processing analysis<br>Social transaction analysis |

The stages of CWA (Rasmussen et al., 1994; Vicente, 1999; Lintern, 2009) are used mainly to analyse the structure of work domain and work tasks, initially through the form of means-end hierarchy. This leads to an analysis of cognitive processes (Reising & Sanderson, 2002) and strategies. Sanderson et al. (1999) reviewed the potential of CWA to inform all stages of the system life-cycle, including requirements, specification, design, simulation, evaluation, implementation, operator training, and maintenance.

CWA is used to structure common observational methods that provide useful material about human information behaviour, often in textual narratives. Nirula and Woodruff (2006) considered CWA as an *"integral precursor to any design iteration"*. CWA has been applied to system design, although most works have focused on the initial stages of the CWA framework, such as Work Domain Analysis (WDA) and Abstraction Hierarchy (AH) (Groppe et al., 2009; Reising & Sanderson, 2002; Janzen & Vicente, 1998; Golightly et al., 2011). For example, Groppe et al., (2009) assessed pilots' operational information requirements during airport collaborative decision making, using WDA. Reising and Sanderson (2002) formalised an ecological user interface design approach with an AH. Janzen and Vicente (1998) applied the AH to quantify human attention allocation within various levels of the hierarchy in a thermal-hydraulic process simulation.

Nirula and Woodruff (2006) conducted a full CWA to understand the design implications of ubiquitous computing in schools. In order to fulfil the requirements of the stages, they started with an observational study, followed by interviews and focused field observations, which gave an indication of the activities in the environment. Verbal protocol with end-users after they had used the interfaces, together with the results obtained from observational studies, were analysed to capture the strategies adopted by users. In this PhD, CWA was used to guide the understanding of railway alarm handling, decision ladders were utilised to facilitate cognitive transformation analysis.

### *4.5.1. Decision Ladder*

The Decision Ladder is a method that was developed for modelling cognitive activity throughout control tasks (Rasmussen, 1986). The Decision Ladder aims to identify various information processing modes. In dynamic socio-technical environments the shift between these modes is difficult (functional fixation). These modes can be categorised into two groups: 1- information processing activities, and 2- the state of knowledge resulting from information processing. This information has been shown with different symbols, to enable predictable design.

Rasmussen (1986) also listed the sequential levels of information processing while the operator is making a decision, as below:

- Detect the need for intervention
- Observe the essential data required for decision making
- Analyse the available evidence
- Evaluate the possible consequences
- Select the target state
- Select the appropriate task, depending on the available resources
- Select the procedure with the least effort required to conduct the task

Rasmussen's Decision Ladder (1986) gives designers a very good overview of various processing modes. It is a template which frames potential cognitive states and processes within a standardised model of cognition: attention, interpretation, evaluation and decision-making, planning and action.

The Decision Ladder can also represent short-cuts through cognitive processing, known as shunts and leaps, which is the kind of cognitive activity that is typical of expert performance. It also enables the impact of automation on cognitive processing to be predicted by demonstrating the impact of interventions on specific cognitive sequences. In most real life decision making situations, these phases do not actually occur or, at least, not in such a structured way. It is mainly a framework to present the logical sequence of information processing. Some argue that this model is too reductionist, and cannot reflect the dynamic work environment (Hoc & Amalberti, 1995) but, since it is very useful in representing the sequence of information processes and states, it has been adopted along with other methods (e.g. verbal protocol).

## *4.6. Participatory observation*

Participatory observation was an underlying approach throughout this research. It is mainly rooted and practised in social science. By allowing the researcher to merge in the domain of the study, observational biases inherited from other methods are minimised. This facilitates a meta-understanding of the domain under study by changing the role of the researcher from a mere observer to an active member within that domain (Robson, 2011; Schensul, Schensul, & Lecompte, 1999). In this PhD, participatory observation involved the researcher as an active member of the Ergonomics team in NR.

As mentioned in the second chapter of this thesis, the railway is an intertwined organisation; there are many different sectors, each with different cultural attitudes and priorities. Participant observation enabled the researcher to become familiar with this culture, as well as achieving a certain level of trustworthiness and engagement within the organisation, concerning various subject matters (Robson, 2011).

As an understanding of the domain depends on the researcher's subjective interpretation, the period of participant observation should be long enough for the researcher's subjective comprehension to be drawn from experience (Robson, 2011). To achieve this, during this PhD programme (approximately three years) the researcher was an active member of the Ergonomics Team, as well as being involved in a number of projects whilst conducting her PhD. Projects with some relevance to this PhD study are briefly discussed below.

The researcher was a member of the Alarm Strategy Working Grouping within the company. This group has been established in NR to develop an integrated understanding of alarm principles: creation, routing, presentation and lifecycle management of alarm data, in both operational and asset management sectors. Members of this group include senior managers within signalling and telecommunication, operational strategy, asset management, electrical control, intelligent infrastructure and ergonomics. During the monthly meetings, the researcher has been able to establish an overview of alarm systems in various control settings as well as their priorities and potential challenges.

One of the major challenges facing the efficiency of railway maintenance is inconsistency of technical equipment available to operators with similar roles and responsibilities. To overcome this issue, NR commissioned the Ergonomics team to study the feasibility of a standardisation of the systems within the ECR setting. The researcher was supporting a senior ergonomist in this project. This project involved the development of an in-depth understanding of current practices carried out by ECR operators, the time required for each of their tasks, as well as issues associated with teamwork and collaboration in and between control room environments.

Within the ECR standardisation project, the researcher was involved with data collection, as well as the analysis of findings in relation to its aims. A number of ECRs were visited as part of this study, including Lewisham ECR near London. This project helped the researcher to obtain a broad understanding of ECR settings in railways. More importantly, the researcher's familiarity with this control room and the rapport established between the researcher and the operators, were reasons for choosing this ECR for some of the studies conducted as part of this PhD.

In addition, the Operational strategy team in NR commissioned the Ergonomics Team to develop a workload assessment toolkit for railway ECR. The researcher led this project. This study was followed by the ECR standardisation study mentioned earlier. It required an in-depth understanding of various tasks conducted within an ECR and of the factors that can influence the complexity of various tasks. This is an ongoing project; the researcher has used her expertise developed through other projects in the same domain, as well as the theoretical understanding captured as part of her research, in order to derive the ECR workload assessment toolkit.

## *4.7. Chapter summary*

This chapter has reported on the methodological approaches utilised throughout this PhD. A combination of qualitative and quantitative methods was used in order to explore and investigate various aspects of the rail domain in the interest of the objectives of this PhD. Looking at the paradigms and research questions mentioned in previous chapters, it became clear that some methodological approaches had to address the domain qualitatively in order to help explore and understand intelligent infrastructure. Hence, mainly interview studies and observations were used. When a number of tasks were selected as representative of intelligent infrastructure systems, more targeted research questions were investigated through a combination of observation studies, verbal protocols and video recordings structured in forms of CWA or CDM. A focused and isolated hypothesis was formed with regard to the optimal level of information required and a small scale lab-based study was conducted to examine the trend suggested by the hypothesis. Indeed, the benefit of using the lab-based study is not in the significant differences, but in the capacity to apply field studies and qualitative approaches to the development of a hypothesis concerning information relevancy and sufficiency for a complex system, such as an intelligent infrastructure system.

# 5. Understanding intelligent infrastructure within Network Rail

In order to develop a thorough understanding of railway intelligent infrastructure it is necessary to know its functionalities and its potential users. However, at the time of starting this PhD, actual intelligent infrastructure applications did not exist in Network Rail (NR).This is despite the fact that they have been launched and examined as part of a long term project over two control periods (each control period is 5 years). Although a number of strategic views were developed, the organisation was unclear about the functionalities, main users and potential interfaces.

Knowing that there had been an intelligent infrastructure project in NR since 2006, it was assumed that a detailed understanding would be available both from members of the intelligent infrastructure and asset management teams as well as the company's documentation. However, a review of NR documentation, reported as the familiarisation process in Section5 5.1, suggested otherwise. It was apparent that within the company the notion of intelligent infrastructure was an ill-defined and vague concept. Despite a number of policy and future planning documents identifying various phases of the project from a technical viewpoint, little thought appeared to have been given to the users and the functions of these systems and how they could co-exist with other control room or on-track tasks.

In order to better understand the scope, policies, roles, equipment, challenges and relevant human factors issues for rail intelligent infrastructure, a series of studies was conducted by the author. These were designed to meet the first objective of this PhD study:

I. Develop a data processing framework that guide and support effective implementation of railway intelligent infrastructure from a human factors perspective

This chapter starts with the familiarisation process that was conducted prior to the interview study. This is followed by a description of the methods of data collection and data analysis as well as a justification of the selected coding schemes used for the analysis of the interview transcriptions. Then the findings of the interview study are reported, subsequently integrated into a data processing framework. A third study is then reported working with railway SMEs to verify the content and sequence of the data processing framework when performing a task similar to those of future railway intelligent infrastructure. These studies are then discussed and the chapter is summarised.

## *5.1. Familiarisation process*

A series of familiarisation activities were conducted in order to accelerate the researcher's understanding of the overall concept and potential users of a rail intelligent infrastructure system. These activities comprised a number of exploratory interviews, attendance at a one day workshop held by NR as well as a review of the company's (NR) documentation regarding the intelligent infrastructure project. Findings from these activities led to the design and implementation of the interview study (Section 5.2); preliminary findings captured through the familiarisation process are presented.

### *5.1.1. Review of Network Rail documentation*

The idea of intelligent infrastructure systems in NR was initiated in 2006, due to the need for change in the maintenance regime. In 2007, a good practice guide was produced by NR, Metronet, Tube Lines and the Railway Industry Association (Network Rail et al., 2007) to facilitate an understanding of the concept of intelligent infrastructure.

The objective of intelligent infrastructure, as presented in the good practice guide is: *'to deliver improvement by application of intelligence through the infrastructure design and maintenance cycle'* (Network Rail et al., 2007, p.3). Intelligent infrastructure was seen to be about measuring and collecting integrated information about the condition of railway assets to improve maintenance efficiencies, enhance safety and operational performance, leading to a more affordable railway.

The intelligent infrastructure project was planned as a railway enhancement project rather than an operational one. Therefore, the need to assign a priority group to the project was not felt until late 2008.

Moreover, as a pragmatic approach is required for the implementation of such a large scale project, the company should have devised a strategy to implement it in stages. The strategy report produced by the intelligent infrastructure team in December 2009 (Network Rail, 2009) identified the main departments associated with these systems as asset management, operations & planning and regulations. This confirms the broad spectrum of functionalities that needed to be addressed by the project.

Monitoring of the infrastructure in a systematic and effective way is the first enabler of developing intelligent infrastructure systems and includes: infrastructure monitoring train, infrastructure monitoring infrastructure, train monitoring infrastructure and train monitoring train. Figure 5-1, taken from Network Rail's strategy report, shows this scoping. The quadrant with the blue box around it (infrastructure monitoring infrastructure) is identified as a higher priority than the infrastructure monitoring train or train monitoring infrastructure. The fourth quadrant (train monitoring train) is completely out of the scope of this PhD as it is the train operating companies' responsibility; at the time of PhD programme, the train monitoring train had not been included within the scope of the company project.

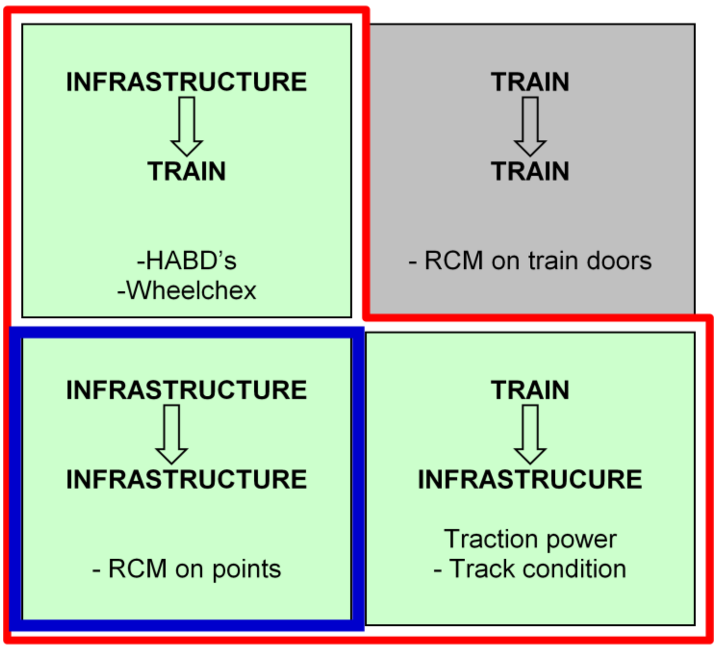



**FIGURE 5-1: INTELLIGENT INFRASTRUCTURE SCOPE QUADRANTS TAKEN FROM NETWORK RAIL, 2009**

In order to guide the project development phases, NR is using ISO 13374 standard for remote condition monitoring (Figure 5-2)(Network Rail, 2009). NR has used ISO 13374 – Parts 1 and 2: condition monitoring and diagnostics of machines-data processing, communication and presentation- to inform various development stages. The model proposed in this standard consists of six stages: 1- data acquisition, 2- data manipulation, 3- state detection, 4- health assessment 5- prognosis assessment and 6- advice generation.

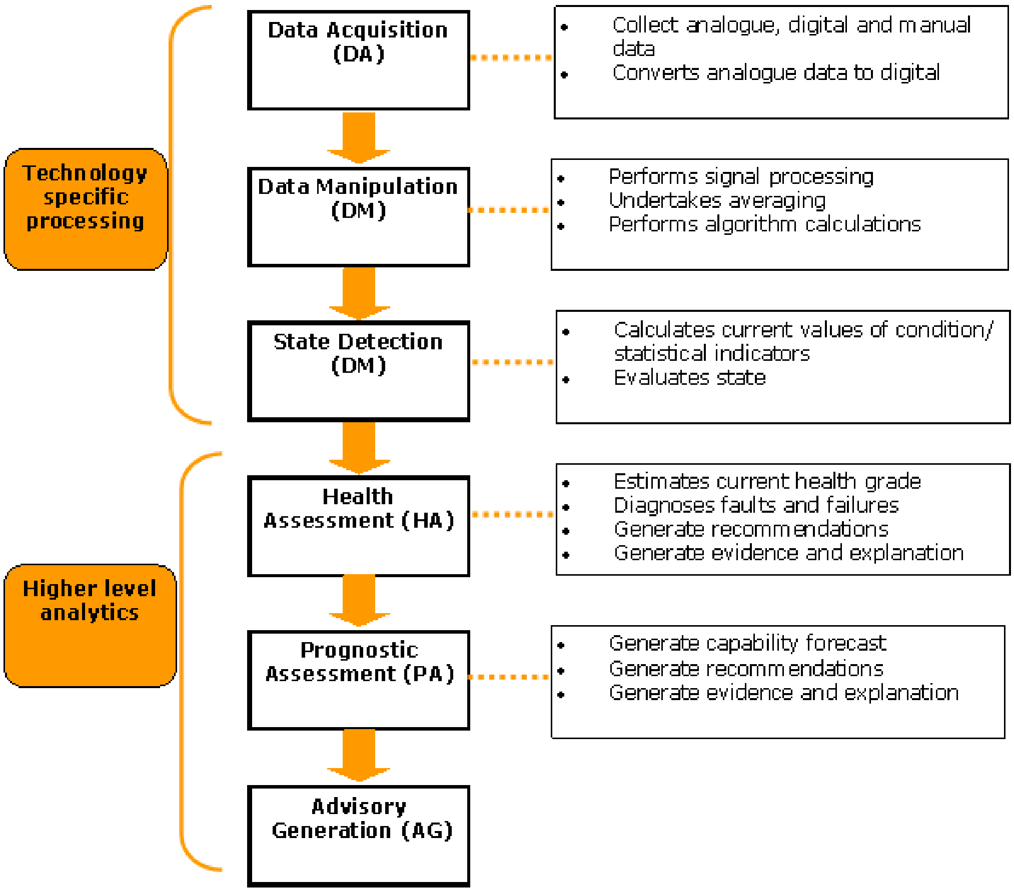



**FIGURE 5-2: ISO 13374 STRATEGIC FRAMEWORK TAKEN FROM NETWORK RAIL, 2009**

A broad range of remote condition monitoring (RCM) systems is now being used by NR all around the country. The first phase was to narrow the scope of the project geographically, with approximately 2000 locations selected.

Assets selected for this phase of the study are those with higher impact in terms of safety and minutes of delay if a failure occurs.

The Edinburgh-Glasgow route was selected to pilot the implementation phase of the NR intelligent infrastructure project. The aims of this phase were to integrate and improve current condition monitoring equipment, develop an interface that can collate and present the data collected from the available RCM systems and to assess the feasibility of an intelligent infrastructure system within the company's current business process.

Four critical assets (in the company, referred to as golden assets) were the focus of the first phase of the pilot. These include 130 point ends, 13 DC (Direct Current) Track Circuits, 24 Signalling Power Supply Cables and the Edinburgh and Cowlairs Interlocking. The area under coverage and a number of golden assets monitored are shown in Figure 5-3 below.

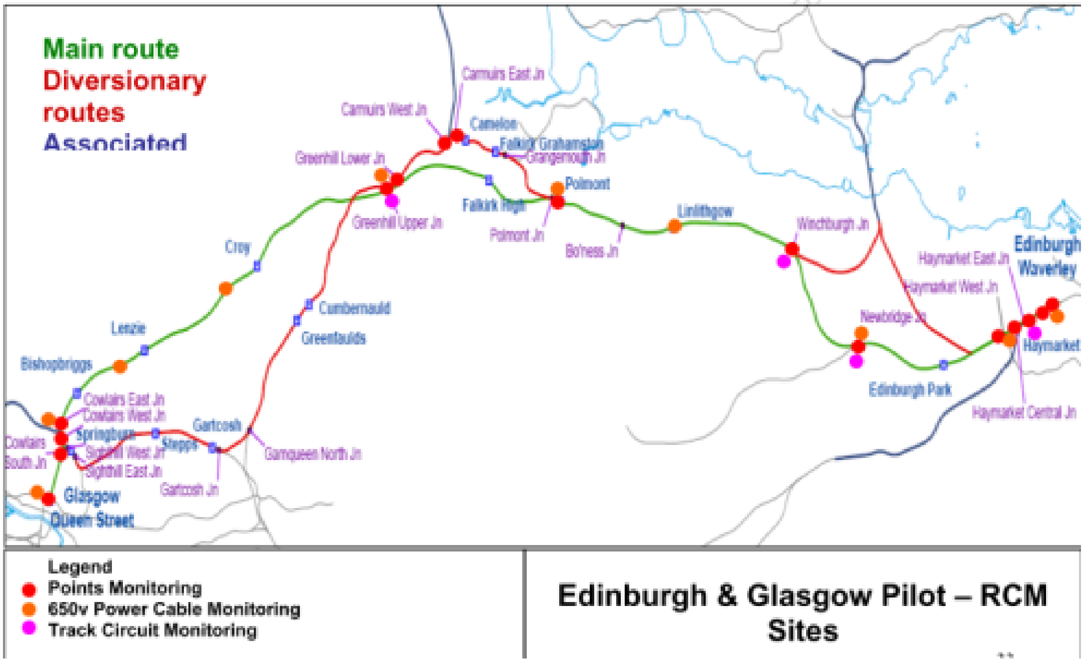



**FIGURE 5-3: EDINBURGH & GLASGOW PILOT MAP, TAKEN FROM NETWORK RAIL, 2009**

Although there are detailed descriptions regarding the technical aspects of this project - the interface as well as the RCM equipment that has to be fitted on the assets - little was known about the business process and the effect of change on the existing maintenance regime.

### *5.1.2. Exploratory interviews*

In October 2008, the researcher interviewed four senior employees of NR (Table 5-1). These were unstructured interviews and participants were asked to describe their understanding of railway intelligent infrastructure.

The selection of interviewees for this part of the study was based on the researcher's naive assumption that intelligent infrastructure was a well defined concept. Therefore, it was believed that an opportunistic sample would potentially provide enough information to guide understanding. However, the lack of understanding of the domain around the company revealed through these exploratory interviews led to a more detailed interview study (Section 5.2).

Four senior employees who were involved with the project were interviewed, one system developer, two ergonomists and one electrical control specialist. These interviewees were asked to discuss the concept of intelligent infrastructure in relation to their area of expertise.

Findings from these interviews revealed that intelligent infrastructure seems to have been seen as a solution to most of the problems currently facing railway performance. In the eyes of these interviewees, intelligent infrastructure is something of a superhero! All participants were aware of its potential benefits and knew about the project to an extent but, ironically, were unable to give a consistent definition of intelligent infrastructure, although they all agreed on the strong connection between RCM and intelligent infrastructure. Furthermore, information management and user engagement were noted as two of the challenges for the implementation of the project.

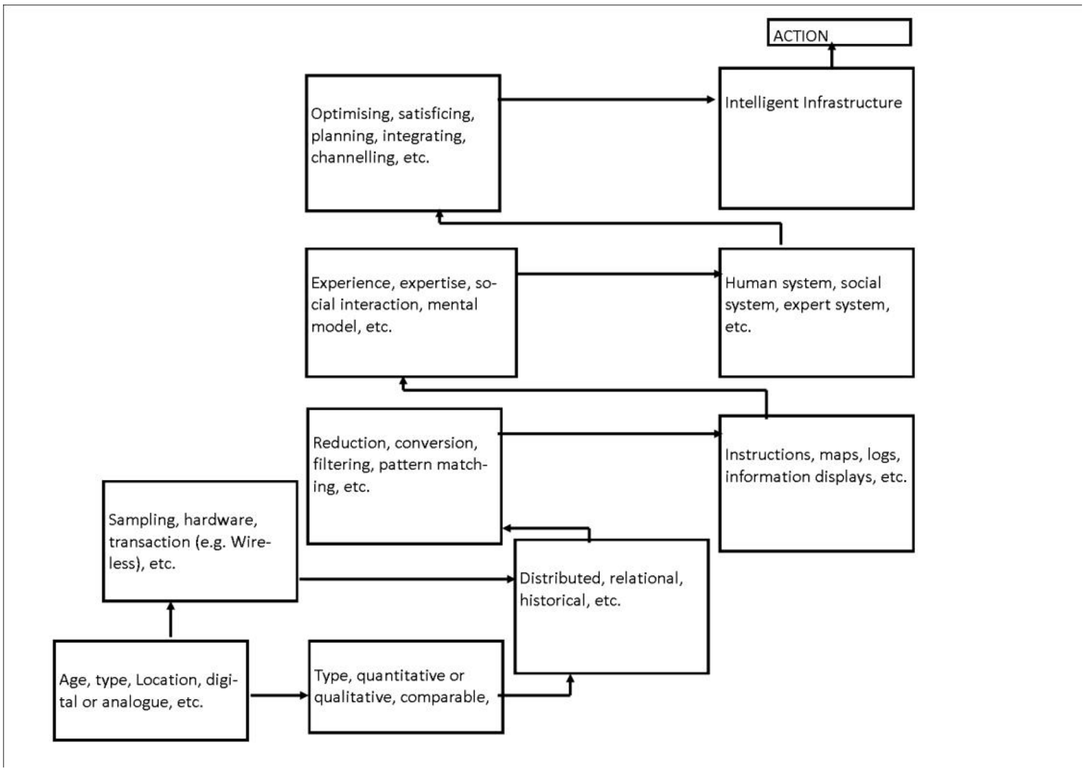
**TABLE 5-1: FAMILIARISATION INTERVIEWS**

| Number of interviewees | Role of interviewees | Duration (per interviewee) |
|---|---|---|
| 1 | Senior system developer | 2Xhours |
| 2 | Senior ergonomist | 1Xhour |
| 1 | Head of electrical control | 1Xhour |

### *5.1.3. Workshop*

In November 2008, NR held a one day workshop to assess the functionality of the semi-functional prototype developed for the Edinburgh-Glasgow pilot. 18 NR employees, senior managers and engineers, whose roles would be affected by intelligent infrastructure systems, as well as system developers from the contracted company, attended this workshop. The author attended the workshop to represent Network Rail's Ergonomics Team.

Issues discussed during this workshop covered the scope and functionalities of the intelligent infrastructure system. Attendance at this workshop provided the basis for a subsequent interviewing phase and was the starting point of sampling for interview participants. At this stage, an early version of the intelligent infrastructure data processing framework (Figure 5-4) was drafted and investigated throughout the semi-structured interview study. An alternative route would have been to wait and construct the framework only on the basis of all the interview material from the full sample, but the availability of such a senior set of interviewees meant that a decision was taken to develop an early version which would be commented on in subsequent interviews.




**5-4: AN EARLY VERSION OF THE INTELLIGENT INFRASTRUCTURE FRAMEWORK DRAFTED AFTER THE WORKSHOP**

This framework describes the dataflow in the potential intelligent infrastructure system. Intelligent infrastructure has to collect and then collate data from various assets (point machines, level crossings, etc.) through existing and new sensors. These data would then be collated and reconstructed in a meaningful way to show key symptoms about a particular asset and to generate an alarm when there is a high chance of that asset failing in the near future. The alarms are then analysed and handled. The ultimate goal of intelligent infrastructure appears to be the ability to assist operators in making more informed decisions and to feed the expertise back into the system.

## *5.2. Semi-structured interviews*

The initial research required to inform the objectives of this PhD study revealed a lack of conceptual understanding in the company about intelligent infrastructure. Therefore, a more comprehensive semi-structured interview study was conducted for a deeper exploration. Although individual interviewees did not have a consistent definition of the concept, data collected from the sample did help an understanding of the potential functionalities, roles, benefits, and human factors issues involved in railway intelligent infrastructure. 20 semi-structured interviews were conducted between November 2009 and January 2010 with rail staff who were knowledgeable about, or were potential users of, intelligent infrastructure and its information systems.

Given the poor company documentation, paucity of thinking about fundamental systems and the lack of real current implementation projects, such an interview study, whilst not ideal, did seem to be the best route to advance understanding and to start to structure the data flows and consequent human factors concerns.

### *5.2.1. Participants*

The first interviewees were chosen on the basis of the suggestions of experts who attended the workshop (Section 5.1.3) as well the recommendation of Network Rail’s Director of Engineering at the time; snowball sampling was used afterwards. Four participants were from companies other than NR and 16 participants were from various departments in NR (Table 5-2).

**TABLE 5-2: PARTICIPANTS OF THE SEMI-STRUCTURED INTERVIEW STUDY**

| No | Company | Role /Department | Note |
|---|---|---|---|
| 1 | High Speed Trains 2(HS2) | Director | HS2 is responsible for developing high speed rail; those at HS2 have a modern approach to traditional railway problems. The director of HS2 was Network Rail’s Chief Engineer when the intelligent infrastructure project was first launched in 2006. His view of the original understanding of the system and the musts, wants and hopes regarding the system provided an interesting insight into the challenges of implementing the project |

| | | | |
|---|---|---|---|
| 3 | Invensys | Research & Development | Invensys was the developer contracted by Network Rail to design and build the intelligent infrastructure interface. Their views were captured since they, as developers, should have a clear idea of the overall functionality of the system. |
| 1 | Network Rail | Director of Railway Systems and Vehicle Engineering | Application of remote condition monitoring systems has been directed and led by railway systems and vehicle engineering. The director of this department has up to date information regarding available RCM equipment, its implications and how it would shape a successful intelligent infrastructure system. |
| 1 | Network Rail | Intelligent infrastructure project manager | The aim of the intelligent infrastructure team within the asset management section is to design, develop and evaluate the intelligent infrastructure pilot and assess the feasibility of expanding this project to a national level. |
| 2 | Network Rail | Ergonomics | An overview of the findings from the familiarisation exercises revealed a lack of understanding of human factor issues. Two senior members of the Ergonomics team who were specialised in alarms and interface development were interviewed to capture the potential human factors challenges. |
| 4 | Network Rail | Information management | The information management team in Network Rail has responsibility to develop system and information requirements for the intelligent infrastructure interface. Views of four members were captured to understand designers' and developers' views of the system. |
| 1 | Network Rail | Signal and Telecommunication | Signalling and telecommunication is responsible for transferring operational data to signal boxes and fixing the failures to ensure signallers will receive correct information to run the service. Although intelligent infrastructure does not directly affect their role, the use of RCM equipment can potentially enhance their |

| | | | |
|---|---|---|---|
| | | | performance. |
| 2 | Network Rail | Corporate development | This department has responsibility to transform and improve the running of the railway Despite the vagueness of such a task, intelligent infrastructure nicely sits in this department; issues like business change and organisational challenges will be of interest to this department. |
| 1 | Network Rail | Infrastructure investment | This department aims to ensure that the infrastructure is kept in optimum condition with regard to cost-benefit models. Intelligent infrastructure is not an immediate operational priority and the savings will emerge in time. |
| 1 | Network Rail | Operation and customer service | Although intelligent infrastructure's current scope does not include issues directly affecting customer service, such as passenger information, ticketing information, etc, the views of the Director of Operations and Customer Service were captured in relation to future policies and various departments' expectations of the way this project is going to affect them. |
| 1 | Network Rail | Maintenance control centre | Currently, maintenance control centres are the main area of work for the intelligent infrastructure system. An interview with a maintenance technician in a control centre aimed to capture his view and understanding of the intelligent infrastructure. This was to explore the user's perspective of the system. |
| 1 | Network Rail | Scope and development | This department is responsible for organising and structuring future policies in the company, depending on the available constraints and demands. |
| 1 | Network Rail | Train technology | Currently much train borne remote condition monitoring equipment (e.g. LIVE train) exists. These would constitute part of the larger scope of intelligent infrastructure project. |

### *5.2.2. Apparatus*

Apparatus used for this study comprised an Olympus™ digital voice recorder to record the interviews and Nvivo ™ software used for the data analysis. An information sheet was designed to guide the participants throughout the interviews (Appendix 12.1).

### *5.2.3. Design*

Information sheets were sent to participants prior to the study to introduce it and to provide a set of questions to be asked during the study. These questions were formed during the familiarisation process (Section 5.1) and were confirmed by Network Rail's Chief of Engineering at the time. They are listed below:

1. What do you understand to be the future of Intelligent Infrastructure for Network Rail?
2. What do you think is the purpose of Intelligent Infrastructure?
3. Do you consider RCM as a type of intelligent infrastructure?
4. What does 'remote' in RCM mean?
5. What does 'intelligent' in intelligent infrastructure mean?
6. How will the information required for an intelligent infrastructure be captured?
7. What do you think are the main functions of an intelligent infrastructure information display?
8. Which control rooms need to be in direct contact with intelligent infrastructure systems?
9. What are the challenges for designing an effective intelligent infrastructure system?
10. What are the main roles and responsibilities of operators working with intelligent infrastructure systems?

Participants were not limited to responses to the questions presented to them. Depending on their expertise and domain of work, some questions were elaborated, whereas some remained unexplored. For example, a member of the Information Management team would not know much about question '10', which refers to potential roles and responsibilities of future railway intelligent infrastructure systems.

## *5.3. Analysis*

Twenty hours of interviews were transcribed (approximately 55,000 words) and analysed. Thematic content analysis (Miles & Huberman, 1994; Neale & Nichols, 2001) was used for this purpose. An example of an interview, along with one of the coding schemes used, is shown in Appendix 12.2.

Thematic content analysis provides an in-depth understanding of the domain from both qualitative and quantitative perspectives. Apart from data collection, which was described earlier in this chapter, four stages are needed to conduct thematic content analysis: data collation, theme definition and classification, higher order theme selection, and presentation of a classification matrix (Figure 5-5).

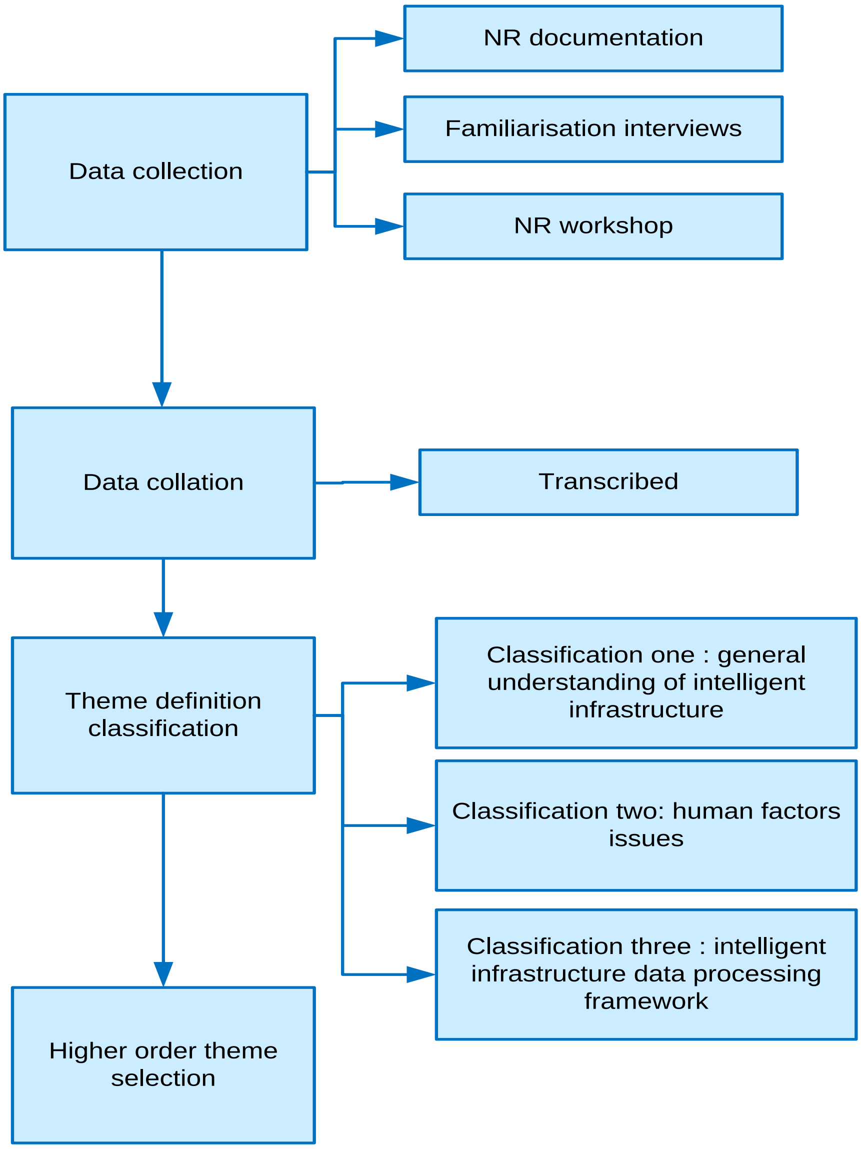



**FIGURE 5-5: THEMATIC CONTENT ANALYSIS OF THE INTERVIEW STUDY**

In order to understand intelligent infrastructure, three questions were raised. These questions guided the classification of the themes which were investigated throughout the interview analysis.

1- What is railway intelligent infrastructure?

Following the early familiarisation stage, there was no apparent consistent understanding of intelligent infrastructure within railways, therefore the first theme of the transcribed interviews was designed to provide a general understanding of intelligent infrastructure. The interviewees were asked to describe what they think intelligent infrastructure is, to consider its use to them and its potential roles. Since the participants were selected to represent key departments involved with the project, it was reasonable to assume that the collation of their understanding would give an indication of the definition of railway intelligent infrastructure.

2- What are the human factor issues associated with it?

Lyons and Urry (2006) recommended key features that need to be understood and put in place for a successful transport intelligent infrastructure system. These include: society and social practices (economic prosperity, social cohesion, and environmental sustainability), governance (market force, public policy and politics), systems (land-use systems, social system, and transport system), transport (travel and traffic) and individuals. Despite greater levels of automated data collection and analysis, people are still at the core of these system features which means good design and implementation requires explicit definition of the key human factors and the systems requirements they pose. Therefore, the second theme was aimed to identify the human factor issues associated with this project.

One of the questions on the information sheet of the interview study asked about potential challenges of the project. This was designed mainly to encourage participants to talk about different problems along with the development and implementation of the project. These challenges and problems were then interpreted in the light of potential human factor issues.

3- What is the data processing associated with railway intelligent infrastructure systems?

Guiding the knowledge and information required for better implementation of a railway intelligent infrastructure system was one of the objectives of this PhD study. In doing so, it was important to understand the flow of information and stages of work for hypothetical intelligent infrastructure tasks. A third classification was established to analyse the interview transcripts in the form of various pieces of data attended to by operators and the flow of information during a hypothetical intelligent infrastructure process. This led to assessing and refining the data processing framework that had been drafted during the workshop.

### *5.3.1. Data collation*

The transcribed interviews were presented on a Microsoft™ Excel™ spreadsheet. Columns of this spreadsheet represent participants' comments focusing on similar concepts (technology, definition, challenges, etc.). Rows of the spreadsheet show the number of participants commenting on those similar concepts; an example extract from the spreadsheet is shown in Figure 5-6.

The researcher's choice of headings for the columns on the spreadsheet was simply to provide a starting point for the analysis and this was modified throughout a number of iterations. Moreover, a member of the University Of Nottingham's Human Factors Research Group with good railway knowledge was asked to review these headings and comment on them.

| Benefit | Current RCM situation | Future plans | Functions | Cognitive functions | Challenge |
|---|---|---|---|---|---|
| We have drawn a conceptual benefit model with two axes benefit and time. Time has an important factor in the context of intelligent infrastructure project | At the moment the how we look after infrastructure is completely passive, something breaks on the track, you as a technician get alerted and fix it | so we need to specify exactly what data we need | This is to identify what state the asset is and it gives binary measures, is it working normally or is it working abnormally | For example if the data shown suggest that you have four days to fix this problem but maybe the operator says I am in the area now and this is a critical asset, a golden asset and it can fail and it is better to fix it as soon as possible. Here scheduling and prioritising is very important to consider | The problem of this rath acquisition is generatin amount of data |
| , we can't afford delays | This is being done to some extent at the moment. For example we do measure point heating and this data is being collected every second, and the time interval setup on it is chosen due to | part of the project is to collect the right amount of data at the right interval and also on the right asset | This is a diagnostic position where we can diagnose from the data we have and say what is wrong with it. Somewhere in here between these two steps you need to inform people somehow | | For example on a point measure various things to switch, force, temper hydraulic pressure, etc, need all of these inform |
| So the idea is to get the right information to the right group of people and stop bothering others. | currently this is the stage where network rail is. We have remote condition measurement systems places on various assets and we can determine whether the asset is operating in its normal condition or an abnormal condition. | A project in Network Rail entitled "Network Criticality" is responsible for this assignment and they have developed a map of critical assets which is assists intelligent infrastructure project team with identification of critical assets | Two types of actions need to be considered: interim corrective action and permanent corrective action. Interim corrective action refers to when the operator has to fix the problem quickly, for example if an error occurs and it is going to cause delay the maintenance team might decide to fix the error straight away, two options are available | | The risk in handling the intelligently is that we a up with huge amount o alerts being raised on d categories with differen and the problem is how present that data to ope that we get the right rea |
| The main objective is to keep the cost and waste of data services down by just collecting the key pieces of data | Today in most cases we just have an alarm and alert approach. Local operators set the limits for the assets in their area and when an abnormality occurs it will | one of the requirements of the intelligent infrastructure projects is to align these various legacy systems | Permanent corrective action: this might involve contacting suppliers with an enhanced set of information to be provided to a more strategic group | | Partially this is due to tl |

**FIGURE 5-6: EXAMPLE EXTRACT FROM THE SPREADSHEET USED FOR EARLY STAGES OF DATA COLLATION**

### *5.3.2. Theme definition classification*

The column headings and the participants' comments guided the analysis of themes. The original headings of the spreadsheet, as shown in Figure 5-6, were definition, purpose, benefit, current RCM systems, future RCM plans, functions, cognitive functions, challenges, roles and responsibilities, intelligence, human factors issues and system distribution. To simplify the analysis, comments related to 'purpose' and 'definition' and comments related to 'functions' and 'cognitive functions', were combined.

The headings shown in Figure 5-6 mainly classified the questions asked on the information sheet and aims to facilitate the analysis of themes directed towards the objectives of the PhD. The rationale for selecting the theme classifications is mentioned in section 5.3; this led to three rounds of coding, as described below. Higher order themes were then selected, depending on the classification conducted in the previous stage. Three higher order themes were selected for the purpose of this study:

- General understanding of intelligent infrastructure systems
- Human factors issues
- Data processing framework

The first round of coding interview transcripts started with a set of classifications but evolved as new concepts emerged. This was focused on developing a general understanding of railway intelligent infrastructure. Issues associated with definitions, benefits, roles and functionalities of railway intelligent infrastructure were explored.

The second round of coding addressed human factor issues, with a focus on the following: automation, decision making, human machine interaction, monitoring, organisational culture, planning, safety and human reliability, situation awareness, system reliability, user engagement, and workload.

Finally, it was important to capture participants' views about the data processing of the future railway intelligent infrastructure. The transcripts were therefore re-reviewed for the third round, this time with a focus on the work and information flow of current RCM systems in use and those for potential intelligent infrastructure systems of the future. The headings used to organise this review were as follows: asset, sensor, data, data processing, database, information, information development, knowledge, knowledge integration, and intelligence. All of the headings used in the three rounds of coding were commented on by two members of the Ergonomics Team, and later verified by railway electrical control room operators (Section 5.5).

Consequently, every interview transcription was coded three times. Nvivo ™ was used to organise these codes and facilitate the merging of different groups of codes. Therefore, it was made possible to specify which human factor issues are associated with which functions within the railway intelligent infrastructure.

## *5.4. Findings of the semi-structured interviews*

Findings of the interview study are presented in four sections. The first three report the specific findings associated with the coding of definition of intelligent infrastructure, human factors issues and data processing. The fourth section synthesises and integrates the findings to form a data processing framework.

### *5.4.1. Railway intelligent infrastructure*

The first round of coding explored the definition and functionality of intelligent infrastructure from potential users' point of view. The findings will be influenced by interviewees' assumptions of what they believe a hypothetical intelligent infrastructure should look like. Intelligent infrastructure is defined as a means of support to more reliable and effective railway maintenance. However, the extent of its capabilities varies in the eyes of different users. Maintenance staff (maintenance control centre, railway engineering) viewed the systems as somewhat more advanced RCM systems, whereas members from the infrastructure investment and corporate development teams seemed to view intelligent infrastructure as pioneering technology that could solve "all" railway problems. The truth probably resides somewhere between these two extremes.

Figure 5-7 shows the coding associated with the general understanding of railway intelligent infrastructure. The percentage of participants' comments referring to each of the themes is also shown. These percentages might represent the interviewee's level of concern or familiarity with various themes. For example, the two highest percentages are associated with the benefits of intelligent infrastructure systems and the system distributions; the former is a potential advantage and the latter is more of a concern.

Intelligent infrastructure uses technology to provide data pertinent to asset condition, thus providing a decision aid. Its main focus is on the provision of information about the asset to support real time condition monitoring as well as high level asset management.

The benefits are targeted at safety and efficiency. These comprise more informed scheduling for the maintenance regime, producing reductions in the costs associated with poor maintenance including regulator financial fines resulting from delays.

The intelligence can either be built into the asset or can lie in the interpretation of the information captured from that asset. This varies between asset types. For example, when assessing the condition of points, enough information can be obtained from the asset on the track to enable the full understanding required for diagnosis and even prognosis of a failure.

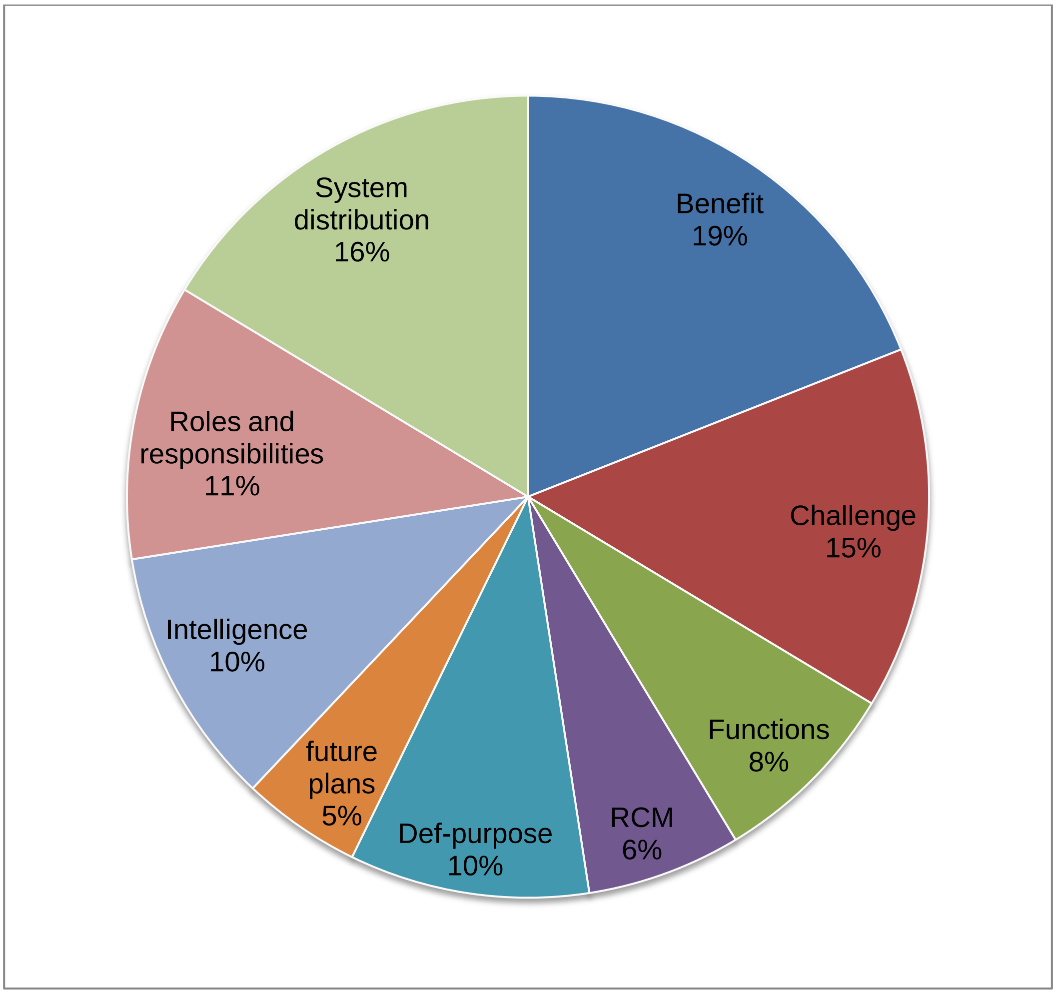



**FIGURE 5-7: INTERVIEW ANALYSIS: GENERAL UNDERSTANDING OF RAILWAY INTELLIGENT INFRASTRUCTURE**

In terms of roles and responsibilities, distribution of the intelligent infrastructure can be layered and distributed both centrally and locally. Therefore, various roles with different demands and priorities are involved. Three main roles were identified as control room operators, track workers and strategic analysts.

Control room operators are responsible for responding instantly to high priority alarms. They are based in local control rooms, which are designed to support an operational railway by conducting temporary corrective actions. Track workers get the information from control room operators regarding a potential failure and then feed back information about the condition of that asset. Strategic analysts receive diagnostic reports from control room operators in order to make decisions about future plans, speed restrictions, maintenance regimes, etc. and feed that information back to both control room operators and track workers. This higher level of analysis is conducted in central control locations. They are responsible for informing future policy and strategy towards adjustments, metrics, trends and other parameters to support permanent corrective actions.

The main functions of operators interacting with railway intelligent infrastructure systems are monitoring, problem solving, alarm handling, fault finding, diagnosis, planning and optimization. Operators are informed of a defect through an alarm or an alert; this is combined with the operator's knowledge of the environment and the level of risk associated with that fault in choosing an optimum corrective action.

Interviewees' knowledge of existing RCM systems and their assumptions about the proposed intelligent infrastructure system led to the identification of a number of challenges. These can be categorised into three groups: technical, business change and corporate development.

Technical challenges were mainly noted by the members of Information Management team (who are responsible for designing and managing the development of the pilot) and are as follows:

- Current RCM systems are designed to monitor fixed assets. As part of the wider scope of intelligent infrastructure it is important to be able to collect and monitor data about dynamic assets (e.g. trains).
- Geographical Positioning Systems (GPS) technologies are very advanced. However, in order to detect point machines centimetres away from each other, they need to be even more accurate.
- Algorithms are required to derive predictive intelligence for the decision makers.

Almost all of the participants agreed that, although these challenges are important as in any other new project, they are manageable and will not determine the success or failure of the project. Challenges of concern to business change or corporate development, however, could have a fundamental impact on the project, including:

- User engagement; there is no value in a perfect system if no one uses it. An appropriate level of engagement and sense of ownership needs to be built.
- Standardisation of the approach and the process; this is mainly to collect the information consistently and to have a similar process to handle it.
- Different groups in the company have different performance priorities, with a particular conflict between running trains and carrying out engineering work.
- Good understanding of an asset's behaviour in different contexts is required.
- Selection of critical assets and sufficient metrics should enable diagnosis without risking safety.
- The extent of safety criticality assurance needs to be identified.

### *5.4.2. Human Factors issues*

The second round of coding analysed the interview transcriptions in terms of the human factors associated with the intelligent infrastructure systems. Some of these issues were grounded in the familiarisation exercise and others emerged from the semi-structured interview study.

The relevant human factor issues identified during the interviews are presented in Figure 5-8. These categories are not mutually exclusive and often overlap theoretically and in practice. As an illustration of this, a number of issues have been represented as a scenario below, with relevant human factors issues underlined in parentheses. Note must be taken that this scenario is just to show an example of the most relevant human factors issues and, in most of these cases, more than one code is applicable. This emphasises the interdependency and complex nature of intelligent infrastructure systems.

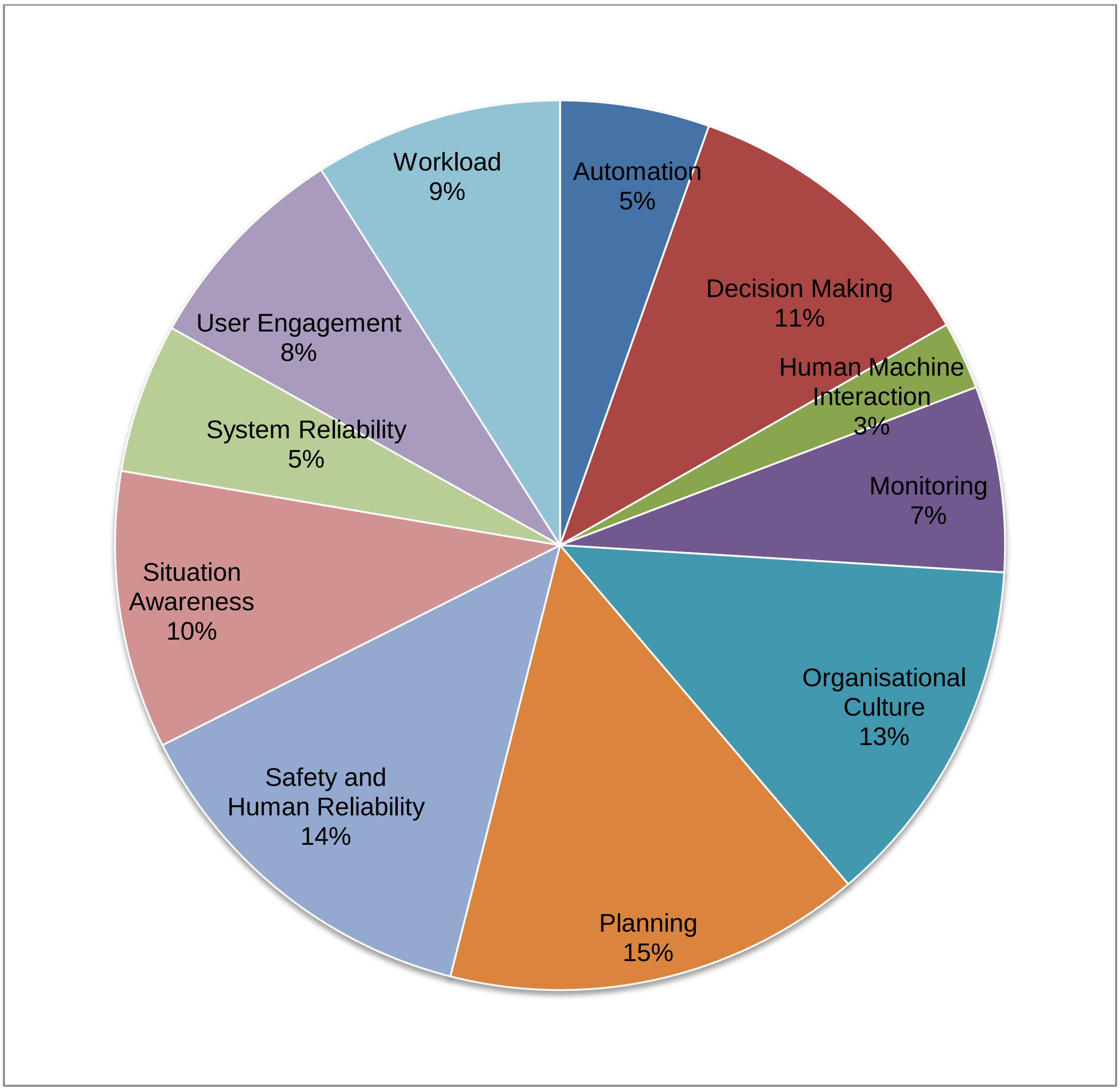



**FIGURE 5-8: INTERVIEW ANALYSIS: HUMAN FACTOR ISSUES IN RAILWAY INTELLIGENT INFRASTRUCTURE**

Scenario: A circuit breaker is located in a very busy junction (situation awareness); it has two other circuit breakers adjacent to it (situation awareness). Sensors attached to the circuit breaker record information about its condition every 30 seconds (system reliability) and send them to a database (system reliability). The data stored will be analysed through the pre-defined algorithms to enable state detection (automation). If it has a significantly different condition from the circuit breakers' normal condition it will generate an alarm (automation) to inform the operator about the abnormality (monitoring). The operator receives the alarm and analyses it to find the potential causes of the detected abnormality (decision making). He/she uses the information presented on the SCADA (Supervisory Control and Data Acquisition) systems (Human Machine Interaction, monitoring, automation, system reliability), consults with his/her colleagues (organisational culture) to diagnose the fault (decision making) and to identify the potential corrective action required. Following this understanding, the operator has to plan (planning) the optimum corrective action (safety and human reliability) and to do so he/she has to consider external factors (situation awareness), such as time of failure (e.g. peak time) and the feasibility of track access to conduct onsite maintenance work, etc.

Figure 5-8 only represents the level of interviewees' direct and indirect awareness of the human factors issues. It only suggests the existence of these human factors. Throughout the course of this PhD, the researcher developed a much better understanding of the importance of these human factors and this will be discussed in chapter nine of the thesis.

### *5.4.3. Data processing in railway intelligent infrastructure systems*

The data processing framework drafted through the familiarisation exercise was assessed through a third iteration of interview transcription analysis. Since participants were selected from the most knowledgeable informants with regard to the intelligent infrastructure project, the concerns connected with data processing, shown in Figure 5-9, reflect well the perceived importance within NR. In this section these themes are explained and, at the outset, it should be noted that terms such as data, information, knowledge and intelligence are not used in exactly the same way as in some of the literature on knowledge (e.g., as in Dreyfus & Dreyfus, 1984). The terms data, information and knowledge are used only to emphasise the changes in the operators' understanding of the situation that is necessary to handle problems in the optimum way. The following describes the different features of the data processing framework.

Asset: any feature used to facilitate the running of the railway is considered to be an asset. This consists of a wide range of equipment on track, such as rail, point machine, level crossing, signal, as well as the embankment where the rail tracks are located. Moreover, control room systems, such as signalling systems or electrical control room SCADA systems can also be considered as railway assets.

Sensor: assets are remotely located and spread over an area as big as the country; sensors are used to enable the collection of data regarding various assets. This ranges from RCM equipment attached to the point machines to event frequency collectors at the ticket barriers to count the number of passengers on each train.

Data: every asset has a number of attributes, such as age, type, location, etc. Moreover, assets contain dynamic attributes, such as the current voltage in a point machine or temperature. These data are logged and collected through sensors and then stored.

Database: the data collected are stored in large databases; these databases can be either relational or distributed.

Information: the data collected in the database has to be interpreted to become meaningful. Influential attributes (e.g., temperature of a point heater) would be analysed on the basis of known standards and made available to operators. Forms of presentation vary from a simple excel spreadsheet to a sophisticated information display.

Information development: merely being presented with a piece of information would not lead to an action. The agent (i.e., the human operator or a machine) should analyse and assess the information made available to them and develop an understanding of the situation.

Knowledge: information developed either through the use of advanced technologies or a human operator's expertise is considered to establish and then extend knowledge of the situation.

Knowledge integration: the railway is a multi-agent and distributed system and, in order to assess a situation optimally, it is necessary to integrate knowledge from various work settings. For example, in a railway signalling control room, the signaller should be aware of the situation on track as well as in the adjacent signalling control centre.

Intelligence: the integrated knowledge then would contribute to the selection of a suitable course of action. Intelligence can relate to any source of decision aid, planning or knowledge base that contributes to this optimisation. At the moment, only the human operator is capable of making such decisions but, as part of the larger scope of intelligent infrastructure system, the intelligence can be built into an asset.

The interviewees were least concerned with issues associated with databases and sensors, mainly because the available technological advances can facilitate these aspects of the project. Intelligence and knowledge integration received the highest expressions of concern, reflecting the need to understand these better.

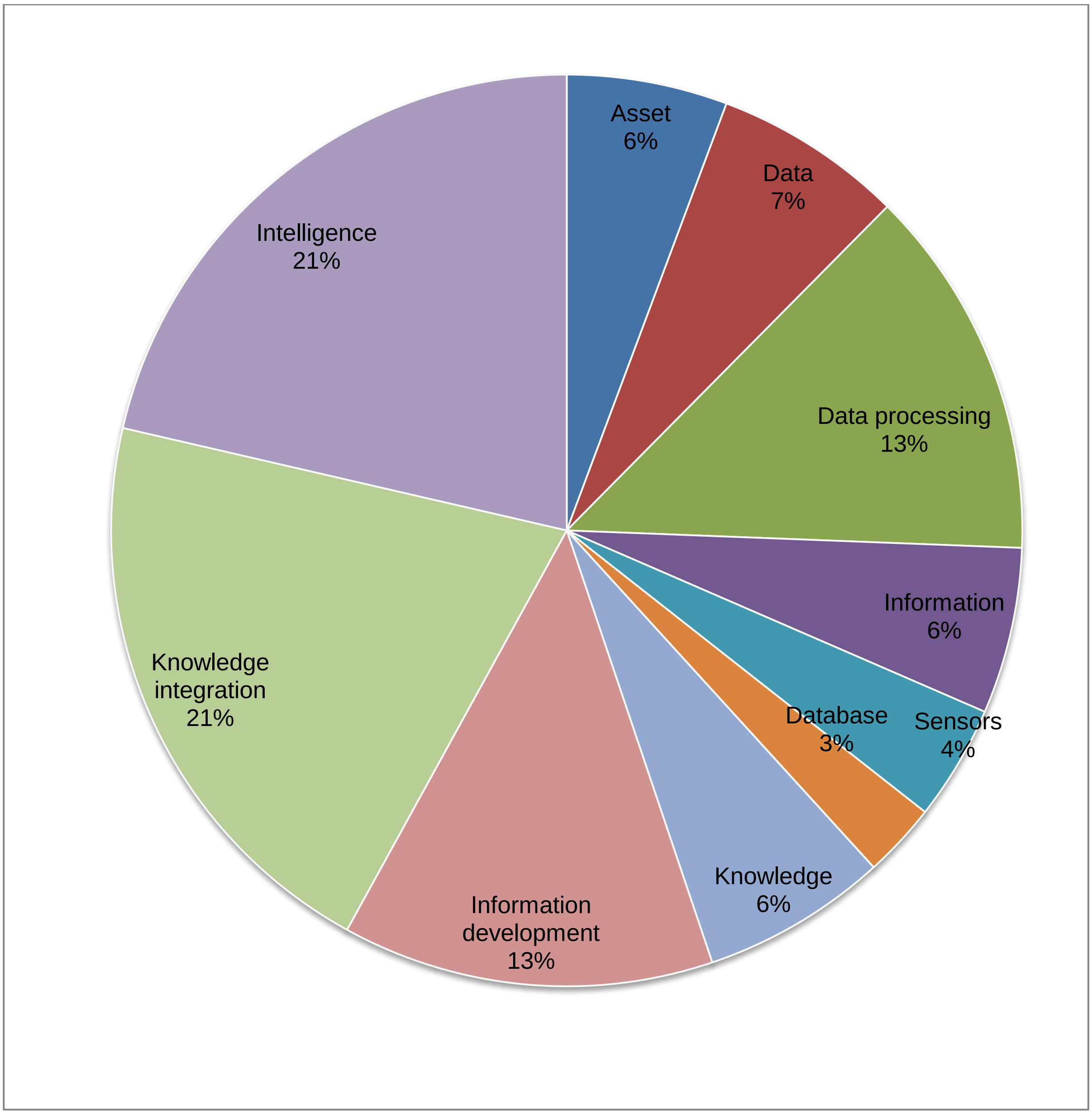



**FIGURE 5-9: INTERVIEW ANALYSIS: DATA PROCESSING FRAMEWORK IN RAILWAY INTELLIGENT INFRASTRUCTURE**

### *5.4.4. Integration of the thematic content analysis into a data processing framework: from data to intelligence?*

Inspection of the outputs from the three different iterations of coding (intelligent infrastructure, human factors issues and data processing framework), to examine their relationships and overlapping areas, led to development of the data processing framework presented in Figure 5-10.

NVIVO ™ facilitates a modelling of the relationships among the themes to identify the relevant factors. This makes it possible to comment on the human factors issues that are relevant to the different functions and roles within intelligent infrastructure. Similarly, it is possible to identify various stages of data processing (described in the previous section) with different functions as well as human factors.

Table 5-3 shows an example of the three coding groups taken from the interview transcripts of one of the participants. This interviewee was the project manager of the NR intelligent infrastructure, who stated:

*"There is a huge amount of expertise involved with the decision making and fault finding; a lot of people are surprised to know what exactly it is that happens to an asset. For example, I was surprised to see that there are cases where fluctuations to resistance – in a point current- are normal; there are many contributing factors and this is where humans become useful. To be honest, we really want to know how an expert does this job because that can be what it is that contributes to reduction in service."*

**TABLE 5-3: EXAMPLE OF THE SYNTHESIS OF THE THREE CODING GROUPS**

| **Coding 1 (General definition of intelligent infrastructure)** | **Coding 2 (Human Factors** | **Coding 3 (Data processing)** |
|---|---|---|
| Role and functions: alarm handling and fault finding<br><br>Challenge: understanding the expertise<br><br>Benefit: the benefit lies in understanding how experts do their job | Expertise and decision making involved with interpretation of the status of assets | Information processing: status of asset is observed (data processing) but due to operator's expertise fluctuations of the resistance are normal. |

The data processing framework shows the transition of data from raw data captured from an asset through to a database that keeps all of the recorded data and the processes required to interpret these (e.g. algorithms, thresholds), leading to a "smart" course of action. Depending on the roles and responsibilities of the intelligent infrastructure users, four levels of understanding have been specified:

1. Data: not yet interpreted facts which possibly represent only the evidence of a problem or even just the existence of an asset.
2. Information: relationships between, and integration of, the facts, maybe in the form of cause and effect.
3. Knowledge: interpretation and reasoning applied to the information.
4. Intelligence: consideration of the asset, its condition and any problems within the whole work or socio-technical system, in a form to support asset management decisions and more extensive problem solving.

Data and information layers correspond to stages 1, 2 and 3 of ISO 13374 (Figure 5-2) and enable remote condition measurement of the infrastructure through capturing, sensing, recording and processing of the raw data. The knowledge layer corresponds to the fourth stage of ISO 13374 and enables remote condition monitoring via development of the information. Finally, the intelligence layer corresponds to stages 5 and 6 of ISO 13374 and enables remote condition management through integration of the knowledge within various external effectors.

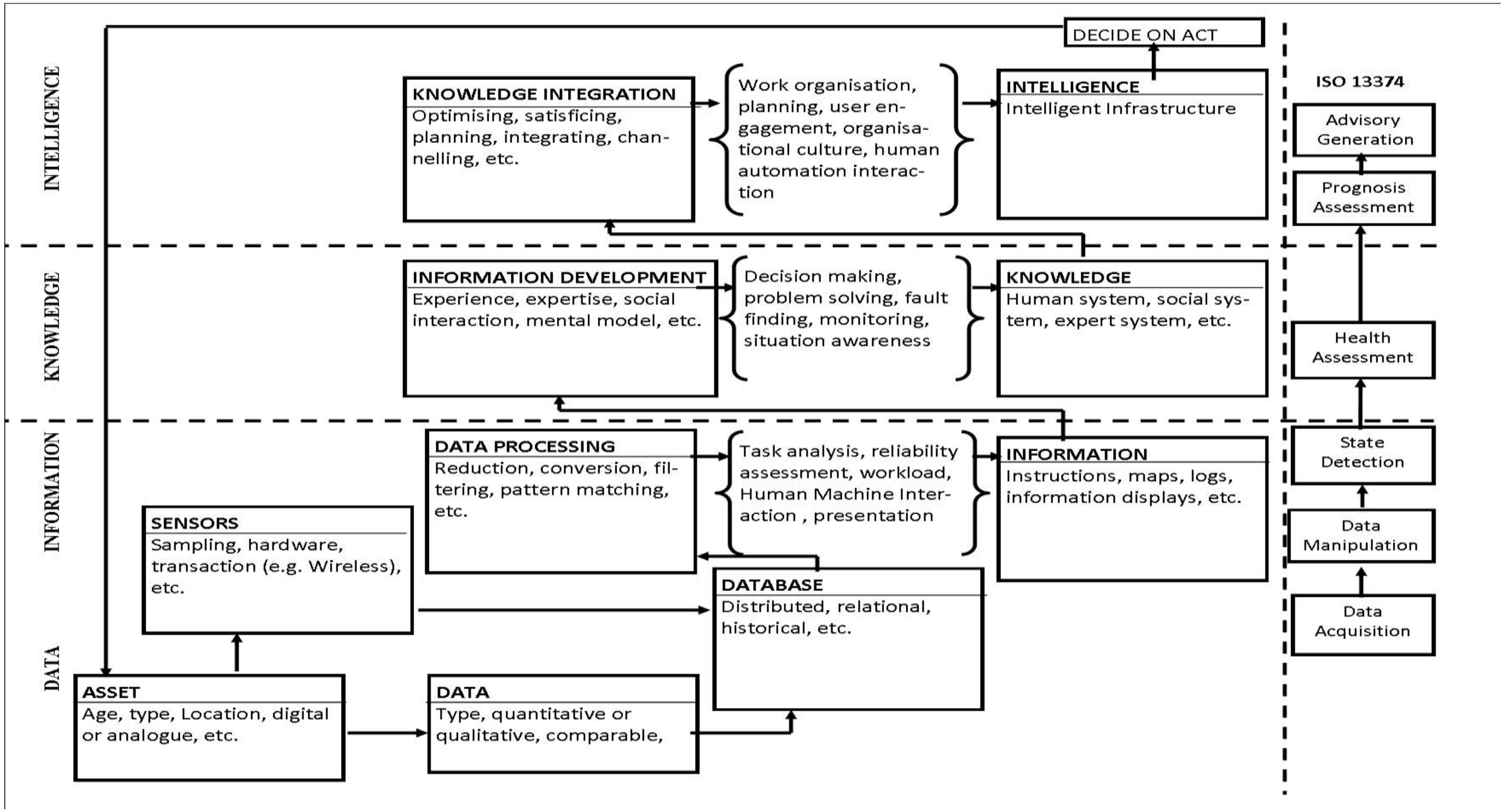



**FIGURE 5-10: DATA PROCESSING FRAMEWORK OF RAILWAY INTELLIGENT INFRASTRUCTURE**

## *5.5. Knowledge elicitation to assess the data processing framework*

The data processing framework developed as described above is a potentially useful tool in understanding the various activities involved in intelligent infrastructure. However, this framework was first established after a one day workshop, and then was iteratively further developed and tested to a limited extent through interviews. However, some further verification (if not validation) was seen as useful and so a knowledge elicitation exercise was carried out to test if it would be possible to confirm the content and hierarchy of the framework.

The approach of the knowledge elicitation was to use an example of an alarm handling scenario to assess the content and hierarchy of information type, and the order in which the layers of data, information, knowledge and intelligence in the framework.

Railway ECR operators were asked to place various pieces of information in the order in which they would potentially need them in order to handle the alarm scenario. They were then asked to group the information within the three categories: data and information, knowledge and intelligence.

### *5.5.1. Participants*

Seven railway electrical control room operators participated, all male with an average age of 53 and with an average of 28 years of experience. The University of Nottingham ethical guidelines were followed. The information sheet and consent forms can be found in appendix 12.3. None of the participants had been involved previously with the interview study and had not reviewed the draft of the data processing framework.

### *5.5.2. Apparatus*

The equipment used included a Dell™ laptop with 15” screen used to view screen shots relevant to the alarm scenario. An Olympus™ digital voice recorder was used to record participants’ comments. An alarm scenario was developed and relevant screenshots of the information displays on the SCADA were simulated accordingly. The development and design of these screenshots are described below.

#### 5.5.2.1. Development of the alarm scenario

An alarm handling scenario was developed through two interview sessions, each of two hours, with an ECR operator. The ECR operator was asked to think of a scenario with the following characteristics:

- It is not a common fault and operators would not know easily the answers to the problem.

- There is more than one correct approach to the problem.

The first session conducted with the ECR operator focused on the selection of an appropriate scenario. A semi-structured interview was conducted and the following questions were asked to highlight the characteristics required for the alarm scenario:

1. What do you consider to be one of the most problematic alarms in your control room? Why?
2. How often does this alarm occur?
3. Do you think this is a difficult alarm or an easy one?
4. What is the procedure for dealing with this alarm?
5. How much “uncertainty” is involved with this alarm?
6. Are there different methods of dealing with this alarm?

Alarms generated due to High Voltage (HV) loss were selected for the scenario. A second session (two hours) with the same ECR operator was then used to understand the specific alarm scenario in-depth and to collect information about how participants might handle it. Screen shots of the pages on the SCADA that might be potentially useful were collected and an initial understanding of how participants might approach the problem was developed. Details regarding various information displays available to railway electrical control room operators are reported in Chapter 6.

The High Voltage (HV) feeder provides electrical supply to a number of outstations on the railway network. Loss of this supply will lead to the outage of a large area of the network and, therefore, it is important to rectify the loss of supply as soon as possible. Since HV supply covers a wide area, unless the fault is from the site controlled by Distribution

Network Operator (DNO), it can be due to equipment failures or circuit breaker trips on the network.

This fault is not very common and operators will not automatically know the solution. This is a very serious failure: it certainly causes service outages but it can also lead to derailments. Therefore, both safety and efficiency of the network is at high risk and operators would feel pressured to deal with this problem as soon as possible.

As the failure that caused the HV loss could be located anywhere in the area covered by that HV feeder, the scope of search for the solution is quite wide. This is followed by a progressive recharge of potentially faulty outstations; if the recharge is successful then that outstation is not contributing to the fault.

In the scenario presented, participants were asked to diagnose the alarm and review the stages required to handle it. The progressive recharge process was not included at this stage since it was not feasible to simulate the situation on a SCADA and the searching task conducted at this stage was not the focus of this study.

Information displays required by the operator to diagnose and handle this alarm scenario were identified. Since there is no simulation environment in the electrical control room to simulate the faulty condition, screen shots of the relevant information displays were edited to replicate a HV loss alarm.

Information displays identified for handling this scenario are: alarm banner, outstation page, AC overview, DC overview, alarm list and event log. The alarm banner is presented on top of an operational display; it consists of colour coded faulty locations (Figure 5-11). Each outstation page relates to a specific faulty location. Figure 5-12 shows the outstation page on South Bermondsey; tracks that could have been affected by HV loss are changed (e.g. rectifier 1543 has gone hollow) and there are signs of circuit breaker tripping on a number of tracks. These two are both located on the same information display on the ECR operator's work station (which is referred to as the operational display).

AC overview is also used by operators to capture an overall understanding of the level of voltage available in different areas as well as the locations which had alarmed. Figure 5-13 shows an AC overview with a HV loss of supply. The colour on various branches shows the available voltages; when it is white it means that there is no voltage available. This is the case from branches to the left of the New Cross Grid feed (Figure 5-13). In addition, all of the outstation locations alarming on the alarm banner are shown in red in the AC overview.

The DC overview can also provide the operator with useful information regarding the fault, as shown in Figure 5-14. DC overview provides information regarding the circuit breaker trips most likely to have failed due to the HV loss. Operators might also use the alarm list (Figure 5-15) and the event log to investigate previous failures, the time at which equipment started to fail and the locations.


**FIGURE 5-11: ALARM BANNER**

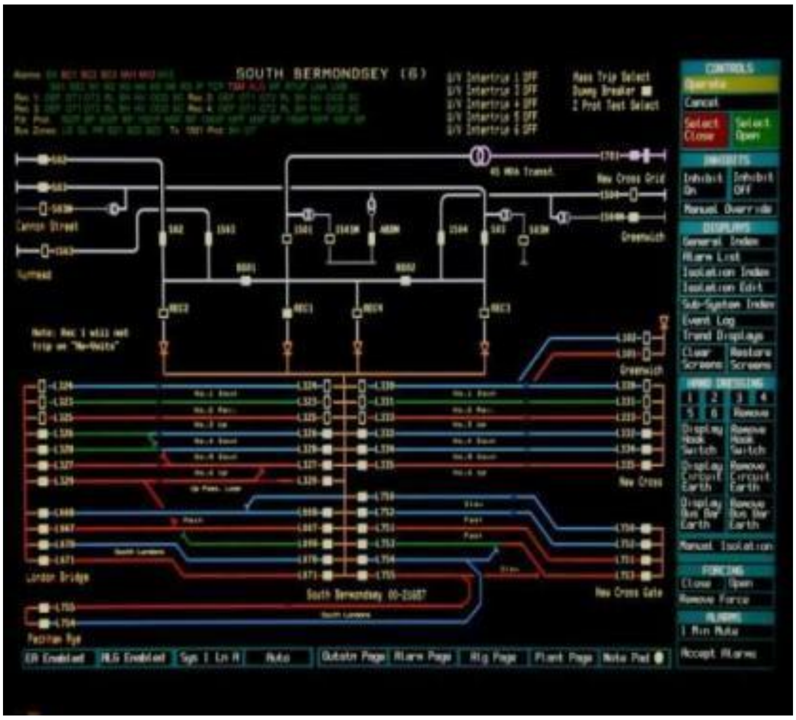



**FIGURE 5-12: OUTSTATION PAGE**

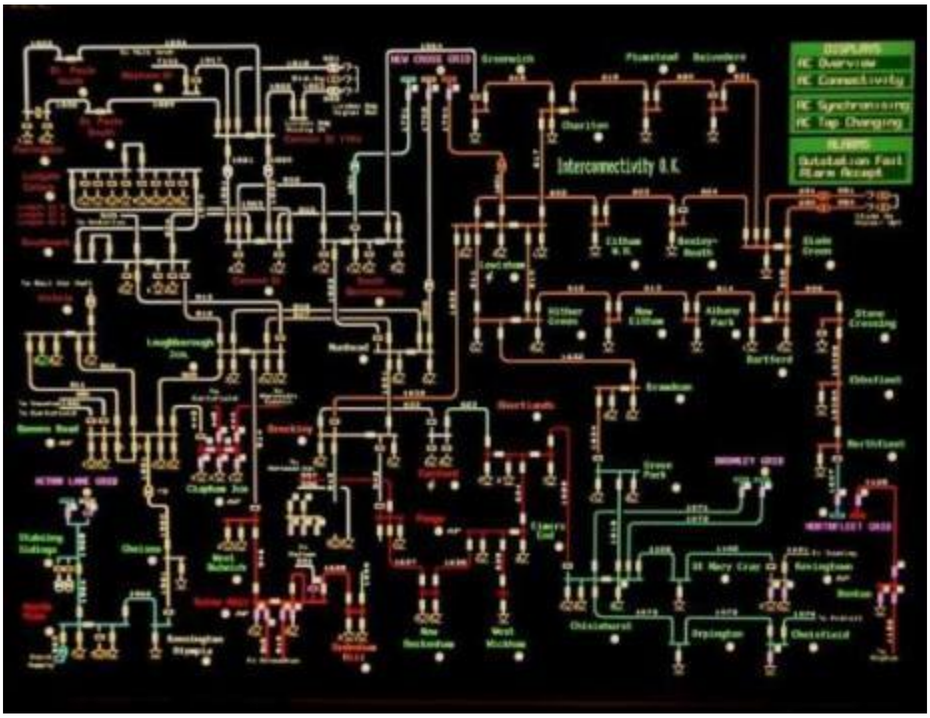



**FIGURE 5-13: AC OVERVIEW**

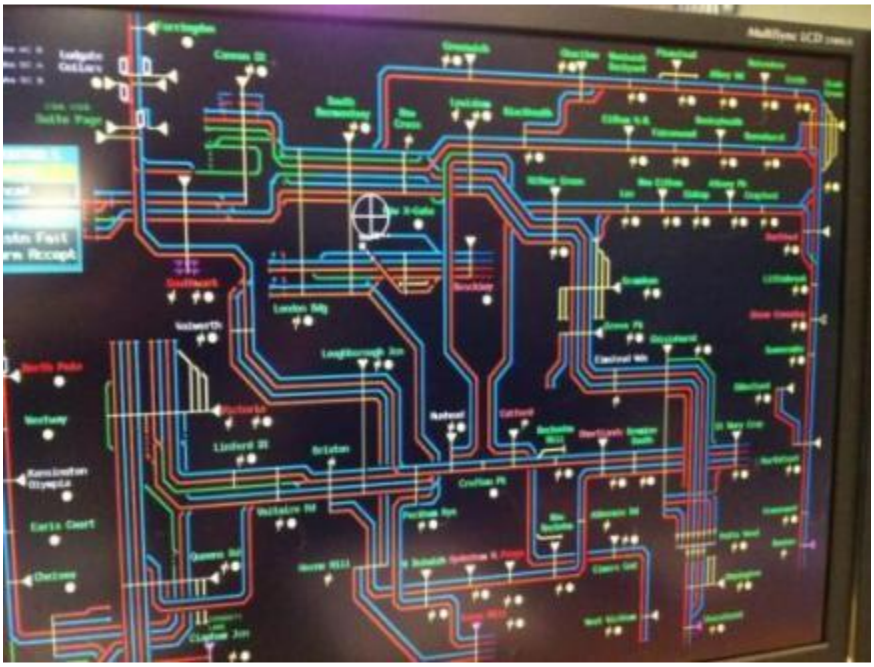



**FIGURE 5-14: DC OVERVIEW**

**FIGURE 5-15: ALARM LIST**

### *5.5.3. Procedure*

This study took approximately 30 minutes per participant. Participants read the information sheet and signed the consent form (Section 12.3). After viewing Figure 5-16, which contained the alarm banner, they were presented with the list of available information displays on a Microsoft™ Excel™ sheet and asked to rank the preferred order of information presentation (Figure 5-16). As shown in Figure 5-16, not all of the information pages available to the operators were selected. In the example below, the operator thought that the AC overview (with connectivity OFF) is of no use and therefore did not rank it at all.

| A | B |
|---|---|
| Available information | Order |
| Outstation page for South Bermondsey | 4 |
| AC overview (with connectivity ON) | 1 |
| AC overview (With connectivity OFF) | |
| Event log | 2 |
| DC overview | 3 |

**FIGURE 5-16: EXAMPLE OF DISPLAY SELECTION FOR ONE PARTICIPANT**

Participants were then presented with the information displays in the order they had requested and were asked to handle the alarm in a simulation exercise. They were asked to talk aloud and their comments were recorded. Whilst viewing each of the pages requested, participants were asked to point out the information they used on each page. (e.g., colour of the alarm and the name of the locations on the alarm banner). The researcher then wrote these pieces of information on cards. Participants then ranked the order of importance of these pieces of information (Figure 5-17).

**FIGURE 5-17: EXAMPLE OF CARD SORTING ACTIVITY**

After handling the alarm and ranking all of the pieces of information according to their use, the researcher briefed participants regarding the data processing framework. Participants were asked to group all of the cards within the three information levels: data and information, knowledge and intelligence. The procedure for the whole of this part of the study is summarised in Figure 5-18 below.

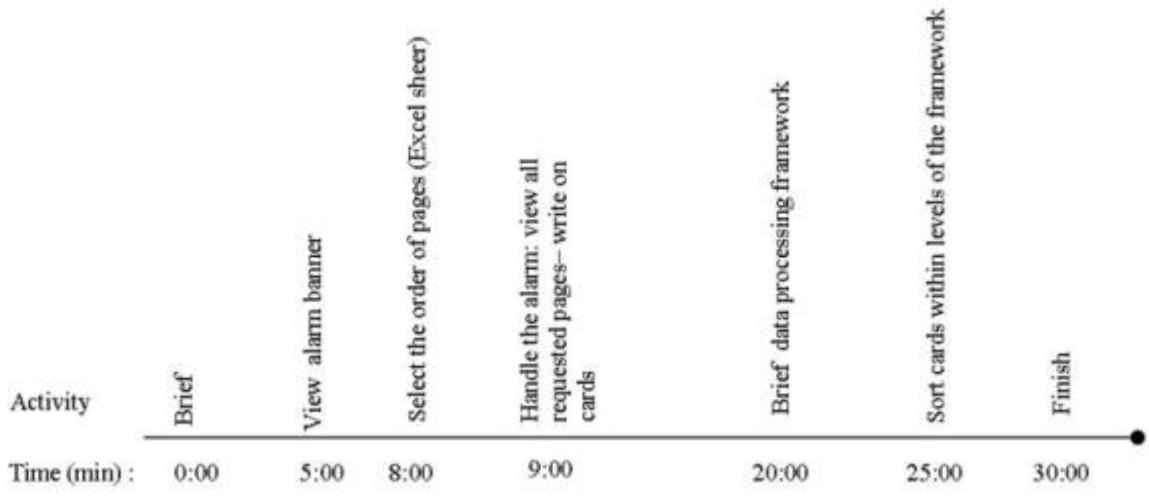



**FIGURE 5-18: TIME LINE FOR THE PROCEDURE**

### *5.5.4. Findings of the knowledge elicitation exercise*

The AC overview was the first page that operators requested to view, with 6 out of seven operators requesting this first. The event log was requested as the second page by three participants, two wanted it to be viewed as their fourth page and one wanted it as his third page. However, one of the participants did not seem to need the event log at all. He mentioned that maybe the event log is useful 20 minutes after occurrence of the fault, but not straight away.

DC overview was requested by three operators as their third option; two operators wanted it to be viewed as their fourth page, one requested it as his second page and one operator requested it as his fifth page. One of the participants mentioned that *"looking at the locations which have alarmed, there is no DC in some of these sites, so I will be drawn to conclude that AC failure has caused the HV loss".*

The outstation page was requested with the most diverse priorities, two of the operators requesting it as their third page, the others requesting it as their first, second, fourth and sixth option, and one operator said that it was not required to handle the alarm. This is the same participant who did not find the event log useful. Only one of the operators requested CCF, and mentioned that this was used for reference purposes only and was not very influential on the diagnosis. These findings are shown in Figure 5-19 below.

The average rank of each of these pages suggests that AC overview is requested 1st, event log is requested 2nd, DC overview is requested 3rd and outstation pages are requested 4th.

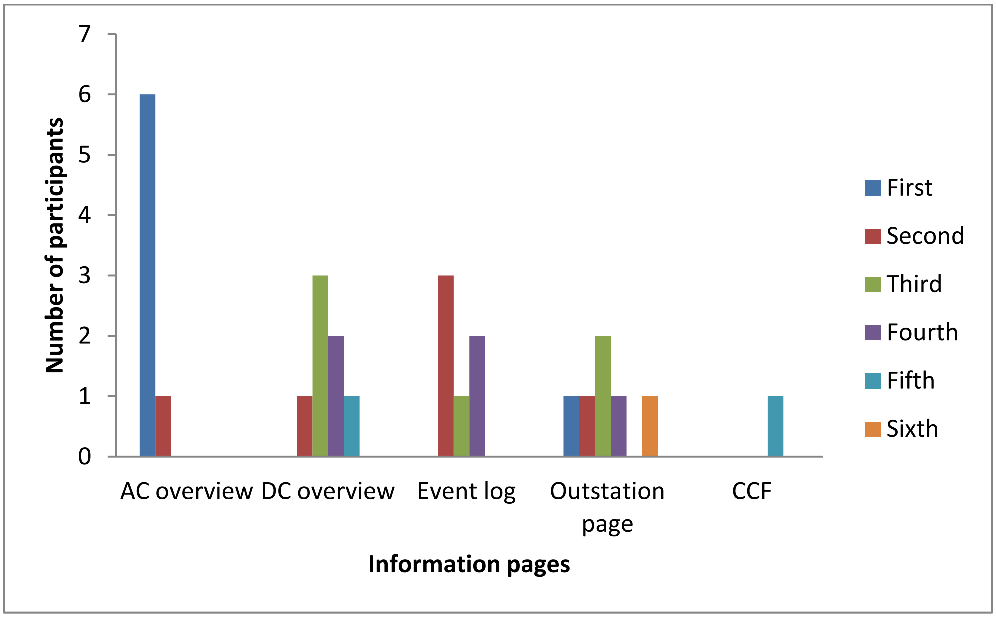



**FIGURE 5-19: ORDER OF PAGES REQUESTED BY OPERATORS AFTER THEY VIEWED THE ALARM BANNER**

Participants attended differently to the various pieces of information on each of the pages they viewed. Various pieces of information associated with different pages and their perceived importance are presented in Table 5-4 below, where all of the sources of information considered to handle the alarm are presented. Furthermore, content of the information on these pages is specified. The rank of these pages, depending on the majority of the participants' views, is shown in the third column of the table. When there was no agreed rank it is noted as 'not decided'.

**TABLE 5-4: IMPORTANCE OF PIECES OF INFORMATION AND THEIR ORDER ON THE PAGES REQUESTED BY OPERATORS**

| Information source | Content of the information considered on each page | Rank |
|---|---|---|
| Alarm banner | Colour of alarm banner<br>Amount of alarmed assets on that location<br>Name of the alarmed location | First |
| AC overview | Colour of the branches coming out of the feeder<br>End of the feeder is open<br>Locations of the alarms (overview)<br>Geographical scope for the tripped rectifiers, colour of alarmed outstations | Second |
| Event log | Time of the first failure in that location | Third |
| DC overview | Amount of CB tripping<br>Status of the tripping, check if it responds to re-energising<br>Location of tripping | Fourth |
| Outstation page | Flashing failed equipment<br>What is the failed equipment (on top of the page)<br>Status of circuit breakers<br>Location of the tripped circuit breakers | Fifth |
| CCF | Trains in the section that seems to have tripped | Not decided |
| Reference book | Diagrams | Not decided |
| Signaller | Layout information regarding the track | Not decided |
| HV Coordinator | Use DINIS (most economical re-feeding solution) | Not decided |
| Distribution Network Operator | Investigate if the loss is from the provider | Not decided |

#### 5.5.4.1. Data processing framework

Participants categorised information on the cards according to the three levels of information of the data processing framework. Operators' comments recorded throughout the study were most useful in this stage. Although ECR operators placed various pieces of information in different groups, in some of the cases they could not draw a definite line between various levels of information. In these cases, the operator's comments were used to analyse the findings in more detail. The content of the information pages identified in the previous section is categorised within the three levels of information, as shown in Table 5-5

**TABLE 5-5: CONTENTS OF INFORMATION PAGES AND THEIR GROUPING IN THE THREE LEVELS**

| Level of information | Content of information on different information page |
|---|---|
| Level 1: Data and information | Amount of circuit breaker tripping on DC overview<br>Names of the alarmed locations on the alarm banner<br>Calls from signal box<br>Confirmation from DNO<br>Colour of the branches on AC overview<br>Colour of the banner<br>Number of alarmed outstations<br>Flashing banner<br>Time of the failure<br>Type of equipment<br>Status of the circuit breaker |
| Level 2: Knowledge | Work in the area<br>Location of train<br>Location of circuit breaker tripping<br>Geographical scope of the tripping<br>Loss of supply at the feeder<br>Location of alarms on the alarm banner<br>Loss of signal supply<br>Fault history on the event log |
| Level 3: Intelligence | Relationship of the feeders with each other<br>Intelligent advisory systems<br>Diagrams on the reference book |

In most of the cases, participants were consistent in their categorisations, but in some cases there were differences. For example, almost all of the participants thought that time of the failure of the equipment presented on the event log has to be among level 1 information, but one participant thought that this more relevant  to level 2.

The prioritisation of the information can be used to determine the content of information required on each page and the order in which they should be presented to the operators. Furthermore, this information is categorised within the three levels of data and information, knowledge, and intelligence. This finding is summarised in Figure 5-20.

Information associated with the first level includes the number of circuit breakers that have tripped, names of the locations, colour of the branches on the AC overview, etc. This confirms the prior understanding of the data processing framework. The information in level one refers to a basic understanding of the system. Therefore, the stages that should be performed either by the machine or by the operator include the categorisation and filtering of this basic data, without the need for much interpretation.

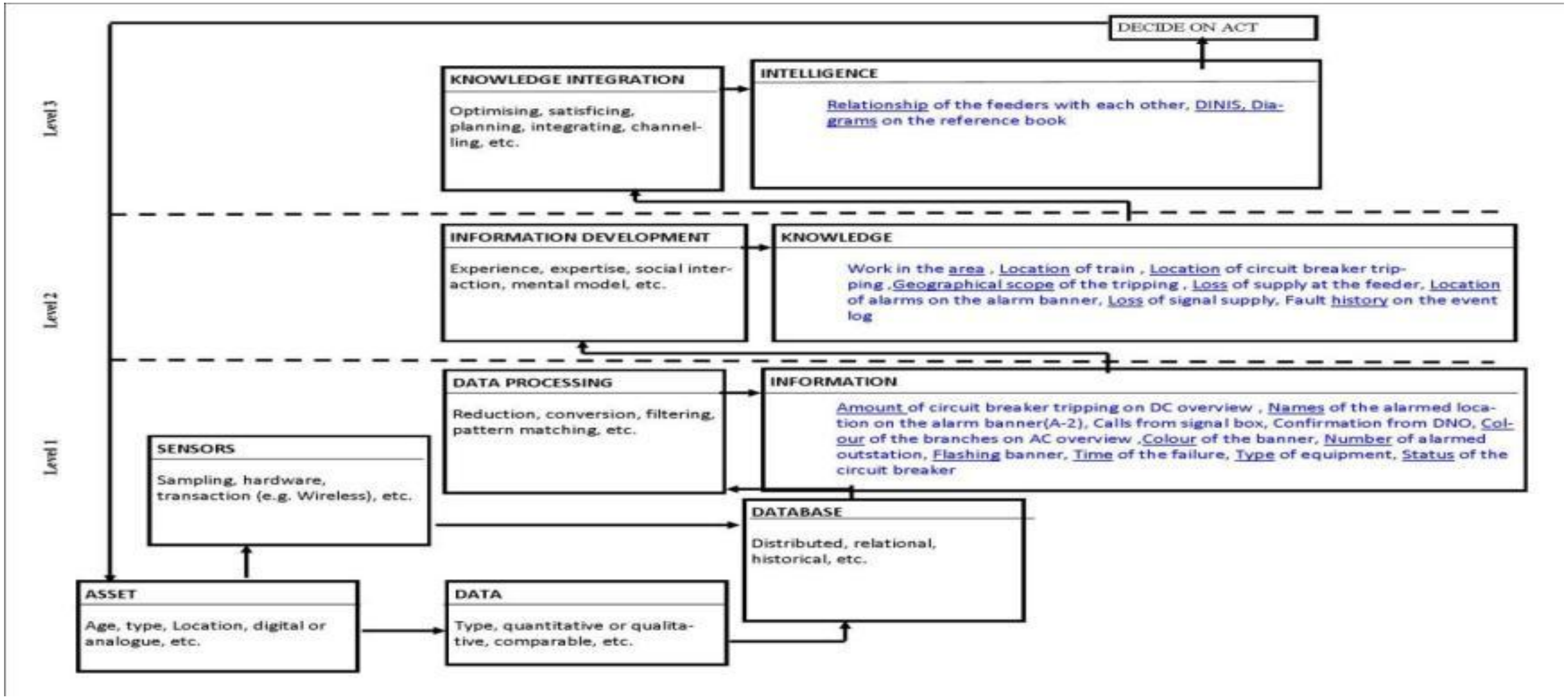



**FIGURE 5-20: DATA PROCESSING FRAMEWORK AND THE INFORMATION REQUIRED FOR HV LOSS ALARM HANDLING**

## 5.6. Discussion

This chapter has described a series of studies that have been conducted to guide the research questions of this PhD study and subsequently its objectives, and in particular to address the first objective: to identify the human factors of most relevance to railway intelligent infrastructure and, in so doing, develop a framework that focuses on data processing requirements to support informed decision making.

Due to the lack of a consistent definition of the railway intelligent infrastructure within NR, as shown by the familiarisation study, the interview study might seem not to be the best way of collecting information about intelligent infrastructure systems. However, the sample of participants was a high level one in terms of systems understanding and ability to influence change in the company, and selection of informants and the open ended questions gave interviewees an opportunity to express their vision of intelligent infrastructure systems. Moreover, the analysis of findings from the interviews showed a consistent pattern which guides the development of an understanding of roles, functionalities, benefits, potential, human factor issues and also the data processing associated with NR intelligent infrastructure. Given the paucity of project implementations, company reports and documentation and lack of agreement on definition and priorities, it is possible that this interview study was the only way to slowly target in on the key issues. Had the sample been more available (they were amongst the busiest people in the company), a Delphi exercise might have been used, but the chances of a second never mind a third agreement iteration were slim.

From these findings, railway intelligent infrastructure is defined as: An integration of existing RCM technologies that is distributed both locally and centrally and used by different operators in identifying and handling faults in the infrastructure assets in order to improve safety and efficiency of the rail service.

The benefits of intelligent infrastructure systems comprised 19% of the comments in total, followed by system distribution (16%). This simply reflects the way the intelligent infrastructure project has been dealt with during the two control periods (10 plus years) after its launch. Almost every interviewee agreed that it is very beneficial to maintain assets before they fail, but they were also alert to the practical challenges of system distribution.

Three key roles were specified for users of the railway intelligent infrastructure system: track workers, control room operators, and strategic analysts. The current focus of the intelligent infrastructure system is on the control room operators. It therefore follows that this role, with a specific focus on its relation to alarm handling and fault finding, was investigated in much of the empirical work of this thesis. Here it should be acknowledged that the concentration of this whole exercise (familiarisation exercise, interviews and KE exercise), and especially the knowledge elicitation, has been centred only on one of the three user roles previously identified, control room operators. Subsequently, all the empirical work reported in the next chapters concentrates on this role. Obviously such a major systems change as intelligent infrastructure will bring with it changes in the priorities, functions and whole role of those using the system, but care has been taken to carry out the detailed field study on alarm handling and fault finding which the large majority of participants had identified to not change, in principle, too radically with new systems. The situation is likely to be very different with, say, track workers and engineers who gather data from on-track, where the whole way of doing work is likely to be very different in future. This is the main reason why the detailed empirical work has not been applied to track work or strategic analysts. However, some implications for how this work will be carried out in future will be addressed in summary form in the overall discussion of chapter 9.

Functionalities of the railway intelligent infrastructure featured in 8% of the comments as transcribed in the interview study. The dominating function selected was that of problem solving and, more specifically, handling alarms and finding the faults identified on the intelligent infrastructure interface.

Although a majority of the semi-structured interview participants and a number of other relevant company staff commented on the framework and generally agreed with its content and sequence of data processing stages, it was useful to adopt a more robust knowledge elicitation technique to confirm various features of the framework. The knowledge elicitation exercise was, in fact, conducted after the alarm handling study reported in chapter 6, although reported here for reasons of thesis logic. Therefore, the researcher had a clear knowledge of the railway ECR, which informed the development of the scenario and choice of various information displays utilised for handling the alarm scenario.

The selection criterion for the alarm handling scenario was for it to be challenging and cognitively demanding so that it would trigger the cognitive processing stages identified in the data processing framework. The HV loss alarm was difficult to handle; operators could have different approaches to solving the problem and a large area would have been affected by this fault.

The data processing framework and the identification of human factor issues associated with railway intelligent infrastructure as described in this chapter comprise two of the main deliverables of this thesis. These have been refined and further investigated through the field studies reported in the following chapters. Therefore, issues associated with this framework will be discussed again and in more detail in chapter 9.

Consideration of the decision making processes under intelligent infrastructure, and best human factors advice on systems design and implementation, necessitates investigation of the cognitive processes relevant at various levels of the data processing framework, according to the role and needs of different staff. Questions need to be asked such as what data will be used for, how massive quantities of raw data could be reduced and filtered for different needs of different stakeholders and what decision support routines are required. Moreover, the decision making processes of track workers, control room operators and strategic analysts are most likely to not require the same type of information as each other, and so this must be accounted for in wider subsequent work. However, for the purposes of this thesis, and since the intelligent infrastructure project was nationally launched in time, two similar domains highly relevant to control room operators as intelligent infrastructure user were selected for detailed investigation - alarm handling and fault finding. These two studies are reported in chapters 6 and 7.

## 5.7. Chapter summary

This chapter described the studies conducted to initiate an exploration of railway intelligent infrastructure and establish a data processing framework and first identification of relevant human factors. Following a familiarisation study with four NR rail experts), it became evident that there was not a common understanding of intelligent infrastructure sufficient to properly inform the work of the PhD. Therefore, a semi-structured interview study was also carried out with a sample of senior company staff with knowledge of, and interest in, intelligent infrastructure. Three themes were selected and applied to a thematic content analysis of the transcripts of these interviews, and synthesis of these themes led to the development of a data processing framework. Finally, in order to verify to an extent the content and hierarchy of the data processing framework, a knowledge elicitation exercise was conducted with control room operators. Findings informed the general understanding of intelligent infrastructure and identified its roles, functionalities and relevant human factors. A data processing framework was developed which showed the hierarchy of information throughout an intelligent infrastructure task.

# 6. Alarm handling in railway Electrical Control Rooms

In the previous chapter alarm handling and fault finding were identified as two of the most important and yet challenging human or human-automation functions of intelligent infrastructure systems. This chapter reports a study relating to the second objective of this PhD study, which is to establish an understanding of operators' strategies for human supervisory control tasks in alarm handling.

Alarm handling will be one of the core functions of intelligent infrastructure systems. This is the case in the current railway maintenance regime and it is going to be a key part of the proposed intelligent infrastructure system.

Since there is no relevant rail intelligent infrastructure system currently in existence, it was important to find a control setting similar to the proposed intelligent infrastructure system. Electrical Control Room (ECR) displays are SCADA (Supervisory Control and Data Acquisition) systems, which are the systems currently in use in the rail industry with the greatest similarity to intelligent infrastructure systems. Therefore, these were investigated and similarities between the two domains are elaborated later in this chapter.

Taking alarm handling as a task representative of a future intelligent infrastructure system and re-visiting the research questions first introduced in chapter two, the following concerns are addressed in this study:

1. How do operators deal with the problem of multiple sources of information in railway problem solving?
2. Thinking about the potential functions of a railway intelligent infrastructure, what is the sequence of activities in alarm handling?
3. What are the railway alarm handling activities and artefacts?

Field studies, semi-unstructured interviews, structured observations and video recordings were used to investigate of the above questions. This was to ensure the capture of operators' cognitive processing while handling alarms, an understanding of which can then guide future design. This guidance will not only develop systems appropriate to operators' requirements, but an understanding of the field will also raise awareness of problematic or risky activities, which can then be reduced.

In this chapter, the techniques adopted to familiarise the researcher with the domain and to prepare the study setting are explained first. Section 6.2 reports the field study conducted in the railway ECR. Analysis of the field study and findings in relation to the research questions of this study are reported in Section 6.3. Findings from the field study were used to facilitate a Cognitive Work Analysis (CWA) and are reported in Section 6.4. Finally, the findings of both parts of the study are reported and discussed in section 6.6.

## *6.1. Domain familiarisation*

The researcher visited Lewisham ECR for two sessions prior to the set up of the field study. The aim of these visits was to become familiar with the domain, to identify peak times as well as key artefacts used frequently while handling alarms and to understand the potential risks of conducting a real-time field study.

Unstructured interviews were performed with ECR operators to initiate an understanding of alarm handling activities and potential challenges. Operators were simply asked to talk about alarm handling in their control rooms and to identify issues affecting the performance of alarm handling. They talked about the process in terms of their experience as well as the control room specifications and regulations. Moreover, having these two sessions prior to the actual study helped the researcher to build rapport with the operators and ensure that they were fully informed about the aims of the study and the various stages of data collection associated with it. These visits also informed the design of an observational checklist, which was then used in the field study (section 6.2).The findings of these initial visits are reported in section 6.1.1 below.

### *6.1.1. Early findings*

Rail ECR alarms are events configured in the system that require the operator’s attention, following any form of abnormality in the rail network’s electrical supply system (e.g. through AC overhead wires or DC third rail). They are announced by an audible alarm and the updating of any related symbols on an alarm banner, as well as the provision of live indications on the SCADA display.

The SCADA display in the ECR has been developed on the basis of Network Rail's system specification recommendations (Network Rail, 2008) and it corresponds to EEMUA standards (EEMUA, 1999). Operators' workstations consist of four colour monitors, one keyboard, a pointing device (e.g. a mouse) and a workstation rack.

Lewisham ECR (Figure 6-1) has three workstations with similar information available to all three. There are four information displays on each workstation: the left screen displays the East London line overview, the centre left screen displays the DC (Direct Current) overview and the centre right screen, which is used for alarm handling, contains all of the operational displays. Finally, the right screen displays the AC (Alternating Current) overview and the AC connectivity page.

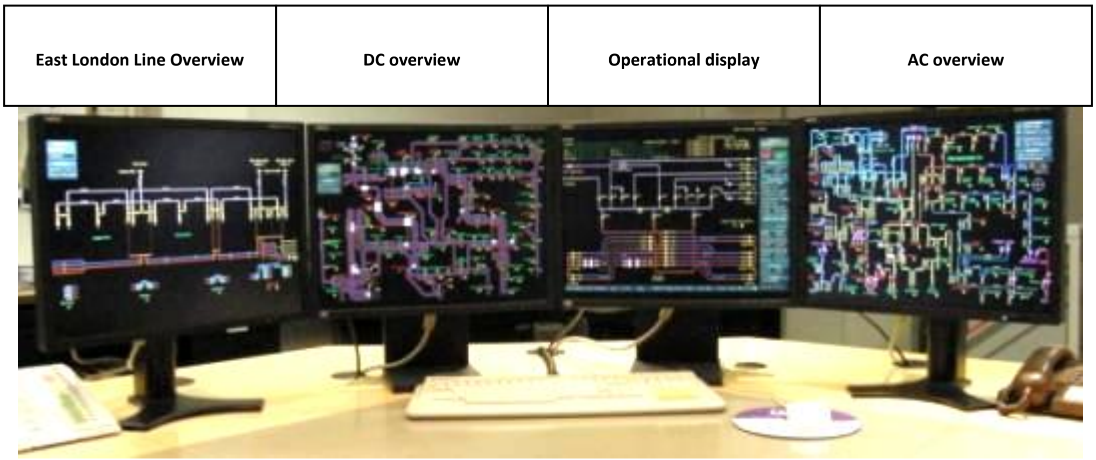



**FIGURE 6-1: ECR WORKSTATION IN LEWISHAM (UK)**

Two ECR operators are active at one time and the third workstation is used for emergencies, when extra staff are required. Of the two workstations, one of the operators is considered to be in charge and acts as a supervisor. Apart from dynamic information displays on their desks, there is also a static board covering one wall of the ECR, as shown in Figure 6-2. This board shows the links and platforms of the area under control. Although the board is now out-dated in some ways, some of the less experienced operators use this to familiarise themselves with the area.

**FIGURE 6-2: LEWISHAM ECR**

According to NR specifications, one of the features of ECR alarms is that they have been prioritised by a ranking system, with six being the lowest priority alarm and one being the highest. System failures are always priority six and the rest of the alarm priorities are configurable by the engineers. Alarm priority is colour-coded, with an additional seventh colour for cleared alarms. For the Lewisham ECR, priority codes used are as shown in Table 6-1.

**TABLE 6-1: ALARM PRIORITIES**

| Numbers | Priority | Colour |
|---|---|---|
| Priority 1 | Extra high | For future use |
| Priority 2 | High | Red |
| Priority 3 | Medium | Pink |
| Priority 4 | Low | Brown |
| Priority 5 | Extra low | This is shown in the event log only, it does not produce an audible or visual alarm |
| Priority 6 | System alarms<br>Clearing alarms | Light grey<br>Green |

Any unacknowledged alarm appears on the alarm banner, which is located on the operational display, shown in Figure 6-3. The alarm banner can contain up to seven alarms and, if there is more than that at one time, an arrow is displayed at the right hand side in the colour of the highest priority alarm not displayed (Figure 6-3). If the cursor is placed over an outstation alarm button and the mouse is clicked, the outstation schematic page will be displayed, from which the alarm can be accepted. Once the alarm is accepted by the operator as a true fault, that outstation name will be removed from the alarm banner panel to be replaced with another outstation with an unaccepted alarm, should there have been more than seven outstations with an unaccepted alarm.

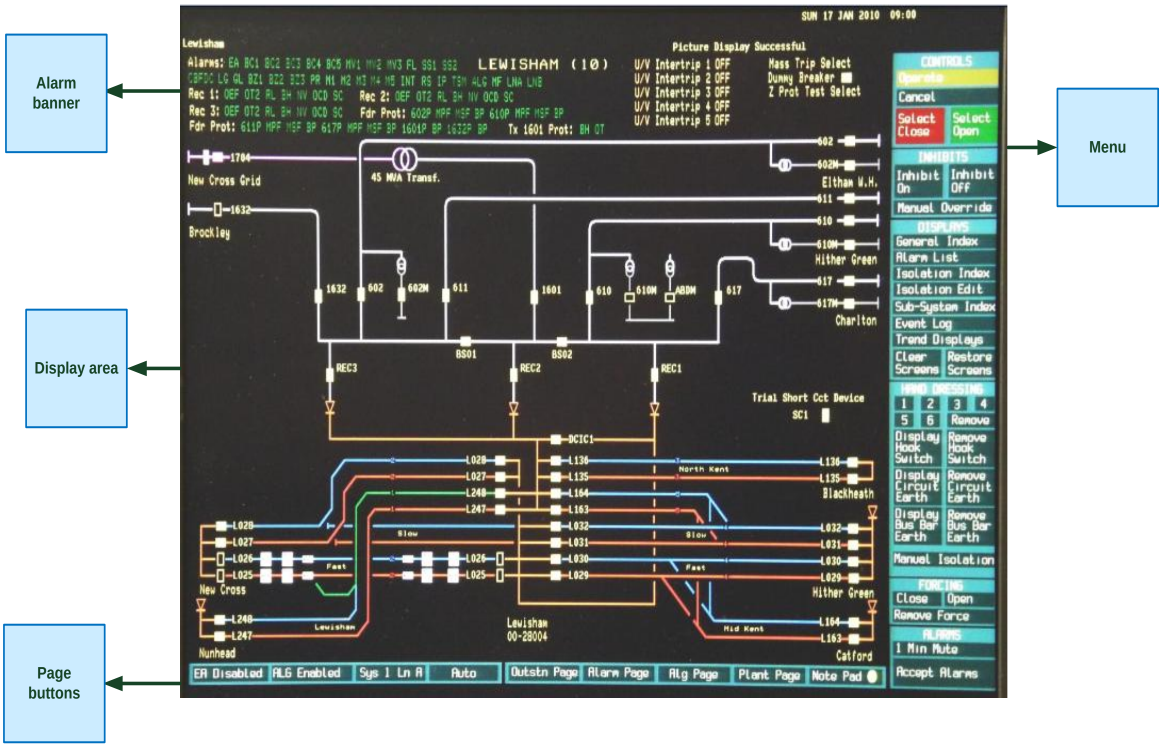



**FIGURE 6-3: OPERATIONAL DISPLAY**

The number of alarms generated in Lewisham ECR in one week from 29/01/2009 to 05/02/2009 was 1884 (Figure 6-4). This means that approximately 10 alarms per hour were generated. Most of these alarms take between 40 seconds to 3 minutes to handle. This number includes alarms and events that operators need to notice but immediate intervention or response is not necessarily required. Cases requiring immediate intervention can be as few as 2 or 3 alarms per hour.

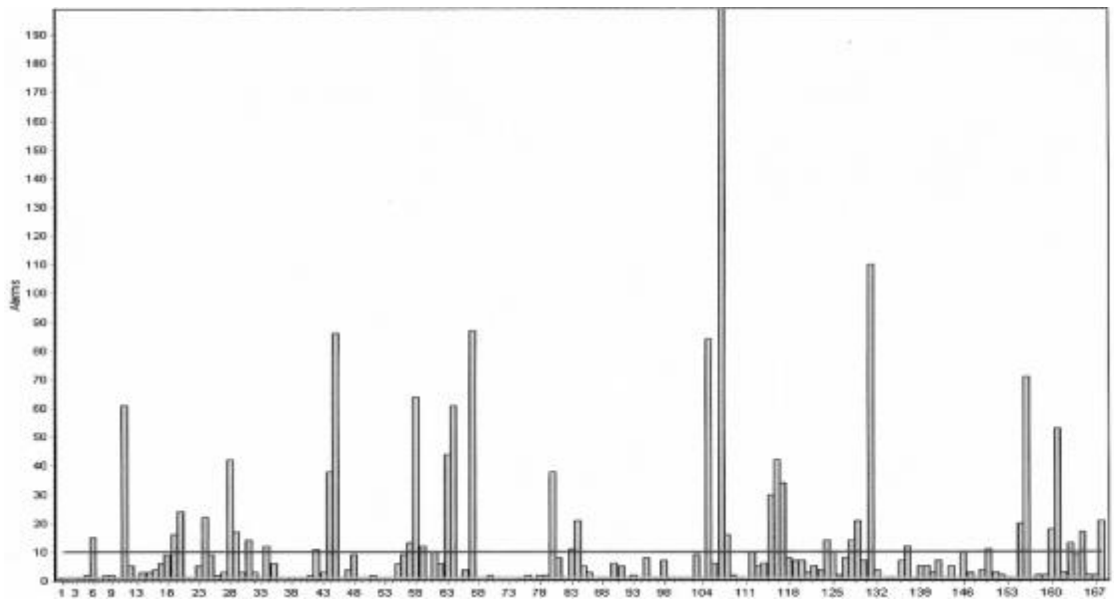


**FIGURE 6-4: ALARM FREQUENCY IN ONE WEEK –THE NUMBER OF ALARMS IN THE HOURS OF ONE WEEK**

In normal situations, many of these alarms will be spurious or confirmations of pre-planned events such as testing, although the operator needs to be vigilant for real alarms amid these low priority events. In emergencies, such as major power failures, the number of incoming events may peak at 200 alarms per hour, which requires the support of relief operators and might lead to major service disruption while the alarms are processed.

During the early field studies, it became apparent that operators had to deal with two types of alarms, referred to as 'expected' and 'unexpected' alarms. Maintenance procedures on the track can cause abnormalities and, consequently, a series of alarms will be generated in the control room. However, in these cases the operators are likely to be expecting the alarm as they know the schedule and details of the maintenance being carried out on the track. Therefore, these alarms would not surprise the operators. This is obviously different to cases when the operators are not expecting the alarm and the alarm therefore alerts them to a new problem.

As noted in the challenges of intelligent infrastructure systems, information overload was considered to be one of the major sources of difficulty in electrical control rooms. Therefore, one of the research questions of this PhD study was to understand how operators deal with multiple sources of information in railway network control problem solving. After the familiarisation visits, operators noted that information deficiencies can mean that alarms may have 'high information' or 'low information'. It should be noted that these terms refer to operators' subjective interpretations of the situation, used since it was not possible to objectively assess the sufficiency and relevancy of the information presented to operators during real-time alarm handling.

'High information' refers to cases in which there is excessive information and the operator is overloaded with unnecessary information (e.g. duplications of sources of information). 'Low information' refers to cases in which the operator does not have sufficient information to diagnose and handle the alarm.

## *6.2. Field study*

The familiarisation visits led to an assessment of the feasibility of and resources required for the field study. Four sessions of 4.5 hours each were planned with the operators. The operators' activities and the use of artefacts when handling real-time alarms (both expected and unexpected) were recorded and analysed in detail.

In order to capture similar numbers of alarms in both groups (expected and unexpected), four different shifts were selected: two day shifts and two night shifts. The familiarisation visits showed that nearly all of the expected alarms occur during night shifts as this is the time usually scheduled for maintenance work.

### *6.2.1. Participants*

Six electrical control room operators in Lewisham participated in the study. They were all male with a mean age of 51 years. According to Network Rail's grading system, which refers to operators' years of experience, qualifications and training, participants were all considered to be competent. They were approached in November 2008 and agreed to participate in the study. Participants were assured about the issues associated with data confidentiality and anonymity. Data were recorded on a basis of the number of alarms generated, not on the basis of the individual attending to them.

### *6.2.2. Apparatus*

A Sony™ digital video recorder was used to record the alarm handling process from the moment the audible siren was generated until it was cleared on the SCADA. A Microsoft™ Excel™ spreadsheet was prepared to structure the findings obtained from the field studies and to provide time-line data of the ECR operator's interaction with the control setting while alarm handling. Moreover, operators were asked to comment on the amount of information presented to them and this comment was also recorded on the spreadsheet. Table 6-2 shows an example of the spreadsheet. This spreadsheet facilitated an understanding of the use of various artefacts used while handling an alarm. Furthermore, since the checklist was time stamped, it was possible to estimate the amount of time each artefact was used, as well as the sequence of use.

The time stamping divides each alarm handling episode into 15 second time frames. In each time frame the use of artefacts was assessed. For example, it was noted if, during the first 15 seconds of alarm handling, the operators were on the phone as well as talking to a colleague in the control room (Face to Face).

Measurements of the occupancy of operators with each of the artefacts provided an understanding of their importance. The total use and overall time used for each artefact were recorded on the checklist.

The final column of the observation checklist specified participants' subjective comments about the amount of information presented to them in relation to handling the alarms. The amount of information to specify one alarm can be more than enough; for example, the operator may get alerted to an alarm through a siren as well as a phone call and flashing annunciators. This would be referred to as 'high information' on the checklist. On the other hand, some of the alarms have no indication at all. For example, alarms known as 'ghost alarms' occur without specific reason and neither of the displays shows any indication of what caused it. This would be labelled as 'low information'. Participants were directly questioned to determine whether the alarm they had been attending to was a case of ‘high information’ or ‘low information’.

Completion of this observation checklist allowed a crude estimation to be made of the degree to which various displays were used during episodes of alarm management. For example, in one episode captured in Table 6-2, twelve uses of various information displays and other sources were noted. In percentage terms, we can see that the alarm banner was utilised on 25% of the occasions of information use (3 out of a total of 12). This allowed some crude estimates to be made of information sources accessed across all 22 alarm handling episodes.

**TABLE 6-2: OBSERVATIONAL CHECKLIST FILLED FOR ONE ALARM EPISODE**

| **Time** | **Artefacts** | | | | | | | | | **Source of difficulty** | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Telephone | Face to face | Alarm banner | Menu | Display area | Page button control | Overview | Static board | Paper | High information | Low information |
| 0:00:01 | ✓ | ✓ | | | | | | | | ✓ | |
| 0:00:16 | | | ✓ | | ✓ | ✓ | | | | | |
| 0:00.31 | | | ✓ | | | ✓ | ✓ | | | | |
| 0:00.46 | | ✓ | | | ✓ | | | ✓ | | | |
| Total (seconds) | 7.5 | 15 | 10 | | 10 | 10 | | 5 | | | |

Finally, a list of generic coping strategies was presented to ECR operators prior to the study and they were subsequently asked to comment on their strategies during various stages of alarm handling. These strategies are taken from Hollnagel and Woods (2005) and are listed in Table 6-3.

**TABLE 6-3: COPING STRATEGIES FOR INFORMATION INPUT OVERLOAD AND INFORMATION INPUT UNDER LOAD (TAKEN FROM HOLLNAGEL & WOODS 2005, PP. 80-81)**

| Strategy | Definition |
|---|---|
| Omission | Temporary, arbitrary non processing of information is lost |
| Reduced precision | Trading precision for speed and time, all input is considered but only superficially; reasoning is shallower |
| Queuing | Delaying response during high load on the assumption that it will be possible to catch up later (stacking input) |
| Filtering | Neglecting to process certain categories; non-processed information is lost |
| Cutting categories | Reduce level of discrimination; use fewer grades or categories to describe input |
| Decentralisation | Distributing processing if possible; calling in assistance |
| Escape | Abandoning the task; giving up completely; leaving the field |
| Extrapolation | Existing evidence is 'stretched' to fit a new situation; extrapolation is usually linear, and is often based on fallacious causal reasoning |
| Frequency gambling | The frequency of occurrence of past items/ event is used as a basis for recognition/ selection |
| Similarity matching | The subjective similarity of past to present items/event is used as a basis for recognition/selection |
| Trial-and-error (random selection) | Interpretations and/ or selection do not follow any systematic principle |
| Laissez-faire | An independent strategy is given up in lieu of just doing what others do |

### *6.2.3. Design*

Four sessions, each of 4.5 hours, were scheduled with 6 ECR operators. Only one workstation (out of the two active workstations) was analysed at each time. As mentioned earlier, there are three desks in Lewisham ECR (Figure 6-5). Desk 'C' is not active and is used only in cases of emergency. Of the two active desks (A and B), one is in charge and has a supervisory role. In order to avoid any bias, two of the field studies were conducted on the supervisory workstation and the other two focused on the other workstation. The details of these sessions are summarised in Table 6-4 below.

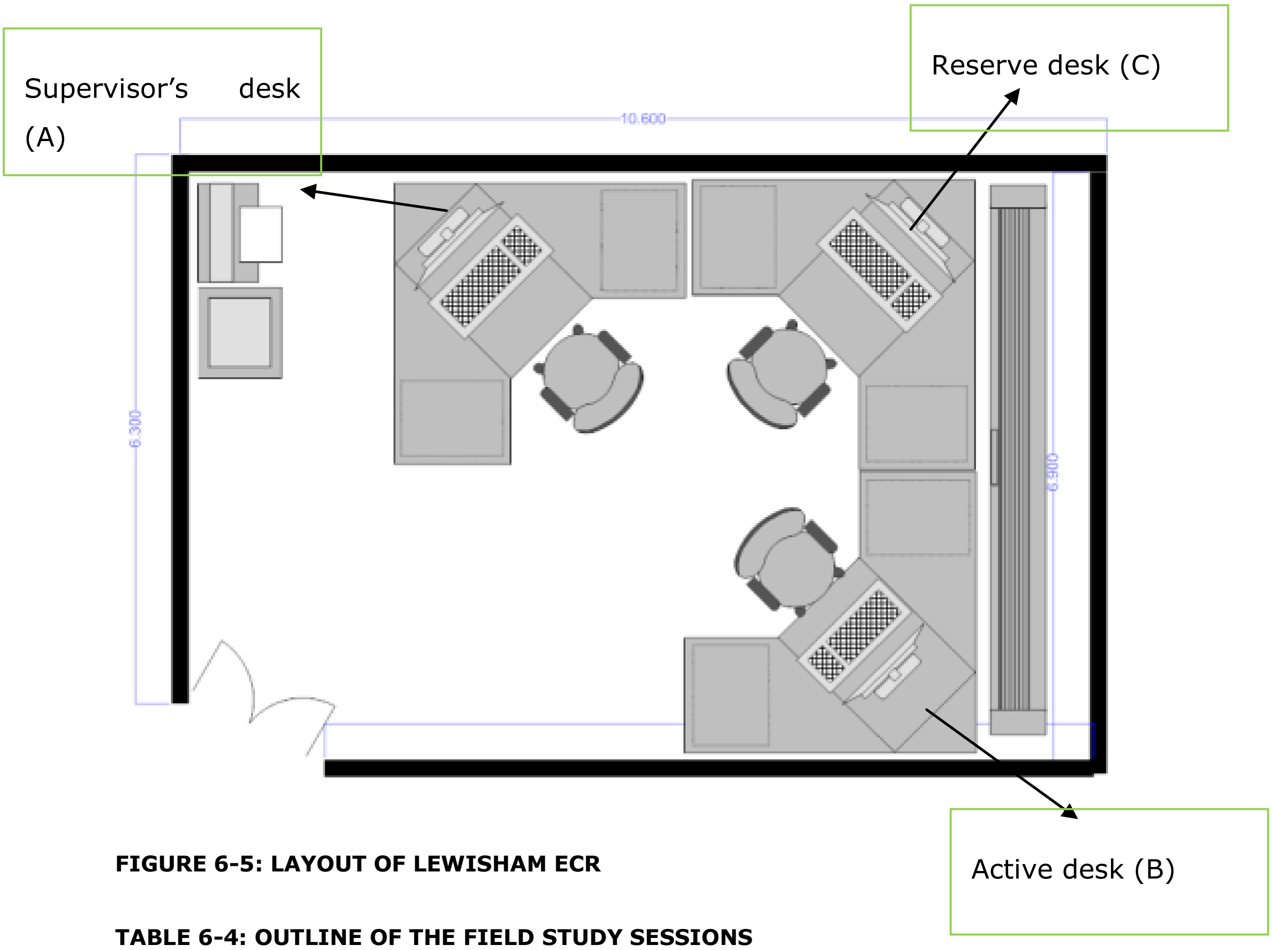



**FIGURE 6-5: LAYOUT OF LEWISHAM ECR**

**TABLE 6-4: OUTLINE OF THE FIELD STUDY SESSIONS**

| Session No | Time/Shift | Workstation studied |
|---|---|---|
| 1 | Day shift | A |
| 2 | Night shift | B |
| 3 | Day shift | B |
| 4 | Night shift | A |

As artefacts utilised for handling alarms are not centralised and are spread out around the control room, it was not possible to fix the location of the camera, which was moved around and zoomed in and out, depending on the alarm episode.

### *6.2.4. Procedure*

Participants were familiarised with the objectives of the research and the scope of the study at the beginning of the session. They reviewed the observation checklist as well as the list of coping strategies. Furthermore, all participants agreed to be video recorded during the study. When an alarm was generated, the researcher would start the video recorder and fill in the checklist. It should be noted that the video enabled revisiting and completing of the checklist with detailed time stampings after the study.

Operators were asked to verbalise their actions regarding the alarm they were handling, also recorded through the camcorder. Finally, their comments regarding the strategies (based on the strategy sheet provided earlier) and whether they were dealing with a case of 'high information' alarm or 'low information' alarm were also captured.

## 6.3. Analysis of field study

During the 18 hours of field study, 22 cases of alarms were generated. Half of these were 'unexpected' and the other half were 'expected' alarms.

The data collected from the observational checklist provided information about the sequence of activities and duration of use of each artefact. A review of operators' comments recorded during the study provided an understanding of the issues and challenges facing the operators while handling alarms. This data were used to develop an understanding of sources of difficulty and possible strategies adopted by operators to cope with these difficulties. Statistical analysis and link charts were used to show the frequency and sequence of activities conducted during an alarm handling episode

### 6.3.1. Artefacts

The following artefacts were utilised by operators whilst alarm handling: menu, alarm banner, display area, page buttons, overview display, static board, paper, phone and face to face communication. Although face to face communication is more of a social activity than physical one, it has been considered as a "social artefact" here since this form of communication represents an important source of information for operators; neglecting it would lead to gaps in the activity analysis. Likewise the telephone (and its use) might be regarded as a mixed physical and social artefact. The artefacts are shown in Figure 6-6 below:

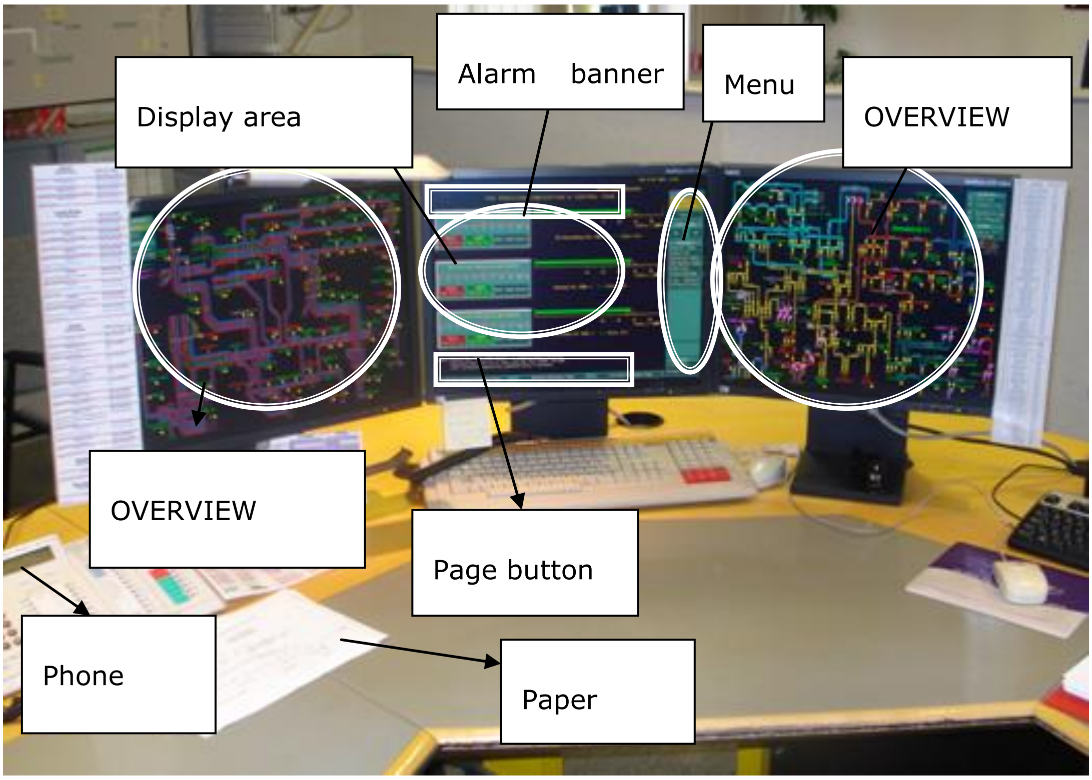



**FIGURE 6-6: ARTEFACTS OF ALARM HANDLING**

### *6.3.2. Frequency and sequence of use*

For the 22 alarm cases, the time line observation checklist provides an understanding of the frequency and total duration of use of the artefacts. An example of a filled-in observational checklist is shown in Figure 6-7 below. A selection of completed observational checklist are shown in Appendix 12.4.

| | tell | F2F | alarm banne | Menu | Dispay area | ge button cr | overview | board | paper | Main activity |
|---|---|---|---|---|---|---|---|---|---|---|
| 0:00:01 | 0 | 0 | 0.5 | 0 | 0.5 | 0 | 0 | 0 | 0 | Notification-acceptance |
| 0:00:16 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | analysis |
| 0:00:30 | 0 | 0 | 0 | 0.5 | 0.5 | 0 | 0 | 0 | 0 | analysis |
| 0:00:45 | 0 | 0 | 0 | 0.33 | 0.33 | 0 | 0.33 | 0 | 0 | clearance |
| 0:01:00 | 0 | 0 | 0 | 0.5 | 0.5 | 0 | 0 | 0 | 0 | clearance |
| 0:01:14 | 0 | 0 | 0 | 0.33 | 0.33 | 0 | 0.33 | 0 | 0 | clearance |

**FIGURE 6-7: EXAMPLE OF OBSERVATIONAL CHECKLIST TO CAPTURE THE TIME ASSOCIATED WITH DIFFERENT ARTEFACTS DURING ALARM HANDLING**

For further analysis, link charts were used to show the interactions between various artefacts. Figure 6-8 and Figure 6-9 show the link charts of expected and unexpected alarms respectively. The number within each circle represents the total duration (seconds) of use for each of these artefacts; the links between the circles show the numbers of direct transfers from use of one artefact to use of another. The total duration of the 11 'unexpected' alarms observed during this study was 919 seconds and total duration of the 11 'expected' alarms observed was 520 seconds. The alarm banner, the display area and the menu on the operational display are the three most used artefacts for handling 'unexpected' alarms. On the other hand, the alarm banner and the telephone are the most utilised artefacts while operators are handling 'expected' alarms. The reason for this difference is that, in the case of an expected alarm, operators only need to verify and confirm an expected event through either a telephone call from a member of the maintenance team or an updated alarm banner.

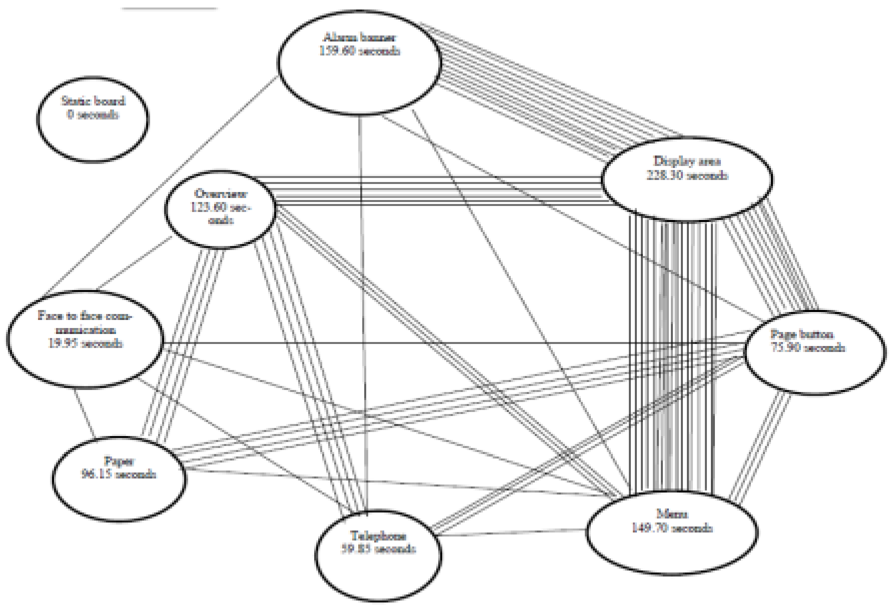



**FIGURE 6-8: LINK CHART FOR "UNEXPECTED" ALARM HANDLING**

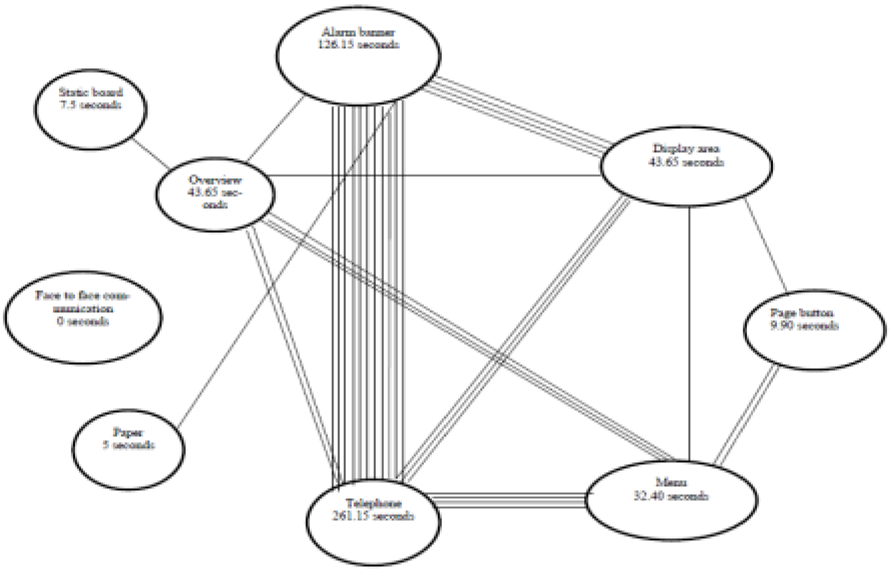



**FIGURE 6-9: LINK CHART FOR "EXPECTED" ALARM HANDLING**

The link charts provide an understanding of the frequency and interactions of various artefacts, although the order in which the activities are performed is not shown. Information about the sequence of activities will help develop an understanding of the context. This understanding can be facilitated through the CWA and the integration of the different forms of analysis, as described in section 6.40 of this chapter.

### *6.3.3. Statistical analysis*

'Expected' and 'unexpected' alarms, as well as alarms labelled as 'high information' and 'low information', were analysed statistically. Hypotheses examined in these analyses were:

H1: There is a significant difference between the use of artefacts in expected and unexpected alarms.

Independent variable: type of alarm→ expected and unexpected

Dependent variable: Number of the interactions with artefacts→ telephone, face to face communication, alarm banner, menu, display area, page button, overview displays, board and paper.

H2: There is a significant difference in use of artefacts between high information and low information.

Independent variable: Amount of information→ high information and low information

Dependent variable: Number of the interactions with artefacts→ telephone, face to face communication, alarm banner, menu, display area, page button, overview displays), board and paper.

An independent sample t-test was used for the statistical analysis. The use of telephones and the display area were found to be significantly different, depending on the type of alarm. There was a significant difference between the number of times operators used the telephone in unexpected (M=0.131, SD=0.340) and expected conditions (M=0.592, SD=0.050); t (86) =-5.044, P<0.01. Also there was a significant difference between the number of times operators interacted with the display area in unexpected (M=0.524, STD=0.503) and expected (M=0.222, STD=0.423) conditions; t (86) = 2.721, p<0.01.

Figure 6-10 shows the mean percentage of interactions with each of the artefacts in the unexpected and expected alarms. Use of face to face communication, menu, display, page button, overview and paper was higher for expected alarms, whereas the use of the phone and alarm banner was greater for the unexpected alarms.

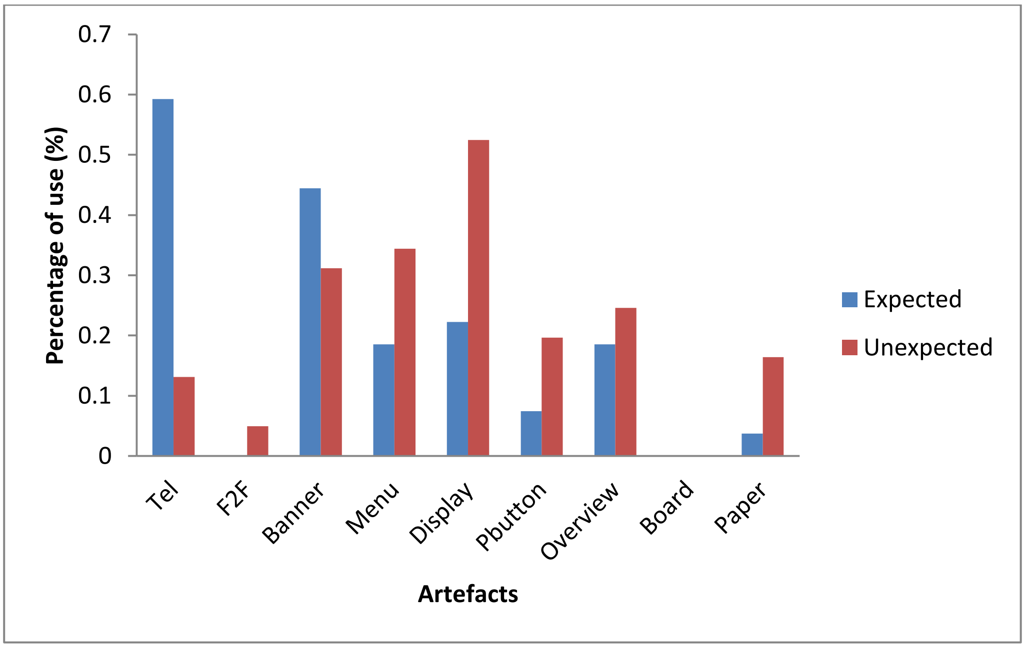



**FIGURE 6-10: ARTEFACTS IN EXPECTED AND UNEXPECTED ALARMS**

In order to investigate the differences in the use of artefacts between high information (M=0.38, STD=0.49) and low information (M=0.84, STD=0.37), an independent samples t-test was applied. The results revealed that the display area attendance is significantly higher in alarms due to high information; t (59) = -3.63, p<0.01. Figure 6-11 shows the mean percentage of the application of artefacts in high information and low information situations.

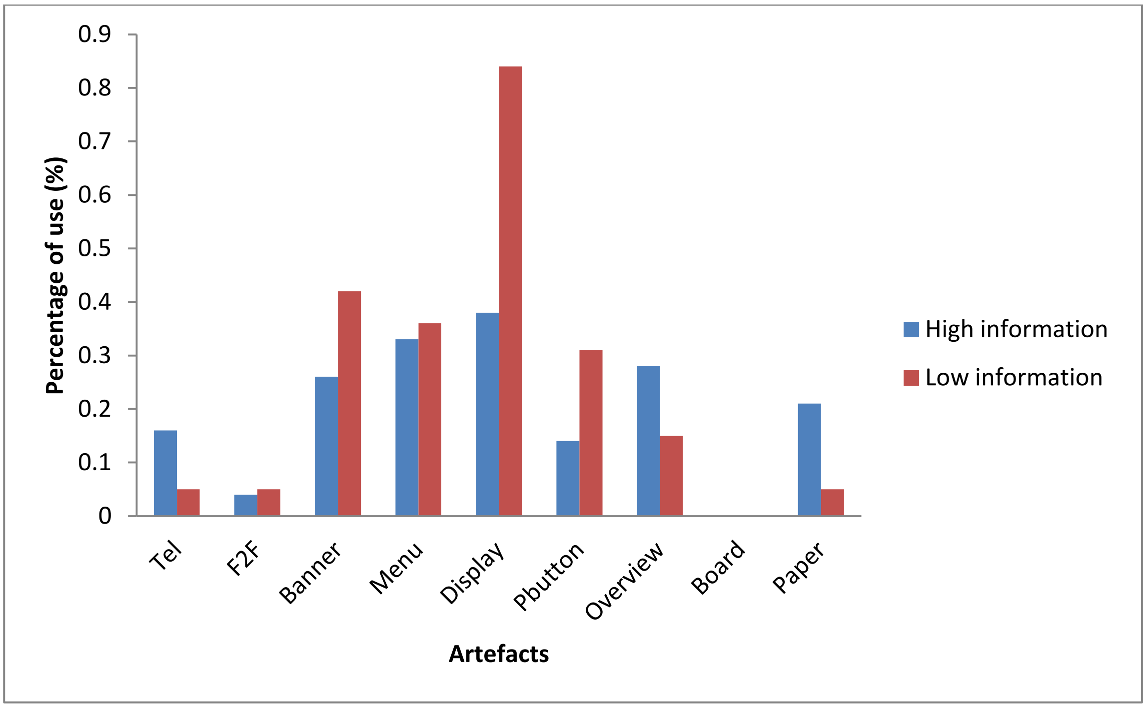



**FIGURE 6-11: ARTEFACTS IN HIGH INFORMATION AND LOW INFORMATION ALARMS**

## *6.4. Cognitive work analysis*

CWA was performed to enable structuring of the data collected from the field study and to direct these towards contextual understanding of the domain. Four stages of the CWA were performed according to Lintern (2009). Table 6-5 summarises these stages and the methods of data collection that fed each stage. It should be noted that, for simplicity, both analysis and immediate findings of various stages of CWA are reported in this section.

**TABLE 6-5: COGNITIVE WORK ANALYSIS OF RAILWAY ELECTRICAL CONTROL ROOM**

| CWA stages (Lintern 2009) | Definition | Methods of data collection |
|---|---|---|
| Work domain analysis | Activity-independent structure of work | 18 hours of field study<br>Semi-structured interviews<br>Open-ended interviews |
| Work organisation analysis | Associates tasks with work situations | Observational checklist<br>Video recordings |
| Cognitive transformation analysis | States and processes required for the tasks | Observational checklist<br>Video recordings |
| Strategies analysis | Identify strategies for each of the states and processes | Video recordings<br>Talk aloud<br>Coping strategy sheet |

### *6.4.1. Work domain analysis*

Work domain analysis focuses on the functional (activity independent) structure of the work and consists of an Abstraction Hierarchy with five levels: domain purpose, domain values and priorities, domain functions, physical functions and physical objects (Figure 6-12).

Domain purpose refers to the overall objectives of the system. Values and priorities refer to benefits if the task is performed successfully. Domain function describes the tasks that have to be achieved. Physical functions are the physical outcomes of conducting the tasks and, finally, physical objects are the artefacts and tools used in the control room to enable these physical functions.

Interviews conducted in the familiarisation visits provided the researcher with knowledge to identify physical objects (e.g. SCADA, maps, logs, etc.) and physical functions required to meet the domain functions. The observational checklist used throughout this study showed the connection between different physical objects and their use for achieving different tasks. In addition, operators' comments highlighted the values and purposes of each function.

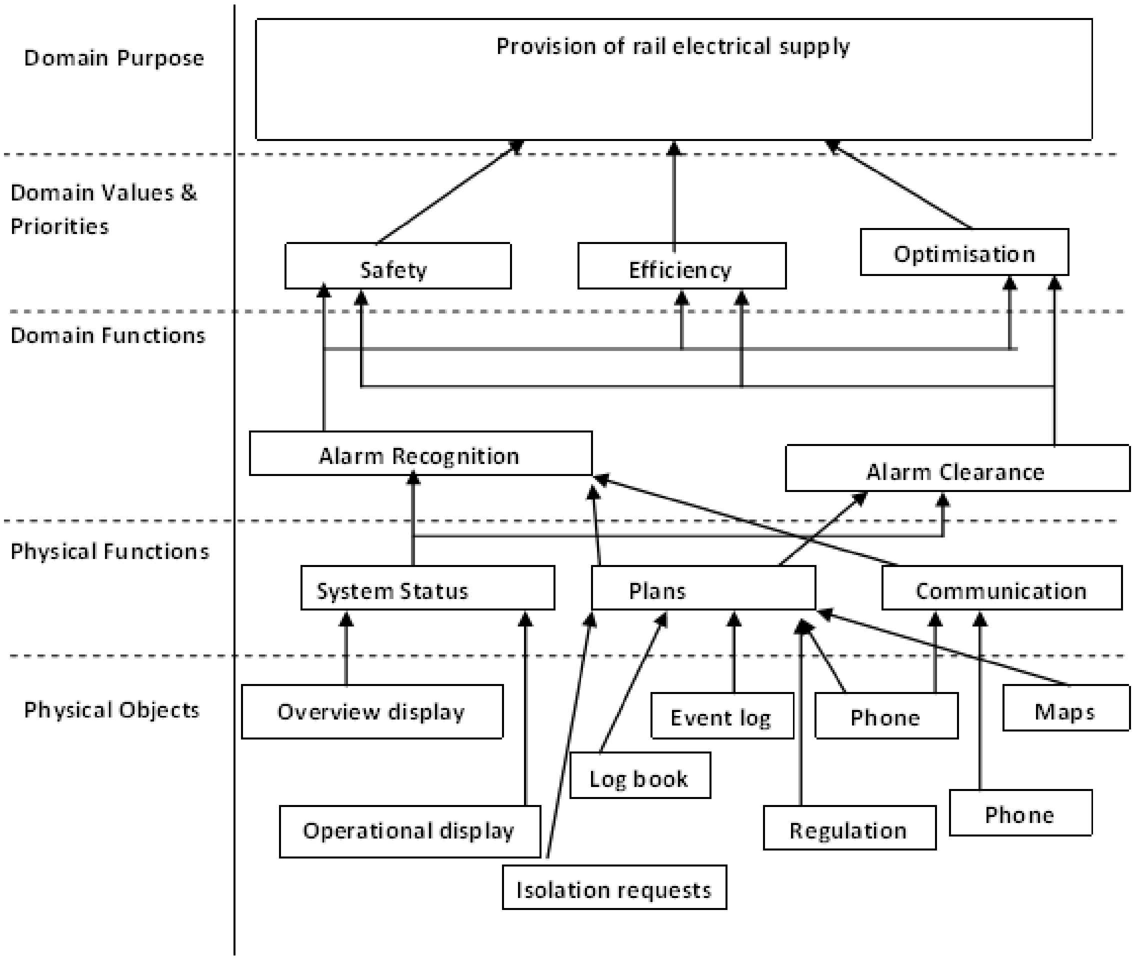



**FIGURE 6-12: ABSTRACTION HIERARCHY FOR ALARMS**

Physical objects utilised by operators during alarm handling include SCADA, log book, phone, map, regulations and isolation requests. Also, the operators might consult with colleagues in the control room or call someone on-site to obtain more information; this form of social relationship is referred to here as 'face to face' communication. Use of these physical objects enables operators to achieve an understanding of system status as well as the optimum plan they ought to develop and follow (Physical functions). Alarm handling can be broken down into two main functions of alarm recognition and alarm clearance (domain functions), with the purpose of ensuring the safety and efficiency of the operation and optimising the use of resources within the railway (domain values and priorities). This activity is embedded within the overall goal of providing a continuous electrical supply to the rail network (domain purpose).

### 6.4.2. Work organisation analysis

Work Organisation Analysis is used to associate tasks required for the domain functions, identified in the abstraction hierarchy, with the situations in which the work takes place (Figure 6-13). It is usual to associate these situations with physical locations. For example, in an air traffic control study (Vicente, 1999), work situations refer to three different locations: pilot's cockpit, air traffic control room and the on ground maintenance team.

For this stage of the analysis, recordings of the alarm handling cases provided detailed information regarding the artefacts used for each of the tasks. For instance, in order to recognise an alarm, operators have to identify the priority of that alarm, locate the fault and assess if the information required for handling the alarm is available. They must then collect the necessary information and, finally, start diagnosing the cause of the alarm. The boxes in Figure 6-13 show the overall spectrum of artefacts that can potentially be used for each task. The shaded circles highlight the most used artefact for each task and the whiskers show the distribution of the artefacts most likely to be used.

This analysis allows the work functions identified at the abstraction hierarchy stage - alarm recognition and alarm clearance - to be tied to specific work contexts and artefacts. By using the matrix in this way, we are able to provide greater clarity in terms of where each of the constraints identified in the AH may be most relevant. For example, the main display is used in all work tasks, whereas the phone is used only in two stages (identify priority and information collection) as is face to face communication (information collection and assess the alarm).

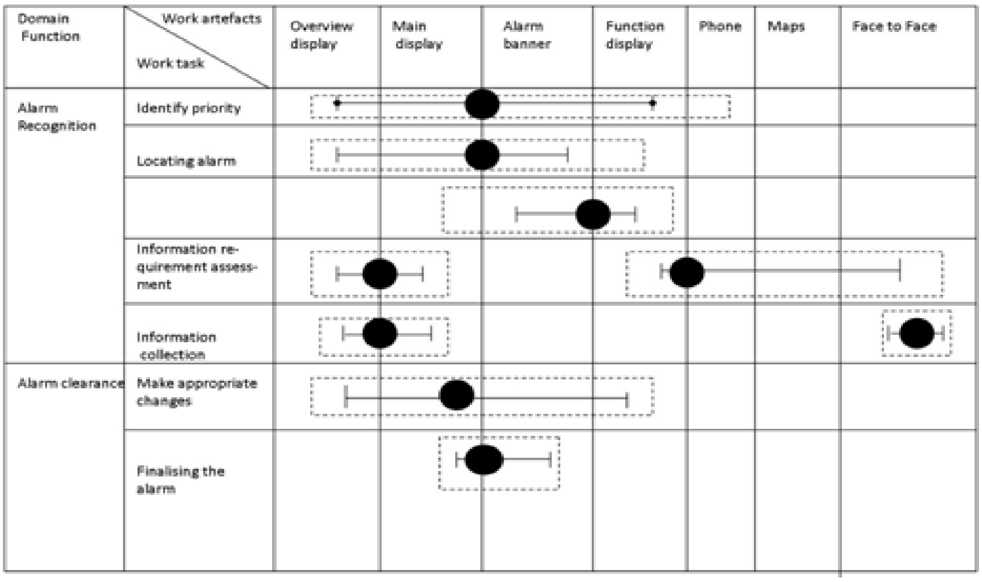



**FIGURE 6-13: ALARM HANDLING CONTEXTUAL ACTIVITY MATRIX**

### *6.4.3. Cognitive transformation analysis*

Cognitive transformation analysis aims to identify the cognitive activity associated with work tasks identified in the previous stage. Two representations are used – state process diagrams (Figure 6-14) and decision ladders (Figure 6-15). The cognitive states and cognitive processes of these work tasks are identified and presented using state process diagrams (Figure 6-14). Ovals in the figure present cognitive states and arrows show cognitive processes that guide the flow between cognitive states.

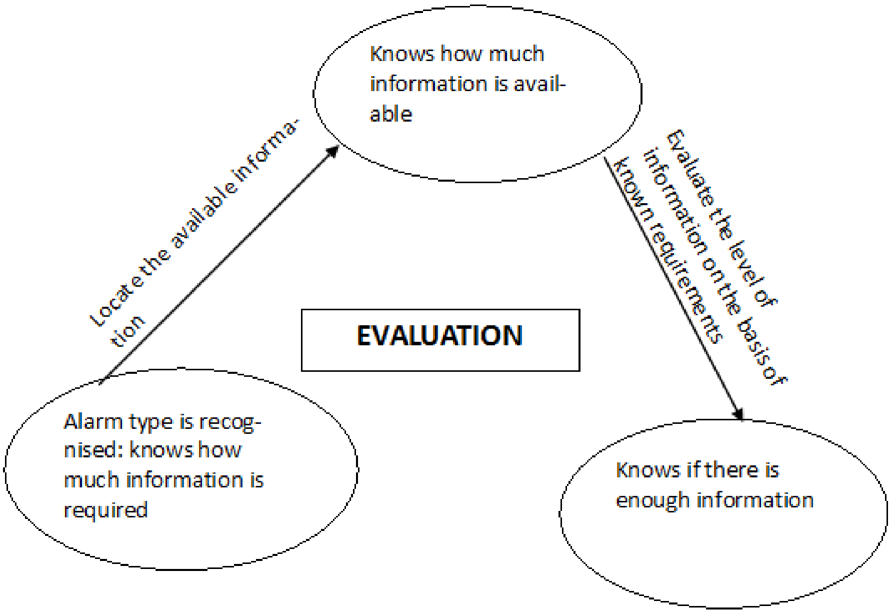



**FIGURE 6-14: EXAMPLE OF A STATE-PROCESS DIAGRAM FOR THE WORK TASK OF INFORMATION REQUIREMENT ASSESSMENT**

The seven tasks noted in the contextual activity matrix (Figure 6-13) were used as the basis for this stage. Operators were asked, retrospectively, to describe the reasoning behind their decisions during these tasks. This provided an understanding of the processes required for the tasks and the states of thinking associated with them. For each task, operators' comments show a pattern in how would they behave and this led to development of diagrams such as that shown in Figure 6-14, other examples are shown in appendix 12.5. These state process diagrams were then compiled in the form of a decision ladder (Rasmussen et al., 1994), as shown in Figure 6-15.

The value of presenting the cognitive activity of alarm handling in this manner is that it allows higher order groupings or stages of processing to be presented. In this case, these are notification, acceptance analysis and clearance. These stages broadly correspond to the alarm initiated activities identified by  Stanton (2006): observe, accept, analyse, correct, monitor, investigate and reset .These higher order stages serve as the basis for the strategy analysis, conducted next.

The decision ladder provides a sequential representation of the cognitive processing relevant to alarm handling. However, it also supports the representation of different routes through the generic process. The bold arrow represents a leap between alarm acceptance and alarm clearance and reflects the handling of expected maintenance alarms, where the operator has prior knowledge of the likely occurrence of the alarm before the actual generation of the alarm. As a result of this existing prior knowledge, no evaluation or analysis is required. By extension, none of the information sources relevant to evaluation or analysis is therefore required. This also demonstrates the additional steps (and information sources) that will be required when the alarm is genuine (i.e. the additional steps required for alarm acceptance and alarm analysis).

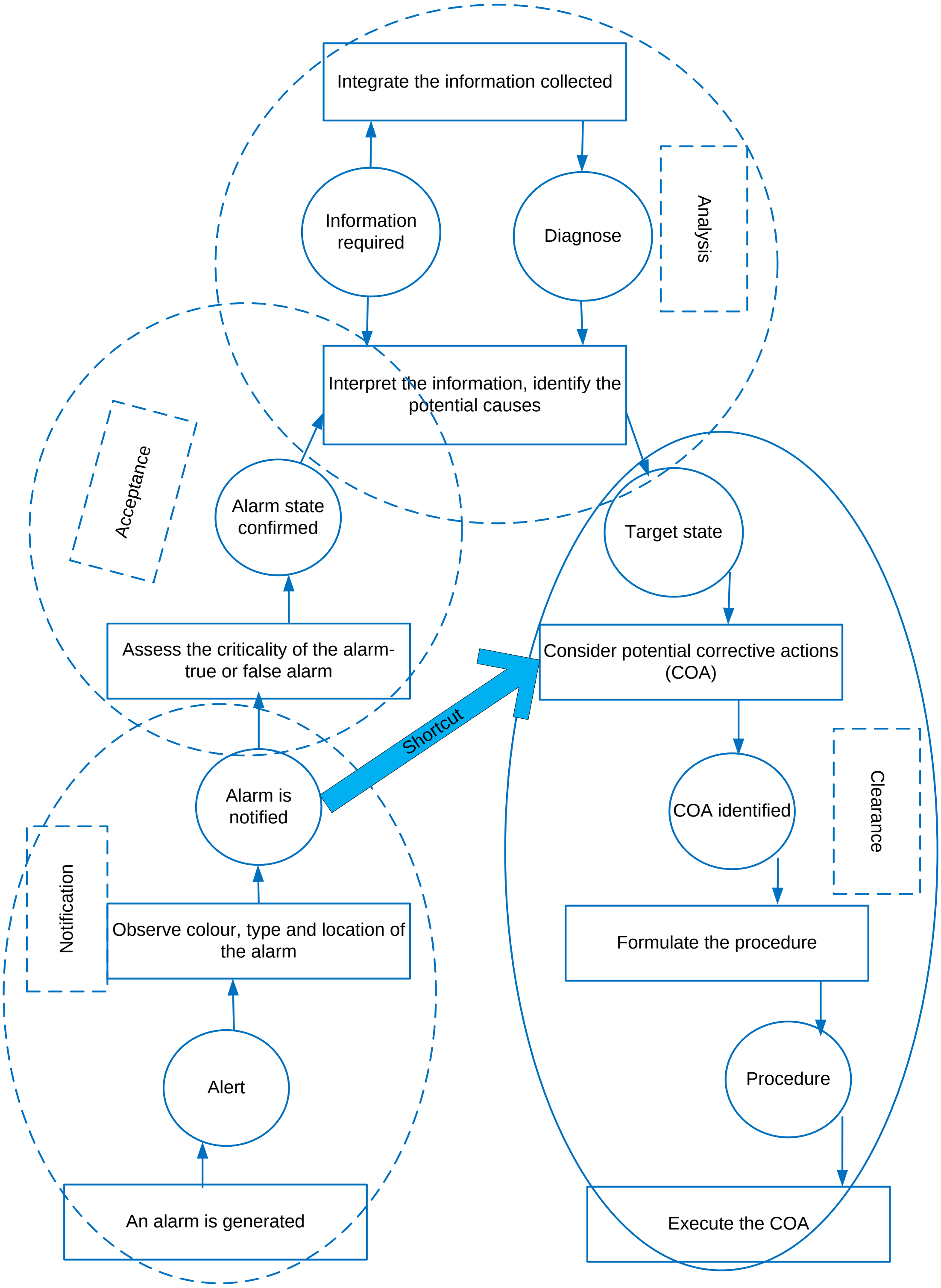



**FIGURE 6-15: ALARM HANDLING DECISION LADDER**

### *6.4.4. Strategies analysis*

Prior to the field studies, participants were introduced to the different types of generic coping strategies (Table 6-3). In the initial observations, participants were prompted, during alarm cases, to specify which strategy they were using at any given point. This made it possible, in the final two observation sessions, to infer the strategies from participants' comments and video recordings. Certain strategies (filtering, queuing, categorising, similarity matching and extrapolation) emerged in the majority of the cases. Figure 6-16 shows an example of a spreadsheet, where operators were asked to identify the strategies they used at different stages of their alarm handling.

| Ti me line | Artefacts | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Social (communication) | | technical artefacts | | | | | | | Coping with complexity | | | | | | | | | | | | | | | | | | | |
| | tell | F2F | main display | | | | Over view | Board | Paper | Time | Time% | Knowledge | Knowledge % | Competence | Comp% | Resources | Res% | | | | | | | | | | | | |
| | | | alarm banner | Menu | Display area | Page button cntrl | | | | | | | | | | | | Ommission | Reduced Precision | Queuing | Filtering | Cutting categories | Decentralisation | Escape | Frequency Gampling | Similarty matching | Extrapolation | Trial and Error | Laissez-faire |
| 0:00:01 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 0.667 | 9 | 1 | 9 | 1 | 6 | 0.67 | | | | 1 | | | | | | | | |
| 0:00:16 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 5 | 0.556 | 9 | 1 | 9 | 1 | 7 | 0.78 | | | | | | | | | 1 | | | |
| 0:00:30 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 5 | 0.556 | 9 | 1 | 9 | 1 | 7 | 0.78 | | | | | | | | | 1 | | | |
| 0:00:45 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 9 | 1 | 9 | 1 | 9 | 1 | 8 | 0.89 | | | | | | | | | 1 | | | |

**FIGURE 6-16: EXAMPLE OF SPREADSHEET THAT WAS USED TO CONSULT ECR OPERATORS REGARDING THEIR STRATEGIES**

From this analysis, it was possible to assign specific strategies to the high-level cognitive processing stages identified on the decision ladder. Figure 6-17 shows the alarm initiated activities, together with the strategies found to support those activities (marked in bold). It was important to recognise the temporal aspect of these strategies. This required synthesising the findings from various forms of data collection (e.g. verbal protocol, observational checklist and video recordings) - to be discussed in the next section.

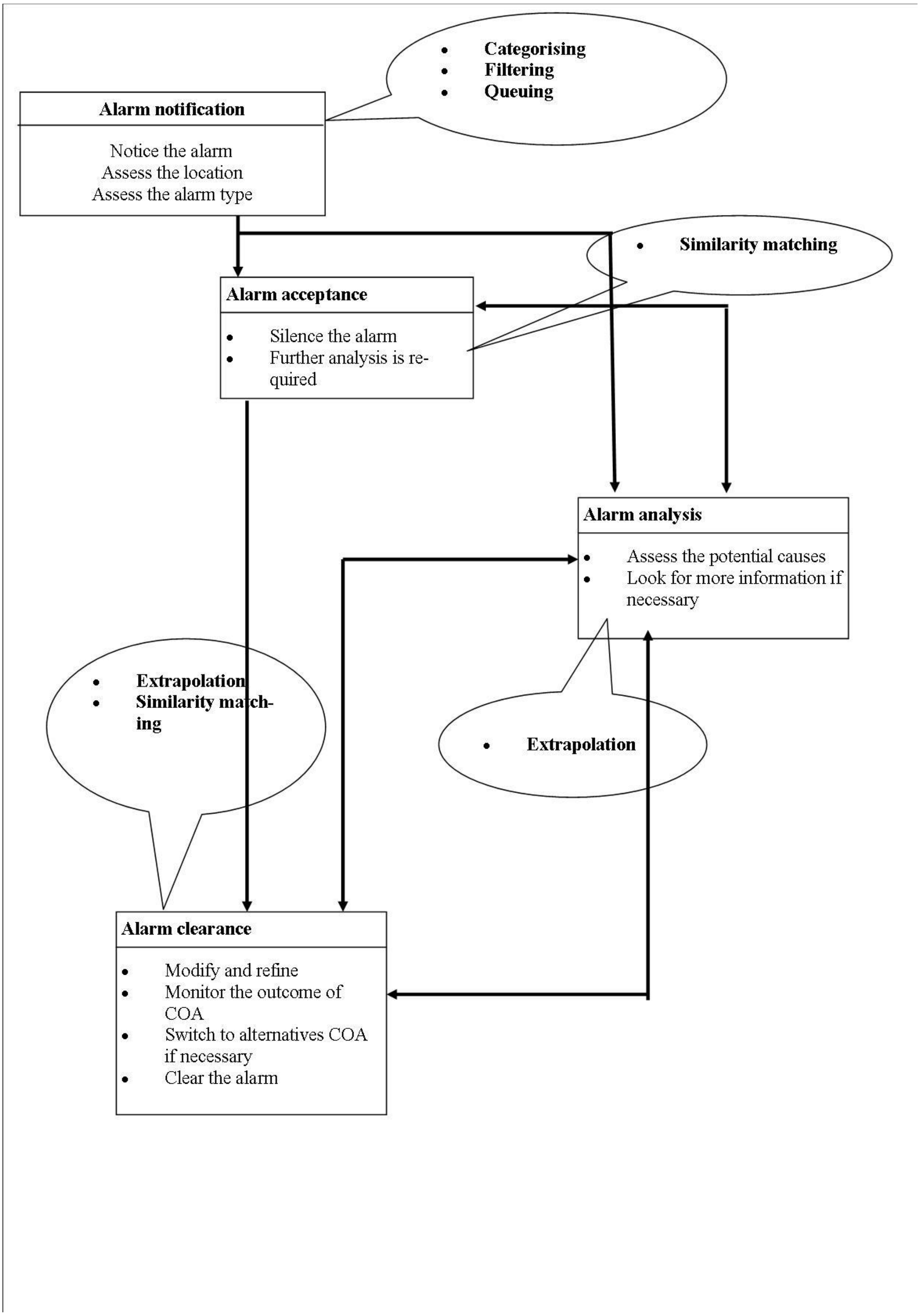



**FIGURE 6-17: ALARM HANDLING ACTIVITIES AND STRATEGIES**

*Notification*:

Several information sources notify operators of the existence of an alarm. These include: the flashing alarm banner, colour codes, acronyms of alarm type and location, sirens, phone calls, a flashing circle around the location on the overview display, etc. Operators have to *categorise* and *filter* these sources to achieve a basic understanding of the alarm. In the case of multiple alarms, operators *queue* them, based on their experience.

*Acceptance*:

The situation awareness we assume to be built into the previous stage (notification) is the basis on which the operator almost immediately accepts the alarm and silences the siren without informing an authorised person. In the rare cases of an alarm where immediate on-site action is required, operators use their knowledge of the track, the electrical equipment, the work that might be taking place out there and the train service running, as well as their experience of previous similar cases in order to assess the criticality of the alarm. The strategy at this stage is mostly *similarity matching,* which is highly related to operators' experience. Usually, this stage is tightly coupled with the analysis and assessment of the alarm.

*Analysis*:

Information presented to the operator is being used by them for the purpose of assessing and evaluating the underlying meaning and causes of alarms. Operators generally analyse alarms by stretching the existing evidence to match them with similar cases (*extrapolation*). Unlike similarity matching, where all of the evidence is matched with a similar previous alarm, here the operator has to use their imagination to fill the gaps until a similarity is perceived.

*Clearance*:

The operator identifies possible courses of action, evaluates them and executes the optimum action to clear the alarm. The operator remembers similar cases and tries to match the stretched evidence to other potential (*similarity matching and extrapolation*) causes and trials the corrective actions of those cases (*trial and error*).

## *6.5. Integration of the findings*

A wide range of methods of data collection and analysis was used to facilitate an exploration and investigation of alarm handling activities in ECR. This section reports the findings that were integrated from the field analysis and the CWA. The first section explains the artefacts used in the ECR for handling alarms and the difference in their interaction and frequency of use, depending on various types of alarms, i.e., expected vs. unexpected; high information vs. low information. The second part describes the activities conducted by operators to handle an alarm and their strategies to cope with system constraints, i.e., information deficiencies.

### *6.5.1. Use of artefacts*

The link charts described in section 6.3.2 reported the frequency as well as the sequence of interactions with different artefacts when operators were handling different types of alarms. The field study suggested that the most utilised artefact during handling the 'unexpected' alarms was the display area. From a total of 919 seconds of the 'unexpected' alarm handling, operators were using the display area for 238 seconds, the alarm banner for 159 seconds and the menu for 149 seconds.

Also, in terms of interaction and sequence of attending to different artefacts, operators attend to the alarm banner first and then observe the display area. Then, depending on the alarm episode, they use the menu to handle the alarm or, if the situation is not yet diagnosed, they attend to the page buttons to investigate the alarm in more detail.

### *6.5.2. Activities and strategies*

This study explored alarm handling in ECR and it became possible to understand operators' higher stage of cognitive processing and the artefacts that support these stages. Activities were identified as part of alarm handling procedure: notification, acceptance, diagnosis and clearance. Furthermore, CWA facilitated the association of these activities with different artefacts. For example, the alarm banner is most used during alarm notification; the telephone is the most used artefact when operators are clearing the alarms. Figure 6-18 shows the duration of use of various artefacts and their use during various alarm handling activities.

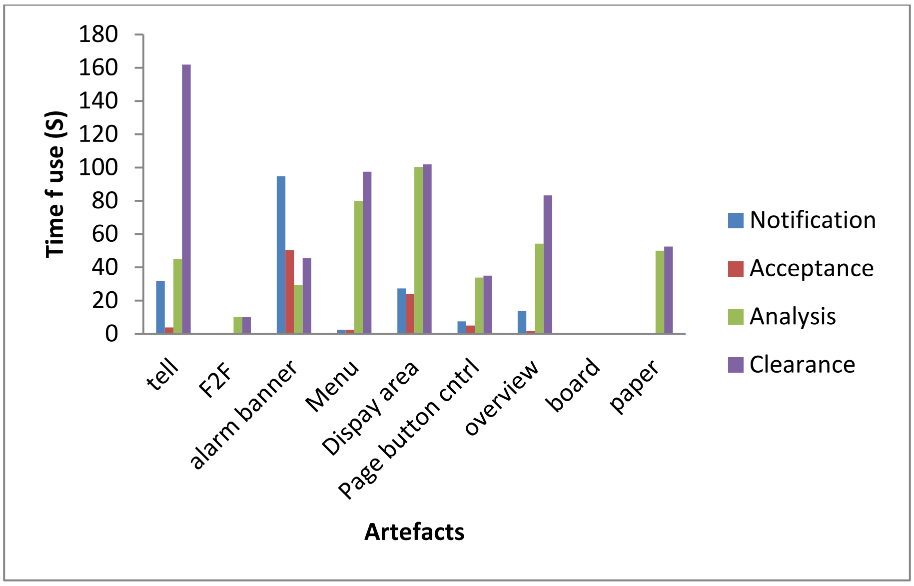



**FIGURE 6-18: ARTEFACT USE AND ALARM HANDLING STAGES**

In summary, this analysis has identified the strategies adopted by rail ECR operators whilst they cope with information presentation inefficiencies of too much or too little information when handling alarms. The main strategies identified are: categorising, filtering, similarity matching, extrapolation. Queuing and trial and error, which emerged in only one of the cases were left out due their limited occurrence. Details of these and their corresponding activities are described in 6.4.4. The last three of them (similarity matching, extrapolation and trial and error) are related to the operator's experience and local knowledge as it was found from their comments (Appendix 12.6). Alarm systems should be designed to provide better support, for instance, by providing historical and statistical information relevant to the alarm. The potential risks are also demonstrated – for example, extrapolation may lead operators to apply inappropriate prior knowledge.

Integration of the time-stamped observational checklist, with the strategy analysis, led to the development of an understanding of the order of activities, as well as the strategies adopted by operators Figure 6-19 and

Figure 6-20 show the order of activities for 'expected' and 'unexpected' alarms. The 'Y' axis shows each of the 11 episodes of alarms and the 'X' axis shows the duration of alarm handling in 15 second pieces.

The comparison between the two (expected vs. unexpected) reveals that, in the latter, only notification and clearance are performed, as the alarm is already known and no acceptance or analysis is required.

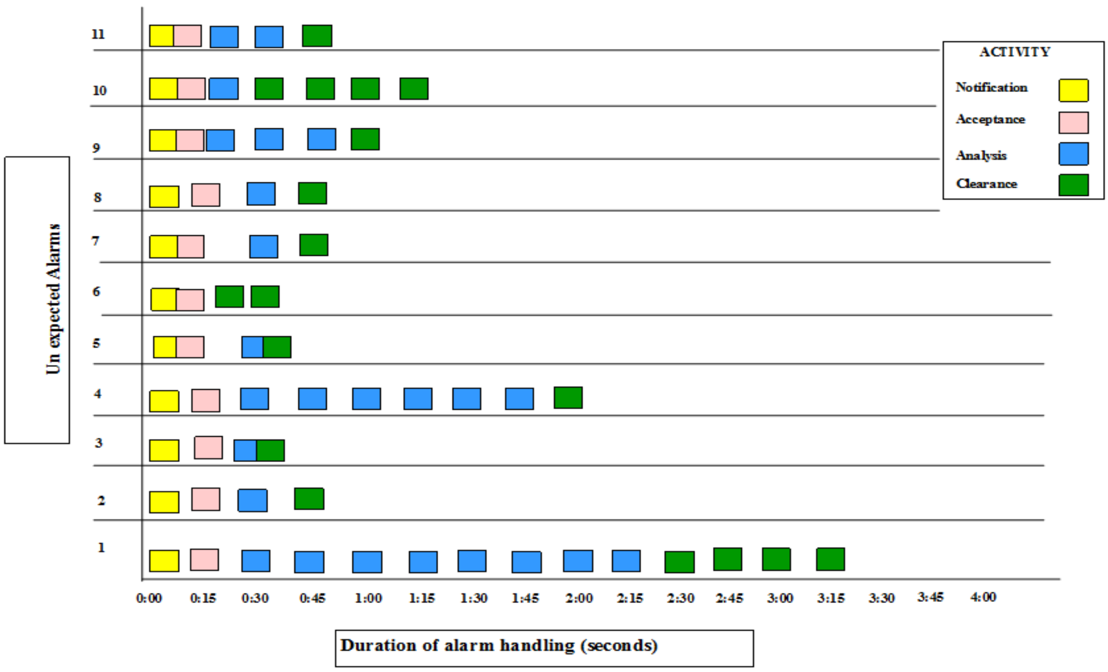



**FIGURE 6-19: ORDER OF ALARM HANDLING ACTIVITIES FOR UNEXPECTED ALARMS**

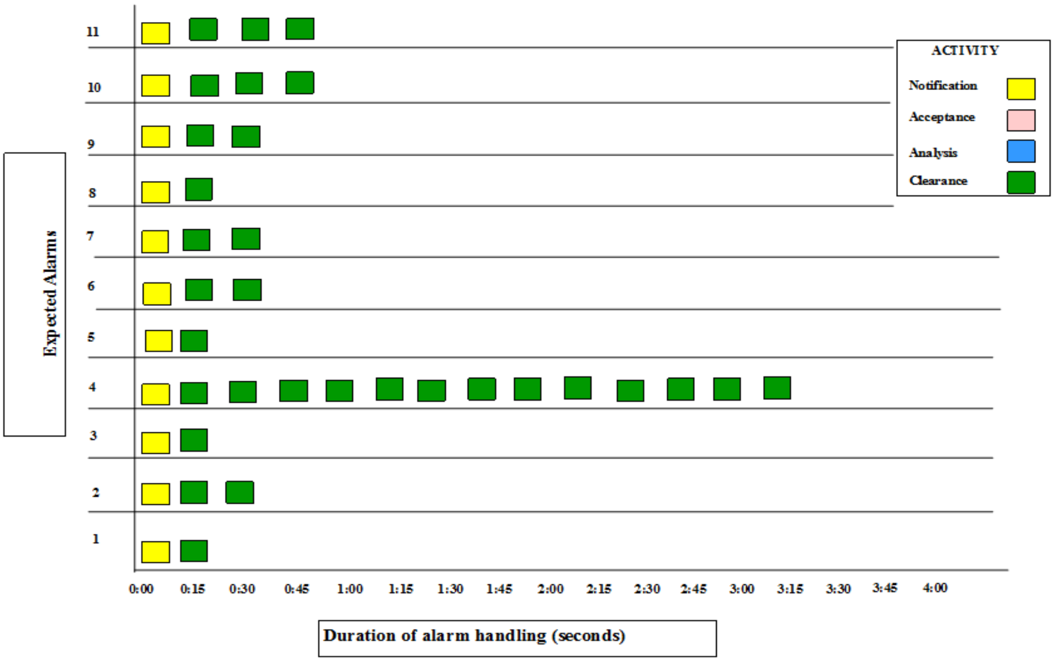



**FIGURE 6-20: ORDER OF ALARM HANDLING ACTIVITIES FOR EXPECTED ALARMS**

The same approach was used to identify the order of strategies used during alarm handling. This is shown in Figure 6-21 and Figure 6-22.

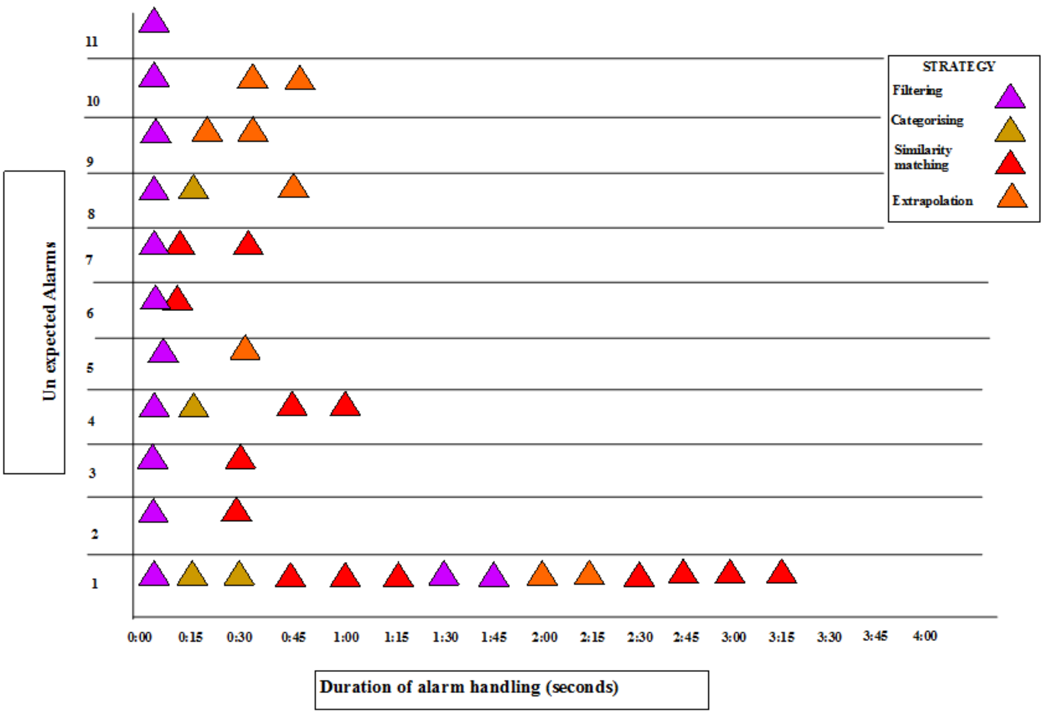



**FIGURE 6-21: ORDER OF ALARM HANDLING STRATEGIES FOR UNEXPECTED ALARMS**

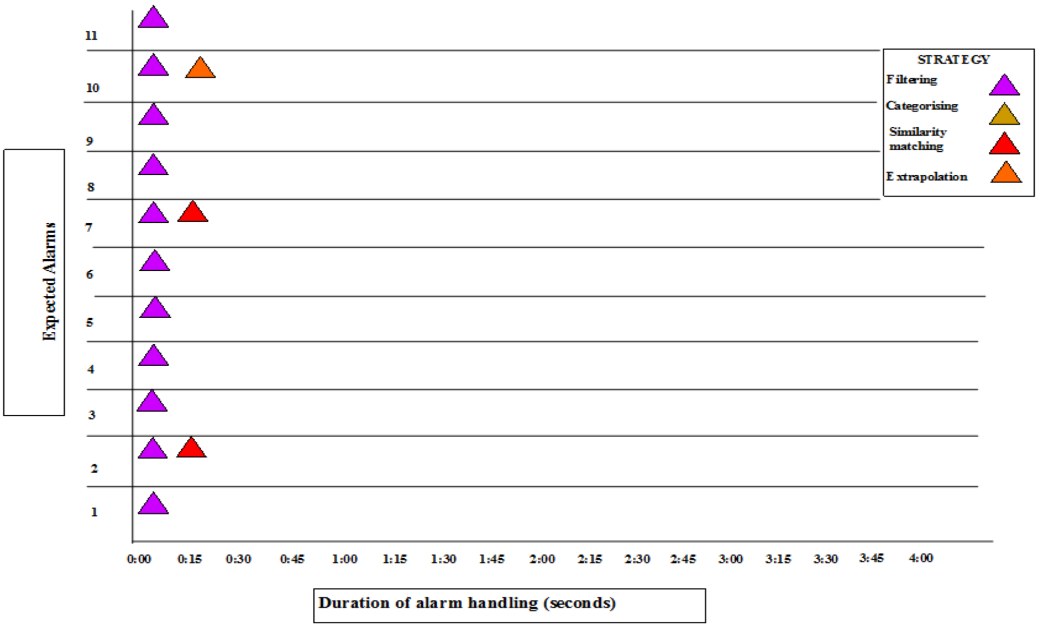



**FIGURE 6-22: ORDER OF ALARM HANDLING STRATEGIES FOR EXPECTED ALARMS**

It is evident from these figures that operators do not need to adopt many strategies when handling expected alarms. They filter the type of alarm as they notice it and occasionally match the alarm with previous similar ones or extrapolate the evidence when clearing the alarm.

## *6.6. Discussion*

This chapter reports a study that was conducted to guide two of the objectives of this PhD study:

- To establish an understanding of operators' strategies for human supervisory control task in alarm handling and fault finding.
- To produce human factor guidance for the future development and implementation of an intelligent infrastructure system in the railway to match and complement human capabilities and needs.

Alarm handling was selected and explored as the representative case of the future intelligent infrastructure system. The findings reported in this chapter so far have identified activities, artefacts and strategies associated with alarm handling. A wide range of data collection and data analysis techniques were utilised to ensure that different features of alarm handling (e.g. frequency, sequence, strategies, time) were included.

In this thesis four stages of CWA have been applied to capture the cognitive processing relevant to alarm handling. The value of each analytical form and how it can help with the design of alarm systems was illustrated in the findings. What emerges from the use of these analyses in combination is how these analytical forms work together to build a detailed view of the cognitive requirements of a given work domain. The abstraction hierarchy showed functions embedded in a physical and organisational context. These functions are elaborated in the contextual activity matrix, in terms of corresponding tasks and work situations. The cognitive transformations underlying these tasks are represented in the decision ladder, which highlights higher order stages of processing. These higher order stages inform strategy analysis, which can lead to design requirements.

One of the indirect findings of this work is the understanding obtained about the process of applying multiple stages of CWA. Certain considerations have come to light that may influence the success of applying this approach. Different stages of CWA aim to explore various aspects of socio-technical environments. It is important to use the right stage for the right purpose and it is not always necessary to perform all stages of CWA. If the requirement of the case presented here was to only explore the domain and provide an initial understanding of ECR alarms, then the first few stages would have sufficed and given additional value in comparison to applying traditional task analysis methods (Golightly, Ryan & Sharples, 2011). If, however, the intention is to generate design guidance then we believe it is better to perform a complete CWA.

CWA is a framework rather than a method; therefore there are few guidelines about which methods should be deployed to apply this framework to the understanding of a system. The choice of appropriate methods to capture data is therefore crucial and the analysis involved can be time-intensive. In the case of the ECR study, a total of 20 hours of observation was conducted together with SME interviews to provide an appropriate level of understanding. It is also important to choose the appropriate methods to elicit data from observations. In this case, observational checklists were used to structure the findings. Finally, and similar to all research in real world socio-technical environments, the success of the analysis is very much dependent on the experience of the researcher, both in the domain she is investigating as well as their comprehensive and thorough understanding of the principles of human information processing.

Familiarity with the domain was achieved in this study through the researcher's involvement in a number of other projects within the NR Ergonomics Team, especially with regard to the railway electrical control domain. A main contribution was the work of the researcher to develop a workload assessment toolkit for electrical control operators (both AC and DC). This project included collecting more than 140 hours of data from 7 ECRs and investigating ECR log books.

CWA can potentially explore the features of complex control systems. It seems, however, unrealistic to conduct all of the stages for every function possible. This thesis has tackled only one of the domain functions of ECR operation (alarm handling) and it might have been impossible or of limited use to apply CWA to elaborate every ECR function. This might explain the reasons for the limited number of research studies in the literature which involve full implementation of CWA. The risk, however, is that by focussing on only one aspect of the system, critical interdependencies between people, technology, and functions within the overall system will be lost. For example, a fuller understanding of people handling alarms might be gained from the joint analysis of their everyday monitoring, planning and optimisation activities. Therefore, it may be valuable to conduct a Work Domain Analysis of the control system as a whole, in order to determine these inter-dependencies and also to prioritise the functions which require more analysis.

The coping strategies investigated in this study were taken from Hollnagel and Woods (2005). These are the coping strategies specifically determined for information overload and underload. This approach was selected because information deficiency was considered to be a challenge to railway intelligent infrastructure (Chapter 5) and railway ECR operators confirmed this problem to be one of their main concerns.

One particular finding of the study is the comparison between expected and unexpected alarms. Ultimately, it seems that intelligent infrastructure would like to provide sufficient information for operators to notice and clear alarms without having to check if they are genuine (acceptance) or analyse their cause (analysis); this is similar to the case of ‘expected’ alarms. Therefore, the operator should not need to extrapolate the information or match the case with similar situations, as these are the two strategies used mainly by operators when handling unexpected alarms. In other words, local knowledge and situational information, as well as a reliable history of previous cases, should be used prior to presenting the alarm to the operator.

Moreover, looking into the differences in the frequency and duration of the use of artefacts between expected and unexpected alarms, it is evident that the alarm banner, display area and menu are being used significantly more in cases of unexpected alarms than expected alarms. Therefore, it is possible to interpret that these artefacts support operators’ diagnosis of the situation. Although these artefacts are associated with the layout of the ECR and not necessarily that of the future intelligent infrastructure system, it is reasonable and even obvious to assume that these features (alarm banner, display area and menu) will be part of the intelligent infrastructure alarm management system.

For example, to improve alarm notification, alarm banners should be designed in a way that easily facilities filtering and categorising of the data. Local knowledge and historical information should be available to assist operators in accepting alarms with confidence. Previous alarm episodes and similar situations should be available to enable operators to diagnose and clear alarms, as they often extrapolate the available evidence to match that of previous situations. Table 6-6 below summarises the design guidance that can inform the development and implementation of railway intelligent infrastructure system via supporting their alarm systems.

**TABLE 6-6: DESIGN GUIDANCE FOR SUPPORTING ALARM HANDLING ACTIVITIES**

| Activity | Main artefacts | Strategies | Design guidance |
| --- | --- | --- | --- |
| **Notification** | Alarm banner | Filtering<br><br>Categorising | • The information presented on the alarm banner should be coded so that it is easy to filter<br>• Codify the types of alarms to facilitate categorising |
| **Acceptance** | Alarm banner<br><br>Display area | Categorising<br><br>Similarity matching | • On the alarm banner, mark the alarm to tell the operator that there are similar previous cases.<br>• On the display area, provide information about the similar previous cases. This is to ensure that operators have a clear overview of the alarm and do not automatically accept it because of some similarities between this alarm and some previous cases. |

| | | | |
|---|---|---|---|
| **Analysis** | Display area<br>Menu<br>Overview | Extrapolation<br>Similarity matching | • On the display area provide details of previous cases and also facilitate playing back the alarm situation |
| **Clearance** | Menu<br>Display area<br>Overview | Extrapolation<br>Similarity matching | • Provide clearance options and ultimately potential outcomes of these courses of action according to previous cases (e.g. their delay contribution, etc.) |

Another important finding of this study relates to the comparison between high and low information alarms. When operators are faced with low information, they use the display area almost twice as much as in cases of high information. However, the overall duration of handling high information alarms is twice as long as low information alarms. This could suggest that operators are a lot better at finding the missing information on the operational display than categorising and filtering the high amount of information presented to them. Another way of explaining this is that current systems are not very good at categorising and filtering information, which should also be a concern for the design of intelligent infrastructure displays.

This study, although among the first to review the ECR domain and develop an understanding of alarm handling in railway ECR, has its limitations. These arose mainly from the resources available to the study and the challenges of real-life research. One particular challenge was the number of alarms observed. Despite the 18 hours of field study, only 22 alarms were generated, which might seem insufficient. However, video recordings of operators while handling alarms and interviews with them after the handling (verbal protocol) facilitated the study of alarms from various perspectives and led to findings pertinent to the objectives of this PhD study.

Another limitation seems to result from the simplified definition of strategy that was used in this study. The term refers to operators' activities and the shortcuts they use when faced with a difficult situation. The reason for this simplicity was also central to the objectives of this PhD, where the aim was to explore challenges of potential intelligent infrastructure functions. Therefore, the first step was to understand what determines a difficult situation in alarm handling as a representative intelligent infrastructure function. The operators' comments and the duration of handling various types of alarms showed that it is worse to be presented with too much information than to be presented with too little information. Similarly, findings from Sarter (2007) suggested that information overload is one of the main contributors to complexity in control rooms.

Alarm handling has been found to be one of the main functions of future intelligent infrastructure systems. Despite the advantages of exploring this domain in an under studies domain such as ECR, in guiding the design of future intelligent infrastructure it is important to explore other functionalities, especially those functions that are distributed differently and also should be handled differently. Furthermore, maintenance control centres seem to be going to the core domain of the intelligent infrastructure system, thus a study was conducted to investigate fault finding in the maintenance control centre. This is reported in the next chapter.

## *6.7. Chapter summary*

This chapter reported a series of studies that was performed to establish an understanding of alarm handling in ECR and to apply this understanding to guide the design of future intelligent infrastructure systems. A combination of qualitative and quantitative methods was adopted to identify operators' activities and strategies while handling alarms. This provided a detailed insight into alarm handling and facilitated guiding alarm systems in the future intelligent infrastructure systems.

# 7. Fault analysis in maintenance control centres

The previous chapter explored and investigated alarm handling as one of the core functionalities of a future intelligent infrastructure system. How relevant functions will be handled within the intelligent infrastructure of the future is not yet known. For example, it is not known whether alarms will be handled as soon as they occur (i.e. within a dedicated control room responsible only for attending to the intelligent infrastructure) or if alarms will be presented in the form of alerts that operators will attend to in their own time since they are responsible for other activities and attending to the intelligent infrastructure system is not their priority. The former condition, in which alarms are handled immediately, has been explored in the previous chapter and the latter is explored in the context of fault finding within maintenance control and is reported in the present chapter.

Maintenance control centres are responsible for monitoring and managing the maintenance of railway infrastructure through the aid of Remote Condition Monitoring (RCM) equipment. They are responsible for a wide range of activities and, since their role is not directly operational (unlike the role of ECROs or signallers), they do not have to respond to alarms and alerts immediately. Moreover, maintenance is the main scope of the railway intelligent infrastructure and maintenance technicians are potentially the main users of the future intelligent infrastructure systems. Therefore, a series of field studies was conducted to facilitate an understanding of this work setting.

The study reported in this chapter aims to guide two of the objectives of this PhD study:

- To establish an understanding of operators' strategies for human supervisory control task in alarm handling and fault finding.
- To produce human factors guidance for the future development and implementation of intelligent infrastructure system in the railway to match and complement human capabilities and needs.

To facilitate these objectives, the study reported in the chapter explore the research questions associated with an understanding of fault finding activities, their potential challenges and operators' strategies to cope with these challenges. This information, together with the findings from the previous chapter, will then lead to a hypothesis regarding the optimal level of information for operators conducting problem solving tasks in the future intelligent infrastructure.

The study presents an investigation to predict the effects of using more advanced artefacts (e.g. moving from current RCM interfaces to future intelligent infrastructure interfaces) in railway problem solving. Investigation of three different types of maintenance control centre facilitated this. These control rooms are similar in terms of their main responsibilities but different in the types of the artefacts available to them. Furthermore, the interview study reported in chapter five revealed one challenging aspect of the development of an intelligent infrastructure system to be the question of its distribution, e.g., local vs. central. The maintenance control rooms selected for this study were different in terms of their level of distribution.

Domain familiarisation was conducted first, in order to obtain an understanding of the three maintenance control rooms selected for this study. Section 7.3 reports the semi-structured interview study conducted in the form of a Critical Decision Method (CDM) technique. Section 7.4 reports the findings and revisits the research questions of this study in the light of the findings.

## *7.1. Domain familiarisation*

Three different types of control room were selected on the basis of the recommendations of a Subject Matter Expert in Network Rail's Ergonomics Team. These control rooms, although similar in terms of their job specifications, had different technologies that were distributed differently. A summary of these control rooms is shown in Table 7-1, referred to as control rooms 'A', 'B', and 'C'. In total, six hours of field visits were conducted in these three control rooms (two hours in each control room).

The main focus of these preliminary visits was to become familiar with various forms of RCM equipment and any other artefacts available to the maintenance technicians. Moreover, details of the main responsibilities, shift work settings and a brief description of fault analysis processes in these control rooms were collected.

A number of Network Rail (NR) documents relating to the system specifications and fault management systems applied in these control rooms were reviewed (Table 7-1). Findings of the preliminary visits and document review led to the design and development of the study.

**TABLE 7-1: THE THREE MAINTENANCE CONTROL ROOMS OF THE PRESENT STUDY**

| Maintenance control workstation | A | B | C |
|---|---|---|---|
| Type | Signalling maintenance | Signalling maintenance | National control centre |
| Location | Local ( in a different room from the signaller) | Local (in the same room with the signaller) | Central<br>(Route control) |
| RCM | 1. Infrastructure event log | 1. Asset monitoring, 2.Track monitoring, 3.Point condition monitoring | 1.Wheel monitoring, 2.Track monitoring 3.Point monitoring, 4.Weather monitoring,5.Asset monitoring, 6.Train monitoring |

## 7.2. *Findings from familiarisation study*

Maintenance control in the railway is responsible for the safe and timely maintenance of the rail infrastructure. Maintenance control can be divided into two groups: signalling maintenance and national control centres. Two of the control rooms studied were signalling maintenance control centres (control rooms 'A' and 'B') and the third one was a national control centre (control room 'C').

### 7.2.1. Maintenance control workstation A

The first maintenance control workstation is part of the West Midlands Signalling Centre (WMSC). The system being used in this signalling centre has been developed by Westinghouse Rail and is called WESTCAD™ (Westinghouse Control and Display). WESTCAD™ is an integrated computer based signalling and maintenance workstation.

WMSC is in the process of migrating signal boxes along the West Midlands into a centralized location, comprising 24 signalling desks. The maintenance control centre is located on the top floor of the building. Currently, this is a one-man workstation, but upon completion of the migration of all of the signal boxes, two technicians would work during each shift.

The maintenance technician is responsible for detecting and dealing with operational failures, attending to fault logs, monitoring equipment to facilitate predictive maintenance and planning periodic and long term maintenance checks.

Indication of a fault on the WESTCAD™ system is either through an alarm on the WESTCAD™ general information display or through the lack of an expected indication response to a control input, which indicates an equipment failure. An example of the general information screen is shown in Figure 7-1 below.

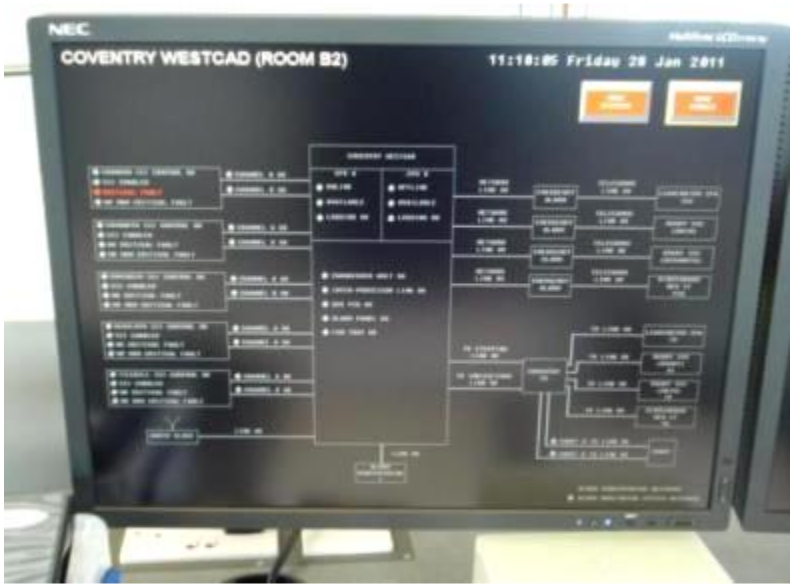



**FIGURE 7-1: EXAMPLE OF A WESTCAD™ SCREEN**

One important aspect of the maintenance technicians' responsibilities in WMSC is to monitor the signalling equipment, which is stored in separate rooms of the same signalling centre. Therefore, the technicians have to monitor the status of these rooms, including their temperature, burglar alarm, etc., to ensure that the equipment is safe and in working condition.

A maintenance technician workstation in WMSC consists of six information displays (Figure 7-2). These include five WESTCAD™ integrated information displays and one display used for web-based applications as well as the administrative tasks that the maintenance technician needs to fulfil as part of his duties. The information displays on the workstation provide information regarding signalling workstations, power supplies, monitoring facilities for the office equipment, modems and other communication links.

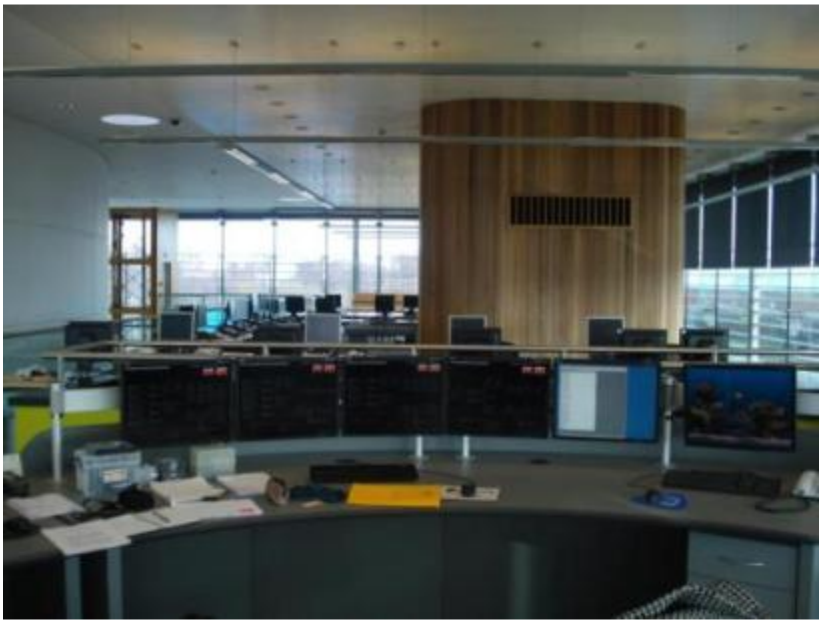


**FIGURE 7-2: WMSC MAINTENANCE WORKSTATION**

### *7.2.2. Maintenance control workstation B*

Manchester South signalling control centre (MSSCC) maintenance workstation was selected as the second work setting of this study. MSSCC comprises two signalling desks, with the maintenance technician's desk located behind the two signallers. Figure 7-3 shows a view of the control room from the technician's desk. Similar to work station 'A', the operator does not have to be present in the control room at all times. Depending on the situation, the technician might be on-site assessing and diagnosing faults.

**FIGURE 7-3: MANCHESTER SOUTH SIGNALLING CONTROL CENTRE**

The technician's workstation has seven information displays (Figure 7-4). Artefacts available to the maintenance technicians include RCM equipment linked to various fault management systems (FMS), which was commissioned for NR. Examples of this include Asset Watch™ (CDS Rail), POSS™ point condition monitoring, Track Watch™ (Balfour Beatty), ANSALDO™, etc. Some of these interfaces are web-based (e.g. POSS) and some comprise stand-alone software, which recalls data from on-track sensors and loggers.

**FIGURE 7-4: MSSCC WORKSTATION**

FMS and RCM systems available to the technicians have different interfaces that are not always consistent in terms of their basic usability issues. Figure 7-5 shows a screen shot of the POSS™ and Figure 7-6 shows the screen shot of Asset Watch™. Apart from the use of similar colour coding (e.g. red for alarms and green for cleared) the format for information presentation differs between these two interfaces. One uses lists and the other uses trends and graphs and, although this is not the focus of the present study, it confirms the lack of consistency identified by the interviewees in the intelligent infrastructure study (Chapter 5).

In addition to the condition monitoring facilities, signalling displays of the area under coverage and Control Centre of the Future (CCF) screens are also available to the signalling technicians. Moreover, since the technicians are located in the same signal box as the signaller, they can overhear relevant information and this, in turn, forms another source of their information when it comes to identifying the cause of a failure on the track.

When a fault is being reported, various types of information are presented to the operator: location, equipment type and a brief indication of the fault. The logbooks also contain information: the date, the technician who had attended to the fault, FMS number, equipment type (e.g. banner repeater, point machine, main signal, position light signal) and equipment ID, controller unit, field unit, indication of a common fault (e.g. lamp failure, lost reverse detection, earth alarm, etc.) and common fix (e.g. filter unit replaced, etc.), as well as the current status of that fault (fixed, active, unknown or cleared on own).

This information is usually summarised in fault logs. Rows associated with each fault on the log are shown in green if they are fixed, red if they are active, yellow if they are unknown and white if they are automatically cleared. Finally, a more detailed description of each fault can be found in the report that is automatically generated. A sample of a fault log is shown in Figure 7-7.

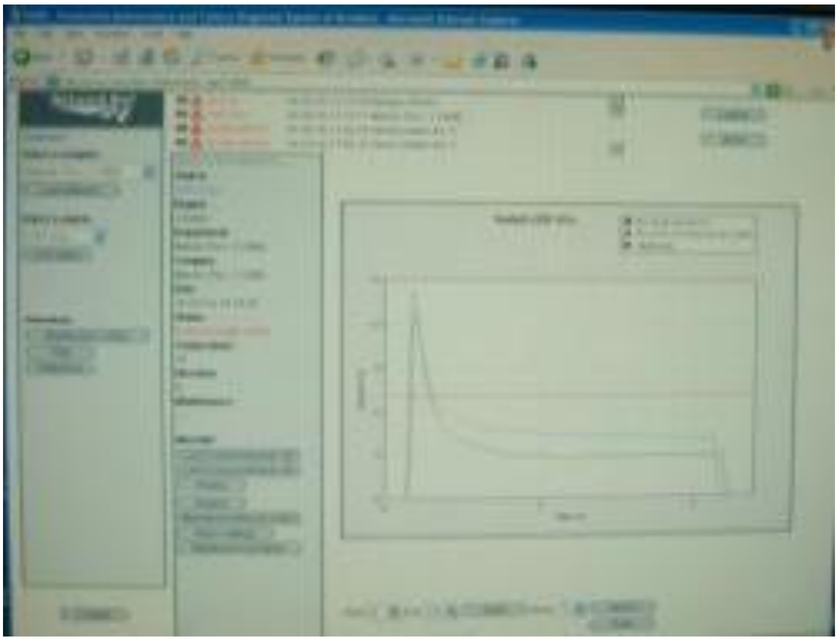


**FIGURE 7-5: SCREEN SHOT OF POSS**

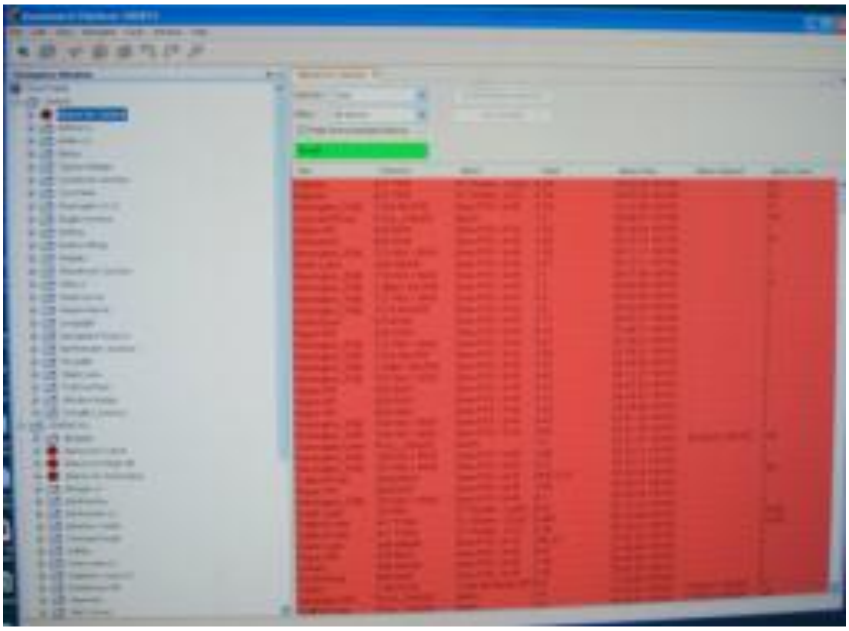


**FIGURE 7-6: A SCREEN SHOT ASSETWATCH**

| Log | Date | Tech. | FMS No | Location | Equipment Type | Equipment ID | Controller Unit Ty | Field Uni | Common Fault | Common Fix | | Cleared / Fixed |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 580 | 07/02/2010 | PE | 453649 | PL51A | Main Signal | S.371 I | POT | LAPS | Lamp Failure | Lamp Replaced | Top green 12.1V | Fixed |
| 581 | 07/02/2010 | JJ | 453697 | DPL44LA | Banner Repeater | BR.3870 ON1 | POT | CLAM | Lamp Failure | Lamp Replaced | | Fixed |
| 582 | 09/02/2010 | NP | 453895 | PL43 | Point Machine | WM.5223 | DEV | CDEV | Failed to get Normal | | build up of leaves | Fixed |
| 583 | 09/02/2010 | NP | 453897 | PL44 | Point Machine | WM.5212 | DEV | CDEV | Lost Normal Detection | | VCC's cleaned | Fixed |
| 584 | 09/02/2010 | KE | | PL01 | Point Machine | WM.5256 | DEV | CDEV | Lost Normal Detection | VCC Contacts Cleaned | LOST N WPOT, DET OBTAINED ON THE KEY | Fixed |
| 585 | 10/02/2010 | PE | 454170 | PL43 | Point Machine | WM.5227 | DEV | CDEV | Lost Normal Detection | VCC Contacts Cleaned | Restored normal on IPS. | Fixed |
| 586 | 11/02/2010 | GH | 454227 | DPL101RB | Point Machine | WM.5176 | DEV | CDEV | Failed to get Reverse | ROA / NFF | | Fixed |
| 587 | 12/02/2010 | GH | 454375 | DPL101RB | Point Machine | WM.5176 | DEV | CDEV | Lost Normal Detection | | CONTACTS CLEANED ON VCC | Fixed |
| 588 | 13/02/2010 | PE | 454440 | DPL101RA | Point Machine | WM.5172 | DEV | CDEV | Slow to Reverse | | | Active |
| 589 | 13/02/2010 | PE | 454443 | DPL49LA | Main Signal | S.3829 I | POT | LAPS | Lamp Failure | Lamp Replaced | Bottom yellow | Fixed |
| 590 | 13/02/2010 | PE | 454445 | DPL47LA | Point Machine | WM.5183 | DEV | CDEV | Lost Reverse Detection | | | Active |
| 591 | 13/02/2010 | PE | 454449 | N/A | | | | | | | No sound from sec desk speakers | Fixed |
| 592 | 14/02/2010 | JJ | 454580 | PL44 | Position Light Signal | GPLS.1707 ON2 | POT | CLAM | Failed to Light | | Tested and found working correct,lamp changed as a precaution. | Unknown |
| 593 | 15/02/2010 | JJ | 454591 | DPL44RA | Point Machine | WM.5217 | DEV | CDEV | Failed to get Reverse | | Reverse obtained after several attempts/No fault found | Fixed |
| 594 | 15/02/2010 | SL | 454640 | PL44 | Point Machine | WM.5212 | DEV | CDEV | Lost Normal Detection | | REGAINED OF OWN ACCORD/No fault found. | Unknown |

**FIGURE 7-7: EXAMPLE OF A FAULT LOG IN CONTROL ROOM B**

### *7.2.3. Maintenance control workstation C*

The third maintenance control workstation used in this study was London North East National Control Centre (NCC), located in York. This centre controls and maintains the route from London north to Scotland. This control room includes a number of operators, such as train operator company's representatives, regulators, and maintenance technicians. Figure 7-8 shows an overview of this control room.

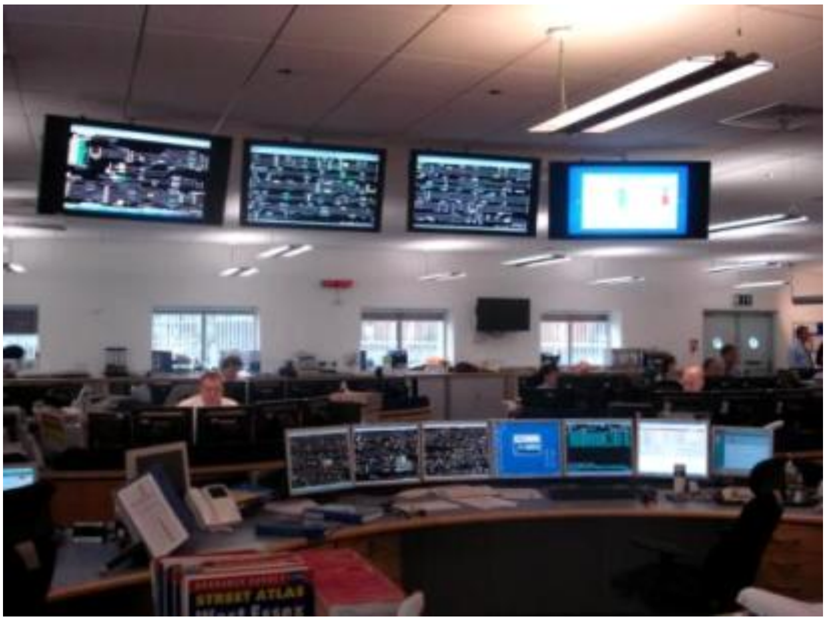


**FIGURE 7-8: LONDON NORTH EAST NATIONAL CONTROL CENTRE**

Maintenance technicians in this control room are responsible for monitoring and dealing with a wide range of faults similar to those in the other two control rooms. In addition, they receive information from weather monitoring stations (e.g., updated information regarding wind and ice), which enables them to make operational decisions and even impose speed restrictions to mitigate weather related risks.

On the maintenance technician's work station in the London North East National Control Centre there are nine information displays (Figure 7-9). These are used for various applications, including weather monitoring, point monitoring, train scheduling, wheel monitoring, e-mail, etc.

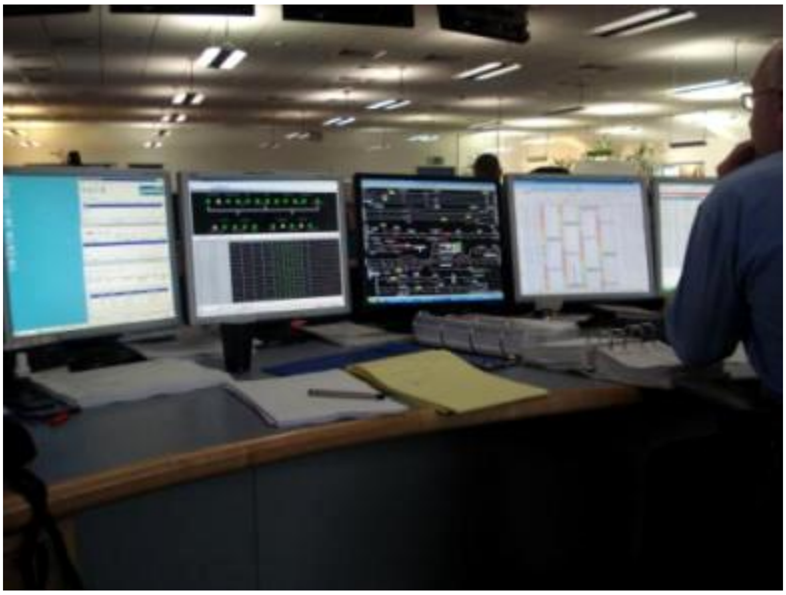


**FIGURE 7-9: MAINTENANCE WORKSTATION IN THE NCC**

### *7.2.4. Summary of the domain familiarisation phase*

The familiarisation visits provided a general understanding of the layout of different maintenance control workstations, technicians' roles and various artefacts available on each of the workstations. This understanding informed the design of the main fault finding study.

In neither of the maintenance workstations is the technician's role a 24/7 responsibility. They occasionally leave the workstation and have on-track visits to collect the information required to deal with the faults. Therefore, it is not possible to record live fault analysis. Technicians are not required to attend to a fault when an alarm is generated. It is usually the case that the faults get logged and technicians attend to them in their own time.

Not being able to conduct an on-line fault analysis, unlike the alarms case in chapter six, meant that video recording was not used. A series of questions, drawn from the CDM, were employed to facilitate the investigation.

## *7.3. The fault finding study*

The 12 hours of study on the three maintenance control workstations comprised a CDM interview study analysing a selection of recent fault analysis episodes. The data were then analysed to address the research questions raised earlier.

### *7.3.1. Participants*

Two maintenance technicians from each of the selected maintenance workstations participated in this study. Participants were all male with an average age of 43 years, an average of 22 years of experience in various sectors of the railway, and they were all experienced at the task under observation.

Preliminary visits informed the procedure used as part of this study. In November 2010 maintenance technicians were approached with the proposed study procedures and they agreed to take part. Ethical guidelines of the University of Nottingham were followed. Participants were assured about data confidentiality and their anonymity. The information sheet for this study can be found in appendix 12.7.

### *7.3.2. Apparatus*

A decision analysis spreadsheet was developed using Microsoft™ Excel™ to probe the functions of fault analysis (Figure 7-10), with factors adopted from the CDM (O ‘Hare et al., 1998), and the spreadsheet was customised to match the rail domain. Technicians were asked to comment on various stages of their fault analysis work. These stages are referred to as ‘goals/activities’. Each goal was then analysed according to the factors identified in the spreadsheet. These factors are:

- Cue identification: for each of the fault analysis stages, operators’ actions are informed by various cues (e.g., visual cue on the event log).
- Data processing: After identifying the relevant cues, operators will process these cues according to their regulations (e.g., categorising the colour coded alarms on the log).
- Information development: operators use their skills and experience to evaluate and analyse the categorised data and convert it to

meaningful information (e.g., taking into account the weather while diagnosing a fault)

- Knowledge integration: operators consider external factors in order to conduct the optimum action (e.g., remembering similar cases which have occurred in that location)

| Activities/ goals | Cue identification | Data processing | Information development | Knowledge integration | Notes | Design implications |
|---|---|---|---|---|---|---|
| Get informed | 1-visual cue on the alarm panel 2- signalman gets an audible alarm and calls the maintenance technician to make enquiry about the equipment | The operator knows that he has to look at the alarm type row to get more ifnromation so it a more filtering and categorisng the display | the acronym showed on the panel is: "feedback discordance equipment" | the operator knows that there is engineering work going on in Picaddely. Time, location, whether it is peak time or not, whether engineering work is going on or not. | Knowing that there is an undergoing engineering work is the most important piece of information | Maybe underline the alarms when there are engineering work going on |
| Check if alarm is genuin | 1- The undergoing engineering work in Picaddely 2-the ANSALDO panel shows that the equipment is not failed. | because he knows that they are renewing power supplys in Picaddely it is normal to get an equipment failure alarm | In addittion to the SA mentioned in the previous stage the operator knows the equipment working properly. | The operator use his historical knowledge about that location or that failure type. It is mainly "similiarity matching". | This is to check whether the equipment claimed to be failed is actually down or not. | Providing some historical data on the higher layers of the system can be useful. At the moment the operator has to click at least 5 buttons to get access to some historical data, so he tries to avoid that as much as possible and |
| Assess why the false alarm was generated? | ANSALDO panel and the log associated with that alarm shows the details of the alarm, so the diagnostics on the ANSALDO is the main source of infromation. | There are visual modules on the ANSALDO log which shows whether the equipment is physically failed or of there is an inut/output failure. The visual cues points out that outputs are missing on the module which implies that something has failed down the line. | Same | | Unlike other control rooms , maintenance technicians need to understand that why the false alarm happened, was it due to a problem with the system or due dur to a problem with the asset. | |
| Diagnose | Looking at the ANSALDO panel shows that one of the moudles is not working properly on the output end | buidling on top of the infrmation integarted in the previous stages the opertaor would know that is definetely due to the power work going on | Same | | seems like many parts of the assessmnet, diagnosis and developing the course of action are using the same infromation. | |
| Course of action | previous stages of assessment reveled that there is no specific risk for any equipment and the reason for false alarm does not require a corrective action so no fault team should be sent on | All above | Same | | If he did not know of the engineering work going on in Picadelly he would have send the fault team on track. | |

**FIGURE 7-10: A COMPLETED DECISION ANALYSIS SPREADSHEET**

### 7.3.3. Procedure

Two data collection sessions, each of two hours, were conducted in each of the maintenance control rooms. All sessions were conducted with one maintenance technician; two maintenance technicians participated from each control room.

Participants were made familiar with the aims of the research, reviewed the decision analysis spreadsheet and were briefed about the meaning of various factors. Participants were asked to think of the most recent challenging fault they had gone through. This also provided an insight into the technicians' perceptions of what comprises a challenging fault analysis.

The researcher then asked the following questions regarding each of the cases recalled by operators (although the order of questions was not fixed and varied from case to case):

- How did you become aware of the fault? What was the cue in identification of the problem?
- What was the most important piece of information that helped you in making your decision?
- How certain were you regarding the information provided to you?
- How did you integrate all different sources of information to come to a conclusion?
- What artefacts did you use?
- In what order did you attend to various pieces of information?
- How aware were you regarding your surroundings as well as the fault's context?

Technicians' responses and any other comments made regarding each fault situation were recorded and used to complete the decision analysis spreadsheet, similar to that in Figure 7-10. Appendix 12.8contains the completed spreadsheet for another fault analysis episode.

### *7.3.4. Analysis*

A total of 25 fault analysis episodes were recorded and analysed, eight in control room ‘A’, nine in control room ‘B’ and eight in control room ‘C’. Each session took around two hours and the operator recalled and reviewed approximately four fault analysis episodes during each session.

A decision analysis spreadsheet was completed for each of the faults; qualitative analysis of these data enabled the researcher to obtain an understanding of fault analysis activities and artefacts. Furthermore, decision ladders were used to structure the sequence of activities and the cognitive states of the technicians while attending to a fault.

Operators’ comments regarding questions like: ‘What was the most important piece of information?’, ‘How certain were you regarding the information provided to you?’ and ‘How did you integrate all sources of information to come to a conclusion?’ provided cues as to the strategies they use to overcome information deficiencies.

It is appreciated that obtaining an in-depth understanding of the strategies used for problem solving requires far more detailed and extended data collection than merely finding a pattern through a number of questions. However, these data are useful in developing a general view of operators’ potential approaches to overcome complications while they are attending to a fault.

Comments regarding each of these questions were recorded and analysed. These were then mapped to the list of coping strategies adopted from Hollnagel and Woods (2005), which was also used in the alarm handling study (Chapter 6). A separate one hour long meeting with one of the maintenance technicians in the WMSC (control room ‘A’) was used to verify and confirm the strategies identified.

Differences in terms of activities and strategies in relation to the type of artefacts and system distribution available to each control room were further analysed. Decision ladders were developed for each of the control rooms, providing a means of comparing activities and strategies in a control room. Activities and strategies were first compared in terms of the available artefacts in each control room and then compared in terms of the distribution of the maintenance workstation within its larger control setting.

## *7.4. Findings*

The findings of this study will facilitate the objectives of the PhD by addressing research questions to identify the sources of difficulty during problem solving; and to identify the sequence of activities and develop an understanding of operators' strategies while analysing faults. This section reports the fault finding cases that were selected by the maintenance technicians in the three control rooms and explains their activities and strategies while analysing faults. As mentioned earlier, these maintenance control centres varied in terms of the equipment available to them, as well as their degree of distribution; and so the control centres could be compared.

### *7.4.1. Characteristics of selected faults in the three maintenance control centres*

25 fault episodes were reported by six maintenance technicians (operator 1 to operator 6 on Table 7-2) in three control rooms. These faults and their types are shown in Table 7-2 below.

**TABLE 7-2: SUMMARY OF THE FAULTS RECORDED IN THIS STUDY**

| Location | Operator | type |
|---|---|---|
| MSSCC | 1 | false alarm |
| MSSCC | 1 | point failure |
| MSSCC | 1 | fiber optic failure |
| MSSCC | 1 | power supply failure |
| MSSCC | 1 | wrong system indication |
| MSSCC | 2 | signal failure |
| MSSCC | 2 | false alarm |
| MSSCC | 2 | input fault |
| MSSCC | 2 | point failure |
| NCC | 3 | bridge bash |
| NCC | 3 | flood warning |
| NCC | 3 | speed restriction |
| NCC | 3 | wind alarm |
| NCC | 4 | ice alarm |
| NCC | 4 | false alarm |
| NCC | 4 | bridge bash |
| NCC | 4 | point failure |

| | | |
|---|---|---|
| NCC | 5 | wind alarm |
| WMSCC | 5 | power supply failure |
| WMSCC | 5 | signal failure |
| WMSCC | 5 | signal failure |
| WMSCC | 5 | power supply failure |
| WMSCC | 6 | intruder alarm |
| WMSCC | 6 | loss data link |
| WMSCC | 6 | loss data link |
| WMSCC | 6 | intruder alarm |

The maintenance technicians were asked to identify and then review the most recent challenging fault finding situations in their control rooms. From the 25 cases of fault finding, 13 types of faults were mentioned by maintenance technicians (Figure 7-11). To an extent, these faults were perceived by the operators to be the most recurring and challenging cases, since as part of the CDM study, maintenance technicians have been asked by the researcher to mention their recent challenging fault episodes. False alarms, point failures and signal failure were selected more than other cases. These faults affect the immediate operation of the railways and operators found them more challenging, possibly due to the fact that, despite the fact that their job specification does not require them to attend to alarms when they are generated, operators still feel under time pressure as the faults affect the operation and contribute to delays in the rail service.

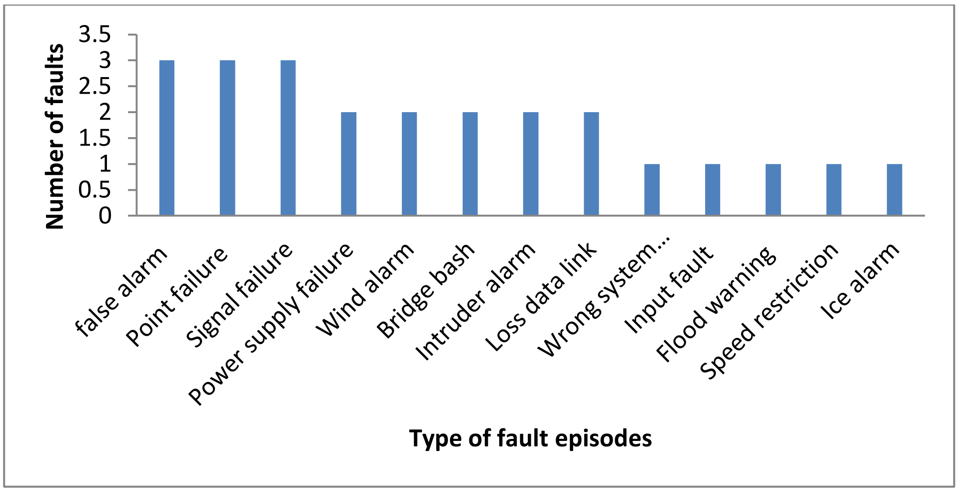



**FIGURE 7-11: NUMBER OF THE FAULTS REVIEWED IN THE STUDY**

A review of operators' comments regarding the reasons that made these cases challenging provided an insight into these problems. It seems that, in some instances, operators did not have a clear view of the fault (e.g. due to the lost communication between the sensor and the logger in 'lost data link') and, in other instances, they had too much information to analyse. Although there were no time constraints associated with handling the fault operators' confusion due to multiple sources of information imposed a challenge (power supply failure). Therefore, as in the case of the alarm handling study, information deficiency (similar to high and low information mentioned in chapter 6) was found to be the source of complexity in the maintenance domain.

### *7.4.2. Fault analysis activities*

In the decision analysis spreadsheet (Figure 7-10) the first column refers to activities and goals. This corresponds to the stages performed by technicians during fault analysis. Reviewing these spreadsheets for all 25 cases (Appendix 12.8), a pattern of activities emerged. In twenty of the cases, the activities conducted to analyse the fault started with notification of the fault, followed by diagnosis of the fault and then deciding on a course of action. In the remaining five cases, where the technician was not completely certain whether the fault was authentic or not, a test of authenticity was performed and, in two of the cases where there was a false alarm, the technician assessed the causes associated with the generation of a false alarm. In these five cases, upon confirming the authenticity of the fault episode, the cause was diagnosed and a corrective course of action was selected.

Therefore, fault analysis in rail maintenance has been categorised into four main stages:

1. Receive notification of the fault →Notification
2. Check if it is genuine →Acceptance
3. Diagnose the fault →Analysis
4. Develop a course of corrective action→Clearance

These activities are summarised in Figure 7-12 below.

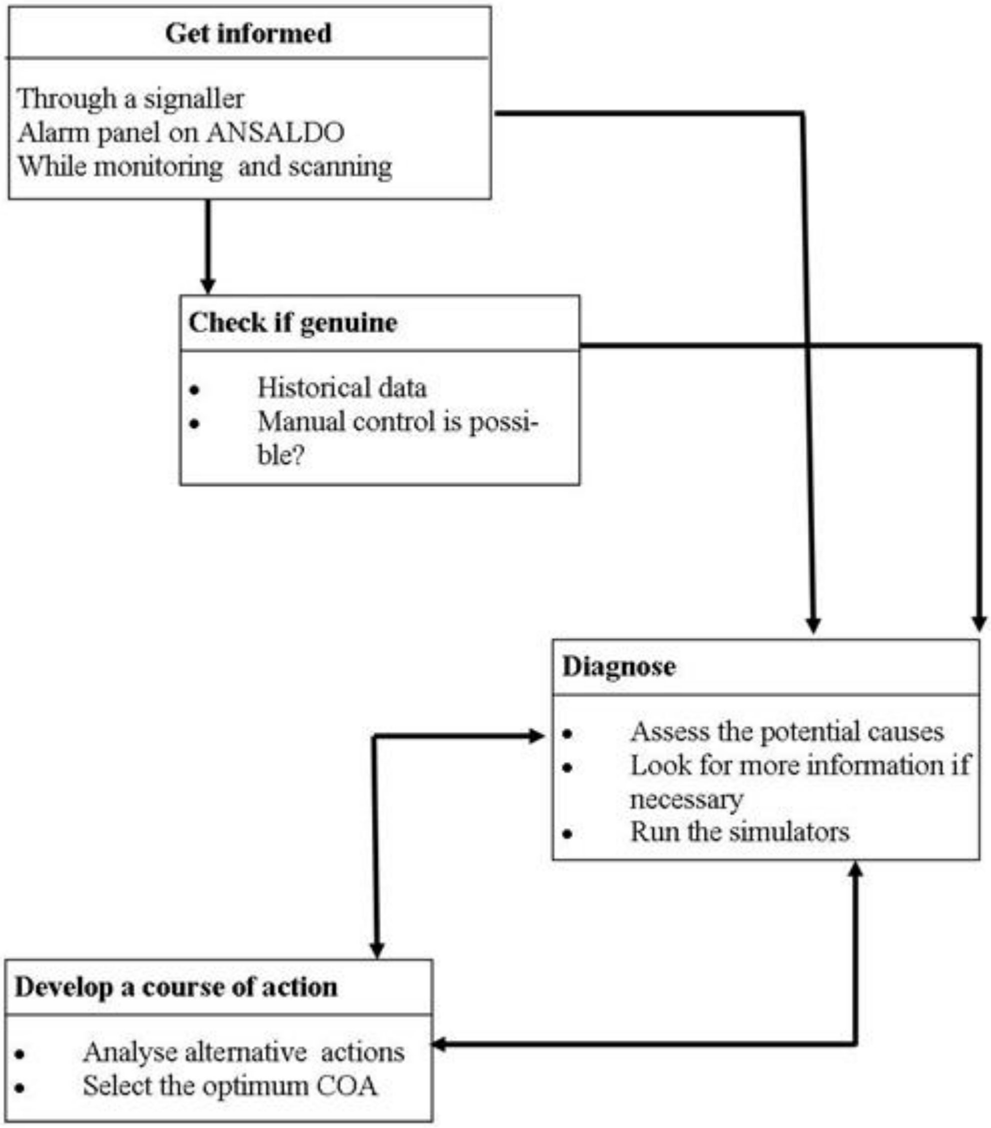



**FIGURE 7-12: FAULT INITIATED ACTIVITIES**

When a fault is being reported, the operator is made aware of it. As well as getting alerted through another controller and audible and visual channels, the operator also has to identify the location from which the fault has originated and needs to start analysing the faulty situation on the basis of their local knowledge and experience.

The second stage is to identify whether the fault is genuine or not. This assessing the credibility of the data presented. If the fault is not genuine and the operator imposes an unnecessary speed restriction or even stops a train to send an investigation team to the track, this can lead to delays and a waste of time and resources, as well as excess costs in terms of fines.

The third stage of fault analysis is to assess the fault, seek potential causes of the fault and diagnose it. Finally, the fourth stage refers to the development and evaluation of the optimum corrective action.

### 7.4.3. Fault analysis strategies

As with the alarm handling study reported in chapter six, deficiencies in information presentation represent one of the main difficulties facing the technician endeavouring to deal optimally with faults. There are at least six information displays on a technician’s workstation. Although it is appreciated that duplication of information is inevitable, due to critical safety issues associated with their roles, technicians also identified difficulties with unnecessarily redundant information and misleading data.

Comments were assessed against Hollnagel and Woods’ (2005) coping strategies. As with the coping strategies found for alarm handling (chapter 6), the strategies adopted by maintenance technicians to analyse the faults include categorising, filtering, queuing, similarity matching and extrapolation. However, maintenance technicians also tend to use the frequency of occurrence of events in the past as a basis for recognition (Frequency gambling) (Table 6-3).

Table 7-3 shows technicians’ responses to the questions for the selection of fault analysis episodes. Boxes within this table refer to their relevant strategies (a subsequent hour long meeting with one of the technicians who participated in this study confirmed the relevance of these responses to the selected strategies).

**TABLE 7-3: TECHNICIANS' RESPONSES TO THE THREE QUESTIONS ABOUT A SELECTION OF FAULTS**

| Fault | What was the most important piece of information that helped you in recognising the fault? | How certain you were regarding the information provided to you? | How did you integrate all sources of information and come to a conclusion? |
|---|---|---|---|
| 1 | I know there is engineering work in Manchester Piccadilly<br>Similarity matching | We have heard about power shut down in Manchester Piccadilly earlier.<br>Extrapolation | Used the diagnostic tools on fault management system to confirm my assumption. |
| 2 | Signaller located in the same control room informed me that they may have lost detection. | I double checked the point on responsiveness on my system and I trust the signaller's call. | The weather was icy on that day and I decided that it was weather related.<br>Extrapolation |
| 3 | Alarm description on the banner<br>Categorising | I know the specific location where this alarm happens; if it's the same location it confirms it.<br>Similarity matching | I look at the back up copy from the system and filter the potential causes.<br>Filtering |
| 4 | The red fault on the display of the fault | Power supply is showing unexpected behaviour: | Filter and categorise relevant information on |

| | | | |
|---|---|---|---|
| | management system<br><br>Filtering | other related alarms are being generated. | the fault management system.<br><br>Similarity matching |
| 5 | Unusual fault on the fault management system | Engineering has just changed the module which is alarming. | Eliminate all possible options to reach a conclusion. |
| 6 | Signalling screen shots, It went red all the way, it was really difficult to miss.<br><br>Filtering | Again having the signaller in the same room was really helpful, also this is SPAD alarm, which is very critical, you really don't think twice. | I rang other signallers in other control rooms to get a bigger picture, everything was alright towards Manchester and was not alright towards Crew. |
| 7 | This location and this specific fault happens all the time and I know from previous cases.<br><br>Similarity matching | 90% of the stuff shown on these fault management systems is false alarms.<br><br>Frequency gambling | I would have to find a way to send a fault team on track to check if the equipment is working. |

### *7.4.4. Comparison of the three maintenance control rooms in terms of activities and strategies*

One of the research questions targeted in this study was whether changes in the artefacts and equipment available to operators would affect the process of fault analysis. Decision ladders of problem solving in each of the three maintenance control rooms were developed to facilitate this understanding.

The decision ladders of fault analysis in control rooms ‘A’, ‘B’ and ‘C’ are shown in Figure 7-13, Figure 7-14 and Figure 7-15. The first figure (Figure 7-13) also shows the four stages of activities of fault analysis associated with various states and processes within the decision ladder.

The question is how these stages benefit from the control rooms’ artefacts and their distribution. Data collected about fault analysis episodes within each of the control rooms were analysed separately to study any differences and similarities.

The shaded areas in Figure 7-14 and Figure 7-15 refer to the activities that are assisted through the artefacts available in those control rooms. In other words, the use of these artefacts and the location of these control rooms provided operators with shortcuts.

The second stage (confirmation) and the third stage (diagnosis) benefit from RCM equipment. In both control rooms ‘A’ and ‘B’, when operators want to check if the fault is genuine, they use their knowledge of the faulty location and the history of that asset. Control room ‘C’ operators had more trust in the system, potentially because the RCM equipment had been maintained more regularly and alarm thresholds had been updated fairly recently. More sophisticated fault management systems and the strategic nature of the role of operators in this control room contributed to this difference.

Although control room ‘A’ had no noticeable support from the only RCM equipment in their room, control rooms ‘B’ and ‘C’ used various pieces of RCM equipment to diagnose the fault and assist the investigation process.

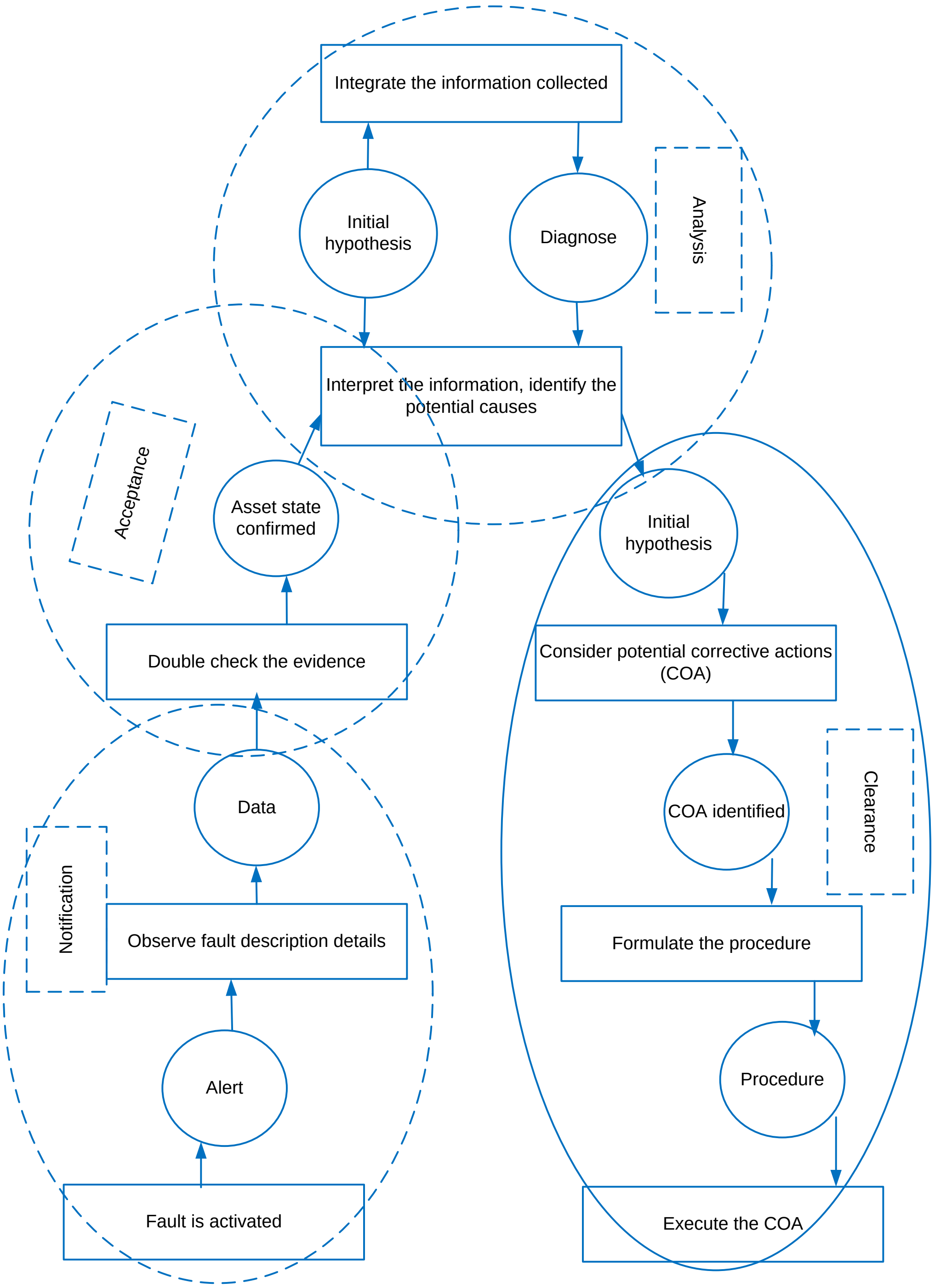



**FIGURE 7-13: DECISION LADDER FOR FAULT ANALYSIS IN CONTROL ROOM 'A'**

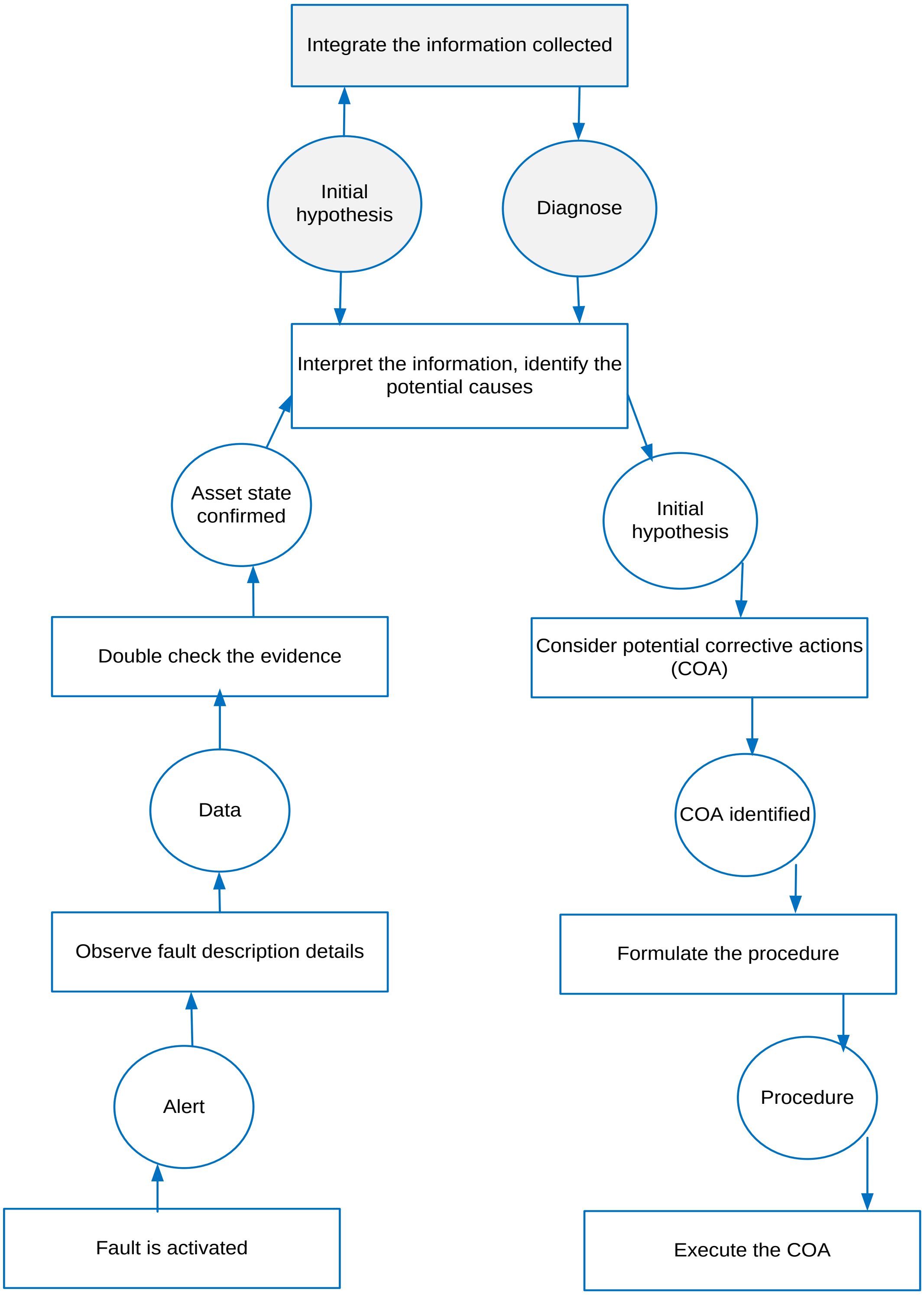



**FIGURE 7-14: DECISION LADDER FOR FAULT ANALYSIS IN CONTROL ROOM 'B'**

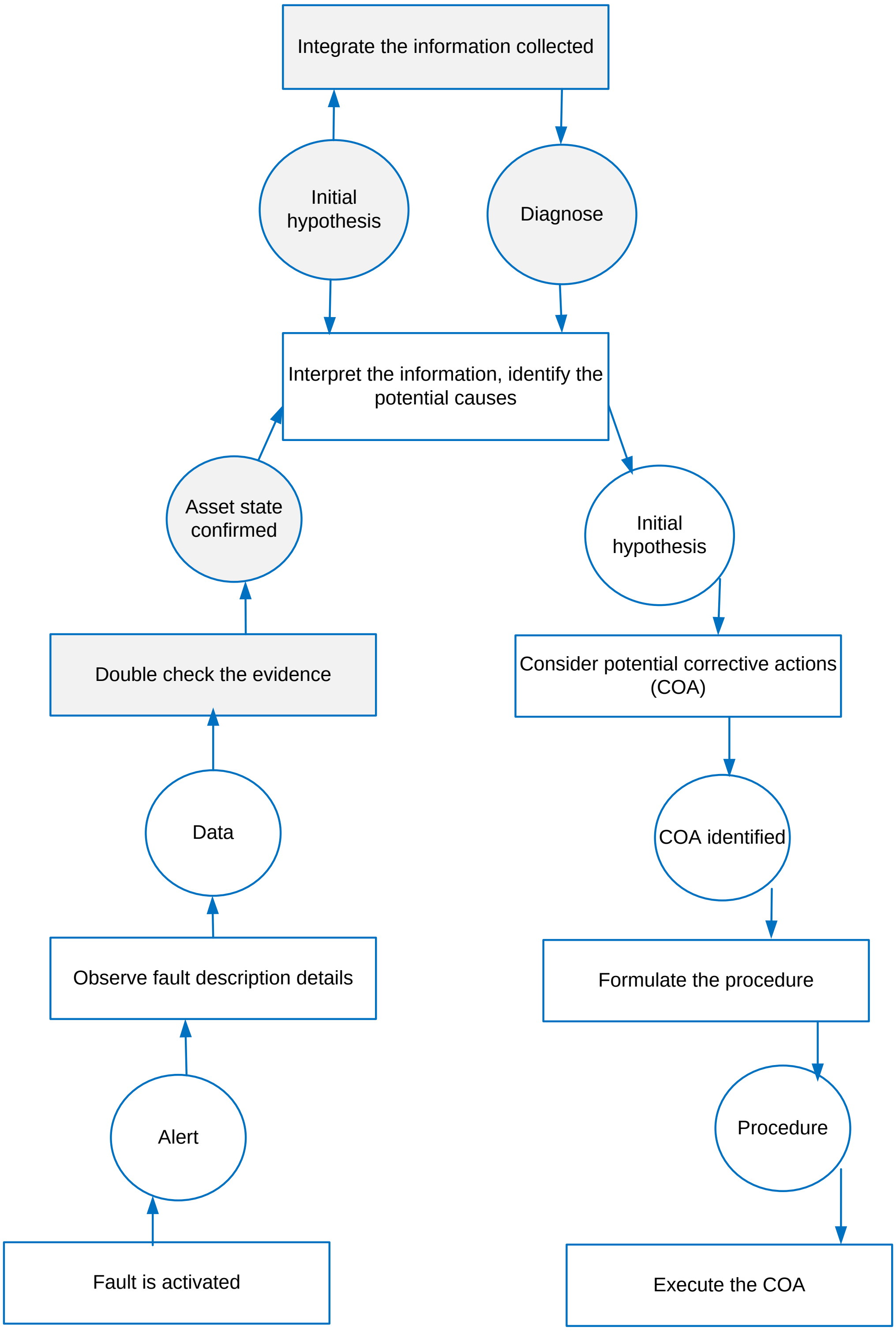



**FIGURE 7-15: DECISION LADDER FOR FAULT ANALYSIS IN CONTROL ROOM 'C'**

## 7.5. Discussion

Similar to the previous chapter, the study reported here informed two objectives of this PhD study: to establish an understanding of the strategies and activities associated with this railway problem solving scenario and also to use this understanding to develop guidance so that these problem solving activities are supported in the future railway intelligent infrastructure. Analysis of this work setting was guided by a CDM interview technique and was structured within decision ladders.

CDM was used to enable an in-depth understanding of operators' activities and decision making in railway maintenance control centres. The reason for selecting this method instead of CWA, which was used in the previous study (Chapter 6), was rooted in the resources available while conducting this study. It was not possible to record live fault analysis and, video recording was not an option. The key factors of interest in this study were artefacts, sources of difficulties in the control room and operators' coping strategies. Decision ladders were used to structure the findings from the CDM interviews and to identify the states and processing involved with maintenance fault finding.

CDM was very useful in identifying operators' decision points (i.e., different stages of fault finding: notification, acceptance, analysis and clearance). The selection of the probes was done with the aim of facilitating an understanding of the cues that operators use in order to deal with faults. Understanding these cues helped to provide an insight into operators' activities and their strategies.

Selecting and using appropriate probes is a key part in the implementation of an effective CDM technique. In this study, these probes were derived from the in-depth field studies conducted in both electrical control and maintenance control settings.

Decision ladders have been used in a number of studies in this PhD. They were used to facilitate the cognitive transformation analysis of the CWA in chapter 6, to explore the sequence of states and processes of fault finding in chapter 7 and to predict the performance of participants during the laboratory study, which will be reported in chapter 8. Since a decision ladder provides a way of structuring information processing according to its sequences, it also guided the development of the experimental prototype for the chapter 8 experiment, which was based on the information and data utilised at each of the stages identified in the decision ladder.

It is possible to use the understanding regarding the activities to inform the third objective of this PhD (i.e. design guidance). The findings reported earlier in this chapter are summarised in Table 7-4 below together with their implication for the design.

**TABLE 7-4: DESIGN GUIDANCE FOR SUPPORTING FAULT FAULTING ACTIVITIES**

| Activity | Strategies | Design guidance |
|---|---|---|
| **Notification** | Filtering | • The colour coding should be used for presenting the alarms on the banner<br>• Central distribution implies less local knowledge and therefore the operators' reliance on the system is important. |
| **Acceptance** | Categorising<br><br>Similarity matching | • An updated status log of ongoing engineering work in different locations should be provided. Knowing that there is existing engineering work currently is down to operators' knowledge and it is not provided within the system.<br>• Lack of system reliability(e.g. too many false alarms) can be very misleading, simply ignoring an alarm because there were many previous cases of false alarm should be avoided by reliable alarm management system. |

| | | |
|---|---|---|
| **Analysis** | Extrapolation<br><br>Similarity matching | • Playback option using simulations should be available so that operators re-build the situation and obtain an overview of the problem. |
| **Clearance** | Extrapolation<br><br>Similarity matching | • The outcome of operators clearance options should be available for example in terms of indicating delay minutes for every minute of persisting the failed asset, this can also be extracted from previous cases where similar assets have been failed in an area with similar traffic and around the same time during the service. |

One of the key findings for the maintenance control centres is related to a comparison between the three control rooms. These control room operators had various quantities and types of artefacts available to them. Control room ‘A’ had logging facilities only, while control room ‘B’ had some RCM available but the system was distributed locally. Control room ‘C’ was a national control centre, had much RCM equipment and covered a large geographical area.

One of the implementation challenges of the intelligent infrastructure system is to decide whether to distribute it locally or bring it together centrally, so the comparison between control room B and control room ‘C’ provides some guidance in that regard. Control room ‘B’ provides operators with detailed trends and graphs associated with faults, which assist them in diagnosing faults. Control room ‘C’, provides diagnostic support and also assists operators in a more confident acceptance of the fault. This is due to the wide range of RCM equipment available in this control room, which provides operators with duplicated and, in some cases, excessive information. Despite the differences in their artefacts as well as their distribution, decision ladders showed that the process of finding, analysing and clearing a fault in these three control rooms is similar. In a way it confirms that the processes involved with problem solving in the future intelligent infrastructure systems are also going to be similar to those found in this thesis.

Looking at the activities and strategies adopted by operators while analysing faults, it seems that there are similarities between the case found in the ECR and the situation in maintenance control. This is despite the fact that, in the latter, the operators attended the alarms immediately after they were generated and, in the former, operators investigated the faults in their own time. Moreover, the strategies were almost similar and included filtering, categorising, similarity matching and extrapolation. However, due to the sheer volume of alerts in maintenance control centres and the high false alarm rate meant that operators simply ignored some faults (frequency gambling), which should alert designers developing a future intelligent infrastructure system. Also similar to the case in chapter 6, some of these strategies reveal imperfect practices in control rooms and knowing them can assist designers to reduce the risk by recognising them early on.

An underlying recommendation from these studies concerns the management of the information presented to operators in order to provide them with the optimum level of information relevant and sufficient to their tasks. This involves giving operators enough information to analyse the fault and prevent them from having to use risky strategies in order to deal with too much information. This is particularly a challenge in an intelligent infrastructure system because information is being shared between various operators across railway control; different operators would need different levels of information presented to them.

The studies reported in chapter 6 and also the study presented in this chapter have identified information relevant to alarm handling and fault finding, including the sequence in which operators would need/prefer them. Considering these cases as potential functions of the intelligent infrastructure system, it is possible to hypothesise about the optimum level of information required. This hypothesis is trialled in a simplified laboratory study that is reported in chapter 8.

## *7.6. Chapter summary*

This chapter reported a study that was conducted in three maintenance control centres with different ranges of RCM equipment. Operators' fault finding activities and strategies were explored through CDM-like interview studies and were structured in form of decision ladders. The findings established an understanding of railway maintenance fault finding activities and strategies and informed the design of intelligent infrastructure systems.

# 8. The impact of presenting different levels of information at various stages of railway problem solving: a laboratory study

The study reported in this chapter mainly informs the third objective of this PhD: to investigate the optimal level of information required for different stages of problem solving and develop guidance for the implementation and development of a future intelligent infrastructure system.

Previous chapters have developed an understanding of the activities and strategies adopted by operators while performing problem solving tasks in railway control. The sequences in which operators attend to or require information has been established. The findings suggest that, not surprisingly, operators' main sources of difficulty, caused by the challenges reported in the chapter two are mainly associated with information deficiencies. Hence, it is safe to assume that with the introduction of intelligent infrastructure systems, this problem is likely to become at least as or more challenging. Therefore, it is important to guide the development of the intelligent infrastructure interface in terms of the optimal level of information associated with problem solving activities.

Revisiting the interview study reported in chapter 5, it was clear that intelligent infrastructure operators' roles will vary in terms of functions, priorities and responsibilities. Therefore, different operators will need different levels of information in order to conduct their activities efficiently. This is supported by the findings of the data processing framework presented in chapter 5, where the hierarchy of information relevant to these roles is shown. The two tasks examined in this study (acceptance and clearance) relate to the key activities associated with the different roles in a future intelligent infrastructure system. From the interview study, it appeared that track workers are mainly responsible for accepting the faults and control room operators are those who analyse and clear them.

The hypotheses regarding the information required for aspects of problem solving, linking them with the roles identified for the potential intelligent infrastructure system, were formed from the studies reported in chapters 6 and 7. These hypotheses were then trialled in an isolated laboratory study, reported in the current chapter. The aim here is not to address these hypotheses in their complete complex forms, but to explore the question of whether different roles will benefit from different levels of information.

This chapter reports a laboratory study conducted to investigate the effect of presenting different levels of information on problem solving activities. The first section of this chapter links the findings from previous studies (Chapters 5, 6, and 7) to inform the hypotheses generated and scenarios adopted for this laboratory study. The development of the experimental prototype and its specifications are reported in the second section. The methods for conducting the experiment are explained in the third section. This is followed by a presentation and discussion of the results of the study in the fourth and fifth sections.

## *8.1. Information requirement for problem solving: integrating the findings from alarm handling and fault finding study*

Studies conducted in the Electrical Control Room (ECR) and the Maintenance Control Centre (MCC) identified the activities and strategies performed by operators to deal with problem solving tasks of relevance to a future railway intelligent infrastructure system. This has led to an understanding of the types of information used and required by operators. The findings from these two studies (Chapters 6 and 7) are summarised in this section to guide the development of the hypotheses explored in the current chapter.

Problem solving in the railways alarm handlings consists of four activities: notification, acceptance, diagnosis and clearance (Chapters 6). Findings from chapter 6 have suggested that, during the handling of alarms in rail ECRs, operators have different types of information available to them. Table 8-1 shows an example of the information available and required by operators when handling alarms, their rationale for using this information and the form in which this information is available to them.

**TABLE 8-1: EXAMPLE OF INFORMATION AVAILABLE WHEN DEALING WITH AN ALARM IN ECR**

| Information | Rationale | Form of information |
|---|---|---|
| Alarm colour<br>Location of the alarm<br>Number of previous alarms | To develop an initial understanding of the type of alarm and its severity | Text<br>Colour<br>Amount of alarmed locations<br>Symbols on the display |
| Relationship between various alarms<br>Previous status of the asset | To analyse potential causes of the alarm | Lists on the event log |
| Local knowledge<br>Historical knowledge (similar previous cases) | To develop an effective course of action | Conversations between operators within control and from neighboring control rooms |

For example, when an alarm is generated, the red colour on the alarm banner attracts operators' attention and helps them to notice the problem. Moreover, the alarm description on the operational display helps the operators to recognise the type of fault. Information about other events occurring in the vicinity of the faulty asset, e.g., engineering work in the location, assists the operators to get a broader picture of the situation. This information is currently obtained through face-to-face communication between different controllers. Although operators are able to handle the alarm with just the data on the alarm banner, the information on event logs and alarm lists, as well as details of the location, can assist the operator to make a more informed decision.

Similarly, in the MCCs, operators attend to and seek different types of information in order to deal with faults. Table 8-2 shows an example of this information, operators' rationale for attending to them and the forms in which the information is available to the operators.

**TABLE 8-2: EXAMPLE OF INFORMATION AVAILABLE WHEN DEALING WITH A FAULT IN MCC**

| Information | Rationale | Form of information |
|---|---|---|
| Colour of the row on the event log<br>Location of the fault<br>Type of faulty asset | To develop an initial understanding of the type of fault and its severity | Conversations with the signaler<br>Text<br>Colour |
| Situational information<br>Previous cases of faults in that location | To analyse potential causes of the fault | Conversations with maintenance team<br>Event log |
| Local knowledge<br>Historical knowledge (similar previous cases) | To develop an effective course of action | Conversations between operators within control and from neighboring control rooms |

When a fault is detected by the maintenance technician, either after monitoring the alert list or having been told by a signaller, the operator investigates the authenticity of the fault by capturing or remembering the situational information (e.g. whether there is engineering work in the faulty area or not) and also from previous knowledge. He is then able to assess the severity of the fault. This process is followed by the application of local knowledge to plan the maintenance and arrange for the maintenance team to go on track and investigate or fix the fault.

Looking at the two examples taken from the ECR and the MCC, it is clear that the information available to operators enables them to develop their knowledge of the problem gradually and assists them in analysis and clearance of the problem. The rationale of the operators for capturing and retaining the information fits in three categories. The first category relates to developing a basic understanding of the problem, followed by the use of information to facilitate the analysis of the fault by investigating the evidence and related events (e.g. previous alarms, situational information, simultaneous faults, etc.). Finally, operators evaluate various corrective options by considering the effect on future operations (e.g. liaising with neighbouring control rooms) and then deciding on the course of action.

These findings suggest that, if, in any way there is a need to separate various stages of problem solving, operators would benefit from specific pieces of information. This would ensure that they are presented with information sufficient to their task and that they are not overloaded with irrelevant information. The next section will expand this notion in the context of intelligent infrastructure where, supposedly, different roles assume responsibility for different stages of problem solving.

### *8.1.1. Problem solving stages for the roles in the future intelligent infrastructure system*

Railway intelligent infrastructure systems will collect or generate large quantities of data from remote sensors and condition monitoring equipment and present this to different operators in different functions. Participants of the interview study (Chapter 5) identified three main roles, which they believed will be extensively involved with the future railway intelligent infrastructure systems.

- Track workers
- Control room operators
- Strategic analysts
- The track worker's role is to repair failed assets; at the very early stage all they need is accurate information about the asset's condition (i.e. whether the point machine is working or not). The control room operator has to monitor the system to detect failures and collect system indications to guide the track worker through the repair. The strategic analyst has to develop good practice for a more reliable and efficient railway maintenance regime. For example, data about an asset's performance is required, along with the delays these assets have contributed to, etc. In other words, problem solving in railway intelligent infrastructure does not start and finish in one control room.

Different roles associated with railway intelligent infrastructure are responsible for a number of these activities. Track workers are responsible for noticing faults and informing control room operators. Control room operators then assess the authenticity of the fault and conduct the early stages of diagnosis in order to assist the operational railway (clearance). This information would then be presented to the strategic analyst, who would recommend long term solutions to the fault and ideally to prevent them in the future (clearance).

This information can be categorised into three different levels. A brief definition of these levels and examples are listed in Table 8-3 below. These levels of information relates to the three levels identified within the data processing framework knowledge elicitation study (Table 5-5).

**TABLE 8-3: SUMMARY OF THE LEVELS OF INFORMATION AVAILBLE TO OPERATORS WHILE PROBLEM SOLVING IN RAILWAYS**

| Level of information | Definition | Example |
|---|---|---|
| Level 1: Data & information | Basic understanding of the system that is absolutely necessary to solve the problem | Type of alarm on the banner, colour of alarm, table of wind thresholds |
| Level 2: Knowledge | Information that assists operators to explain possible causes of the fault as well as the basic information required to detect the state of the failed equipment | A table of all weather monitoring stations and their active alarm. |
| Level 3: Intelligence | Information regarding future state of the system | Where will be the next wind alarm |

It is reasonable to assume that future operators of intelligent infrastructure, depending on their roles and responsibilities, will require various levels of information. This hypothesis is investigated in the study reported in the current chapter.

Due to complexity and the distributed nature of problem solving tasks and the lack of an existing intelligent infrastructure system other than the pilot mentioned in chapter two, this hypotheses is explored within a simulated environment. The idea is to separate the stages of problem solving tasks under study (acceptance and clearance) and present operators with different levels of information. Details of the scenario that was simulated are presented in the next section.

## *8.2. Laboratory study; scenario and participants*

In order to facilitate the simulated laboratory study to investigate the hypotheses mentioned earlier, the participants chosen to interact with the simulated interface and the problem solving scenario should be carefully selected so that the research questions of the study can be addressed without compromising the study's ecological validity.

Episodes of weather related alarms and more specifically 'wind alarms' were simulated for the purpose of this study. Wind alarms were one of the most common faults identified in the fault finding study (Chapter 7). Moreover, decision ladders developed within the fault finding study (Chapter 7) led to an understanding of the activities associated with this particular type of alarm. These decision ladders were used to hypothesise about participants' performance in this experiment.

In terms of the participants, it was not sensible to recruit real operators, since there was a need to ask participants to perform different stages of problem solving tasks (acceptance and clearance as separate tasks). On account of their expertise, real operators would not be able, cognitively, to separate one stage/task from another. Therefore, trained students were used for the purpose of the laboratory study.

The scenario selected for this study appears very simple in terms of imposing cognitive demands on real operators. However, it was thought suitable for the student participants. Moreover, this scenario was selected so that it was easy to separate different stages of problem solving during the experimental study. Had it been complicated, it would have been very difficult to draw the boundaries between various stages (acceptance and clearance).

Although a wind alarm is a railway related fault and despite the fact that the participants were all university students with no domain specific knowledge, they were still able to understand the concept easily and quickly.

### *8.2.1. Background*

Wind alarms are generated by the VAISALA™ railway monitoring system. VAISALA™ provides site-specific monitoring of weather conditions and their effect on service disruptions. Wind speed and the presence of ice on rail tracks are two features of this monitoring system which have been used in this study as examples of an alarm scenario.

Wind alarms are activated when the wind gust speed sensed from the weather station is higher than a set threshold saved in the monitoring system. The alarm is shown on the wind alarm’s main window (Figure 8-1) and it is accompanied by an audible siren. There are, typically, two types of trains (class 373 and general) used in the UK. Since the weight of these two classes of train is different, gust speed affects them differently. Therefore, there are two sets of thresholds on the system: 35 mph (miles per hour) for class 373 trains and 45 mph for general trains. Moreover, the train speeds are known, which is relevant to the type of train as well as the type of rail track on their route. If the wind is higher than these thresholds, it can potentially lead to train derailments. Maintenance technicians monitor weather stations located in their area of coverage and intervene when the system generates an alarm. Similarly, when there is ice on the track, the maintenance technicians should inform the driver to adjust the train speed accordingly. Ice alarms are shown in tables on the alarm management systems.

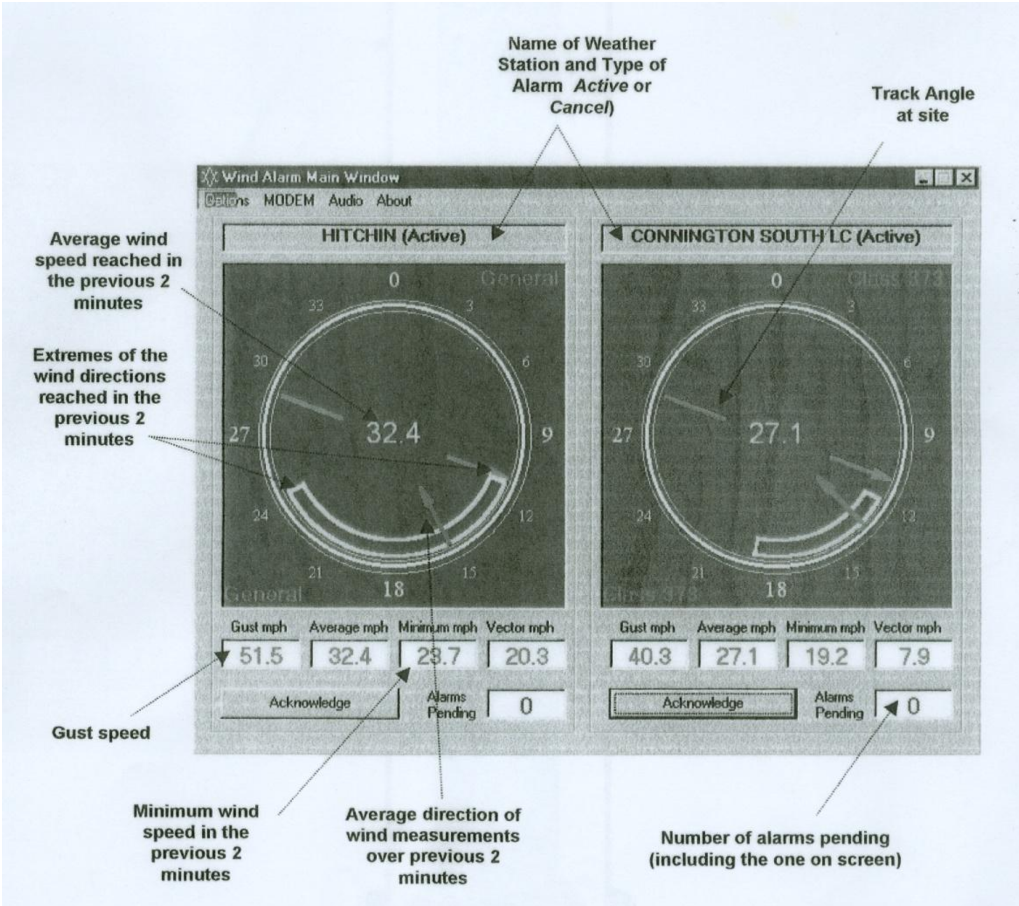



**FIGURE 8-1: WIND ALARM MAIN WINDOW ON VAISALA™ ALARM SYSTEM TAKEN FROM VAISALA™, 2000**

Both wind and ice alarms have to be responded to urgently. Ice and frost on track can be predicted from the temperature of the track presented in a table. Wind gust occurs more unexpectedly but operators can estimate the next location that will be affected, since gust speed and direction is available on the wind alarm's main window (Figure 8-1).

When a wind alarm is generated, the panel shows the average wind speed in the last 2 minutes, current wind speed and wind gust speed, the direction of the wind and the direction of the track.

The operators notice the alarm when an audible siren is generated. Depending on the type of alarm and type of train under the windy conditions, the operators instruct speed restrictions. For class 373 trains, the recommended speed is 110 mph and for general trains it is 80 mph. In order to clear the alarm, the operator informs the train drivers that they are about to enter the windy area and requests that they reduce their speed to the acceptable range.

## *8.3. Experimental prototype*

The wind alarm panel used in railway maintenance control centres is E-prime 2.0 ™ presented on a 15" Sony VAIO™ laptop. This prototype displays screenshots of the wind alarm's main window (Figure 8-2). Some additional information is also displayed on the screen with pre-set time intervals E-prime 2.0 ™ is a software that is able to design an experimental study using drag and drop interfaces and simple scripting for the run of the experiment. Therefore, it is possible to define the sequence of activity live logging of participants' responses and their completion times.

To obtain a clear view of the information to be presented to the operators while handling these alarms, real wind alarms reviewed in the fault analysis study (Chapter 7) were used.

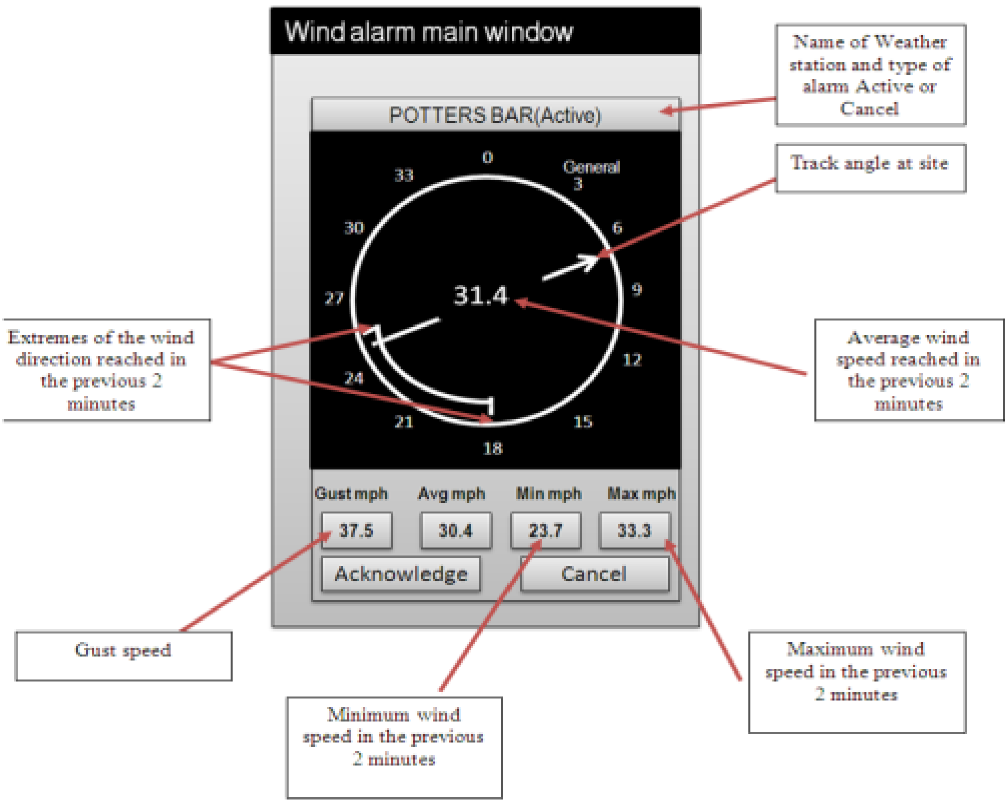



**FIGURE 8-2: EXAMPLE OF A SIMULATED WIND ALARM WINDOW**

### *8.3.1. Experimental tasks*

Two experimental tasks were selected for this study: 1- alarm acceptance and 2- alarm clearance, two of the main activities performed during a problem solving scenario reported in chapters 6 and 7. They were selected because they incorporate the other two activities that have been identified, i.e., noticing the alarm and diagnosing the alarm. One cannot accept an alarm without noticing it; similarly, it is impossible to clear an alarm without diagnosing it. Also, both of these activities, i.e., accepting and clearing the alarm, require the operator to interact with a system to input information. In this way it became possible to use this information, which could be measured, to assess the impact of the presentation of different levels of information on users' performance. Moreover, returning to the alarm handling AH described in chapter 6 (Figure 6-12), two alarm handling domain functions were identified as 'alarm recognition' and 'alarm clearance' which relates to 'acceptance' and 'clearance'.

It should be noted that these tasks are simplified forms of the activities observed in real wind alarm situations. Charts displayed below are used to show the various factors participants had to consider when conducting these tasks.

#### 8.3.1.1. Task 1: accepting wind alarms

When an alarm is generated, operators have to check to see if it is authentic or not. This is referred to as alarm acceptance. When there is a wind alarm, an audible siren will be generated to inform the operator of the alarm.

Participants had to check the wind gust that was shown on the alarm's main window and compare it against the threshold table provided to them. If the wind gust speed presented on the main window was higher than the threshold, then the alarm was true and participants had to accept it. In order to accept an alarm, participants were instructed to press '1' on the keyboard and, to cancel the alarm, they had to press '2'. This is shown in Figure 8-3 below.

Participants were asked to click on the numbers '1' and '2' on the keyboard instead of typing 'accept' and 'clear'. E-prime 2.0™ did not have the facility to use the mouse click option on the screenshots of the prototype, so numbered codes were used to reduce the bias of participants' speed of typing or potential variations caused by clicking on the mouse. Participants had reminder sheets available to them so that they would not need to memorise the codes.


**FIGURE 8-3: SEQUENCE OF ACTIVITIES DURING ALARM ACCEPTANCE**

#### 8.3.1.2. Task 2: clearing wind alarms

The second task was to correct the fault by imposing a speed restriction on the train that was entering the alarmed location. The recommended speed restriction varies depending on the type of trains; therefore, the participants had to identify the type of train and impose the specific speed restriction accordingly. This is shown in Figure 8-4.

Moreover, if operators were presented with information about ice alarms, they were advised to consider this in their clearance task. If there were also problems with ice in the alarmed location, a new set of speed restrictions had to be recommended. Note that attending to ice alarm information was optional for participants. This is shown in Figure 8-5.


**FIGURE 8-4: SEQUENCE OF ACTIVITIES OF ALARM CLEARANCE**

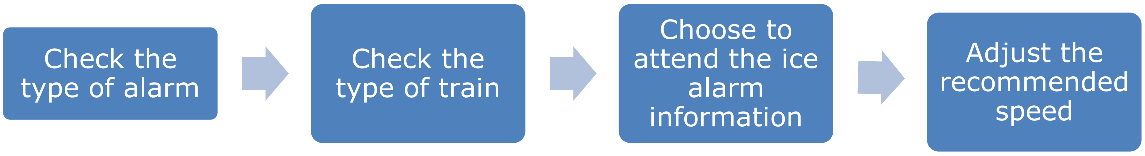



**FIGURE 8-5: SEQUENCE OF ACTIVITIES OF ALARM CLEARANCE WHEN ICE ALARM INFORMATION IS AVAILABLE**

### *8.3.2. Levels of information*

Three levels of information were examined in this experiment. These levels refer to the information available to participants during the experimental trials. The findings reported in chapters 6 and 7 led to an understanding of the information required and utilised by operators while conducting their tasks. Decision ladders developed from this understanding led to predictions of the performance of participants in the present study. In this section, an example of the screenshots of the experimental prototype, as well as its associated decision ladder, is explained.

The available information in each of these conditions is summarised in Table 8-4 below:

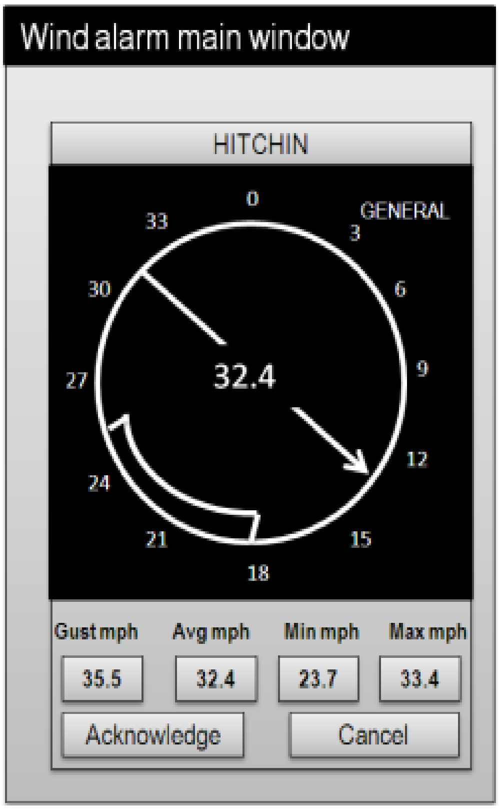
**TABLE 8-4: INFORMATION AVAILABLE IN THE THREE LEVELS OF INFORMATION**

| Level | Task | Information |
|---|---|---|
| **One** | Alarm acceptance | Location of the alarm<br>Wind gust speed<br>Threshold tables |
| **One** | Alarm clearance | Location of the alarm<br>Wind gust speed<br>Type of train<br>Speed restriction guidelines |
| **Two** | Alarm acceptance | Location of the alarm<br>Wind gust speed<br>Threshold tables<br>Wind alarms in other locations<br>Ice alarm information |
| **Two** | Alarm clearance | Location of the alarm<br>Wind gust speed<br>Type of train<br>Speed restriction guidelines<br>Ice alarm information |

| | | |
|---|---|---|
| **Three** | Alarm acceptance | Wind gust speed<br>Threshold tables<br>Wind alarms in other locations<br>Ice alarm information<br>Wind gust speed in the neighboring weather station |
| **Three** | Alarm clearance | Location of the alarm<br>Wind gust speed<br>Type of train<br>Speed restriction guidelines<br>Ice alarm information |

#### 8.3.2.1. Level one

Level 1 refers to the basic understanding of the system. In the context of the present study, this refers to alarm thresholds and recommended speed restrictions for different types of train. Figure 8-6 shows an example of the experimental prototype with the first level of information available to the participants to conduct an alarm acceptance.




| Wind Gust | Locomotive Class |
|---|---|
| 35 mph | 373 |
| 45 mph | General |

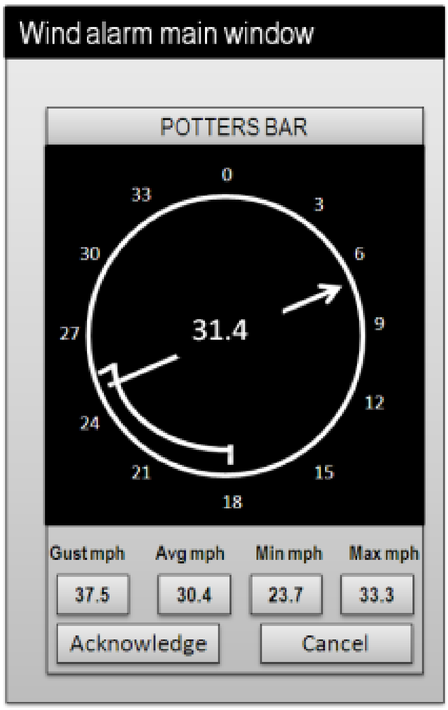
**FIGURE 8-6: PROTOTYPE OF LEVEL 1 TO CONDUCT ALARM ACCEPTANCE**

Figure 8-7 shows the experimental prototype with the first level of information when participants are asked to conduct an alarm clearance task.

The first level of information contains no diagnostic indication of the system and therefore participants cannot use this information to find the cause of the fault. In other words, the information provides only a binary understanding of the system (failed/working).

A decision ladder corresponding to alarm acceptance (task 1) in level 1 is shown in Figure 8-8 and the decision ladder corresponding to alarm clearance is shown in Figure 8-9. The shaded circles and rectangles show those states and processes that are not supported when presented with this level of information.

As shown in both of the decision ladders, this condition enables all of the states, apart from the state in which the decision maker can investigate and evaluate alternative options. Since the information presented is the absolute minimum, it does not allow the user to assess various possibilities.




| Locomotive Class | Speed Restriction |
|---|---|
| 373 | 110 mph |
| General | 80 mph |

| Train | Type |
|---|---|
| T106D | Class 373 |

**FIGURE 8-7: PROTOTYPE OF LEVEL 1 TO CONDUCT ALARM CLEARANCE**

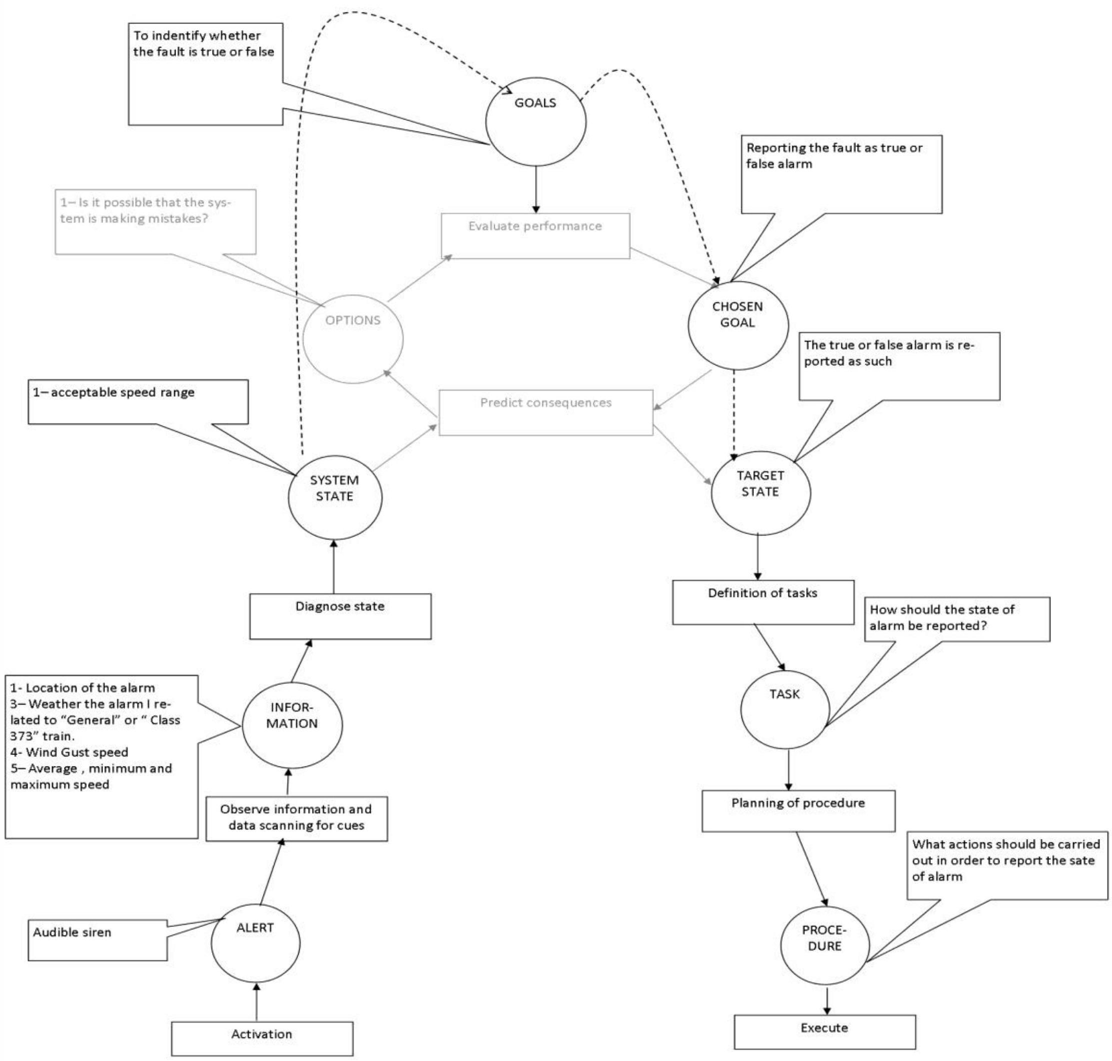



**FIGURE 8-8: DECISION LADDER OF ALARM ACCEPTANCE WHEN PRESENTED WITH THE FIRST LEVEL OF INFORMATION**

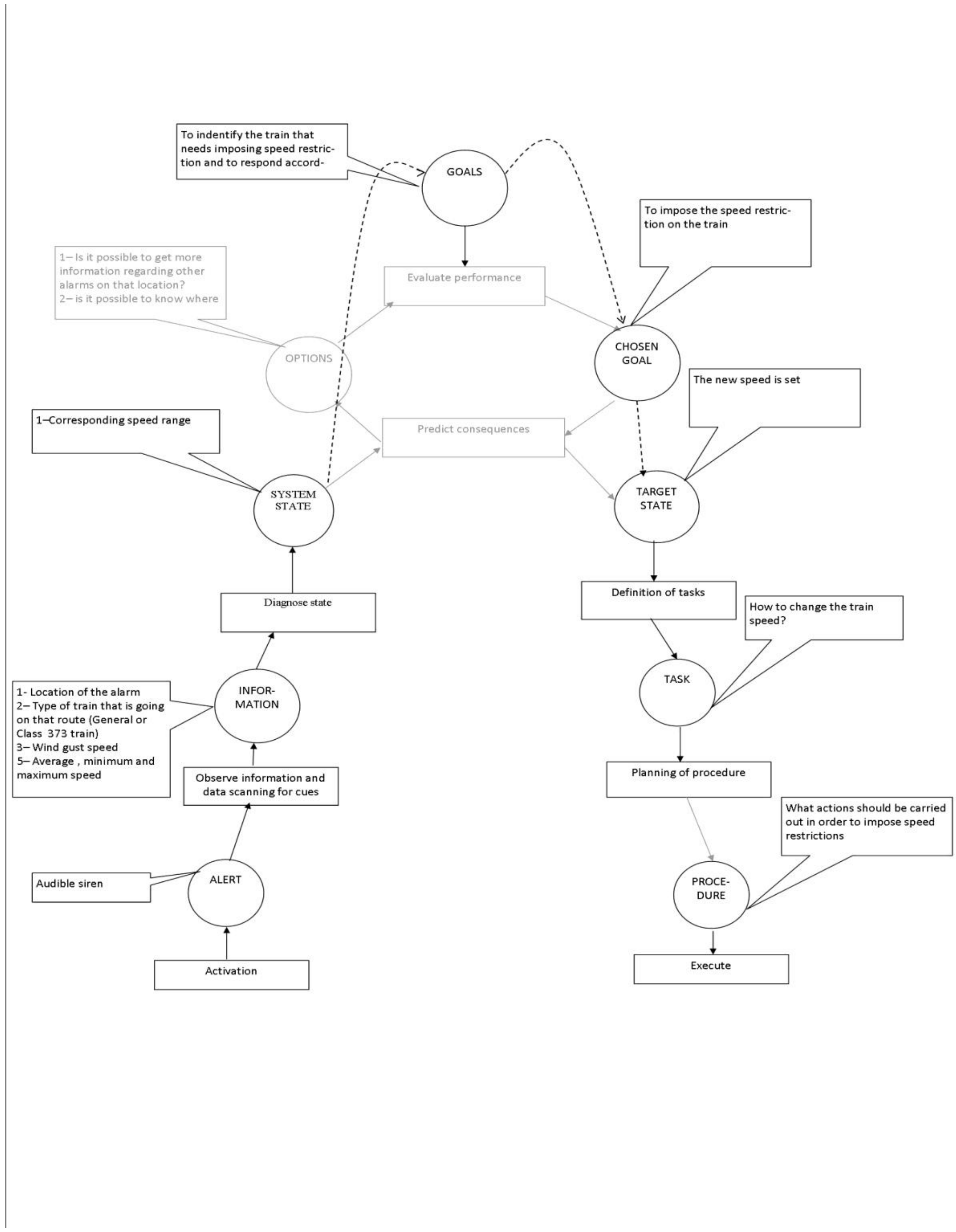



**FIGURE 8-9: DECISION LADDER OF ALARM CLEARANCE WHEN PRESENTED WITH THE FIRST LEVEL OF INFORMATION**

#### 8.3.2.2. Level two

Level two provides participants with information that can be used to explain the possible causes of the fault as well as the basic information required to detect the state of failure (level 1). In this condition, participants were also presented with information regarding an ice alarm in that location. The experimental prototypes for the second level of information during alarm acceptance and alarm clearance are shown in Figure 8-10 and Figure 8-11 respectively.

Figure 8-12 and Figure 8-13 show the decision ladder of alarm acceptance and alarm clearance tasks when participants were presented with the second level of information. As shown in both decision ladders, under these conditions, participants have some information to enable them to evaluate various options. Findings from the alarm handling and fault finding study reported in chapters 6 and 7 confirmed that information regarding the location of the fault (in this case the presence of an ice alarm at the location) enables operators to assess various options and to guess the causes of the fault.

It should be noted that the second level of information includes first level data (basic wind threshold tables) as well. Therefore, more information is presented to participants.

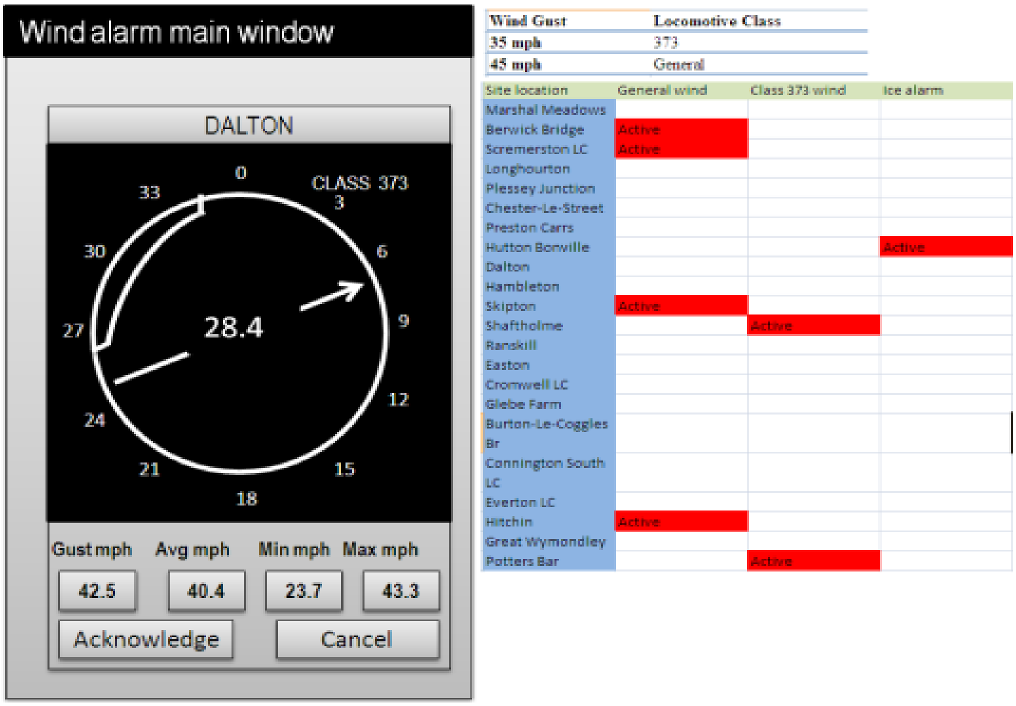



**FIGURE 8-10: PROTOTYPE OF LEVEL 2 TO CONDUCT ALARM ACCEPTANCE**

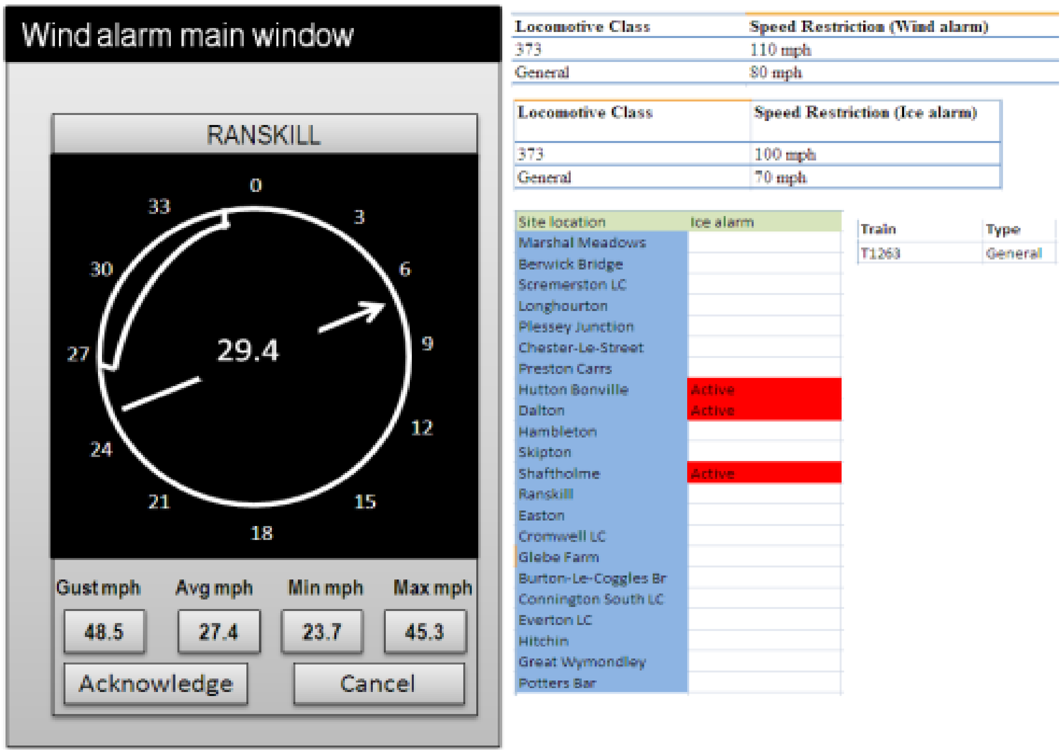



**FIGURE 8-11: PROTOTYPE OF LEVEL 2 TO CONDUCT ALARM CLEARANCE**

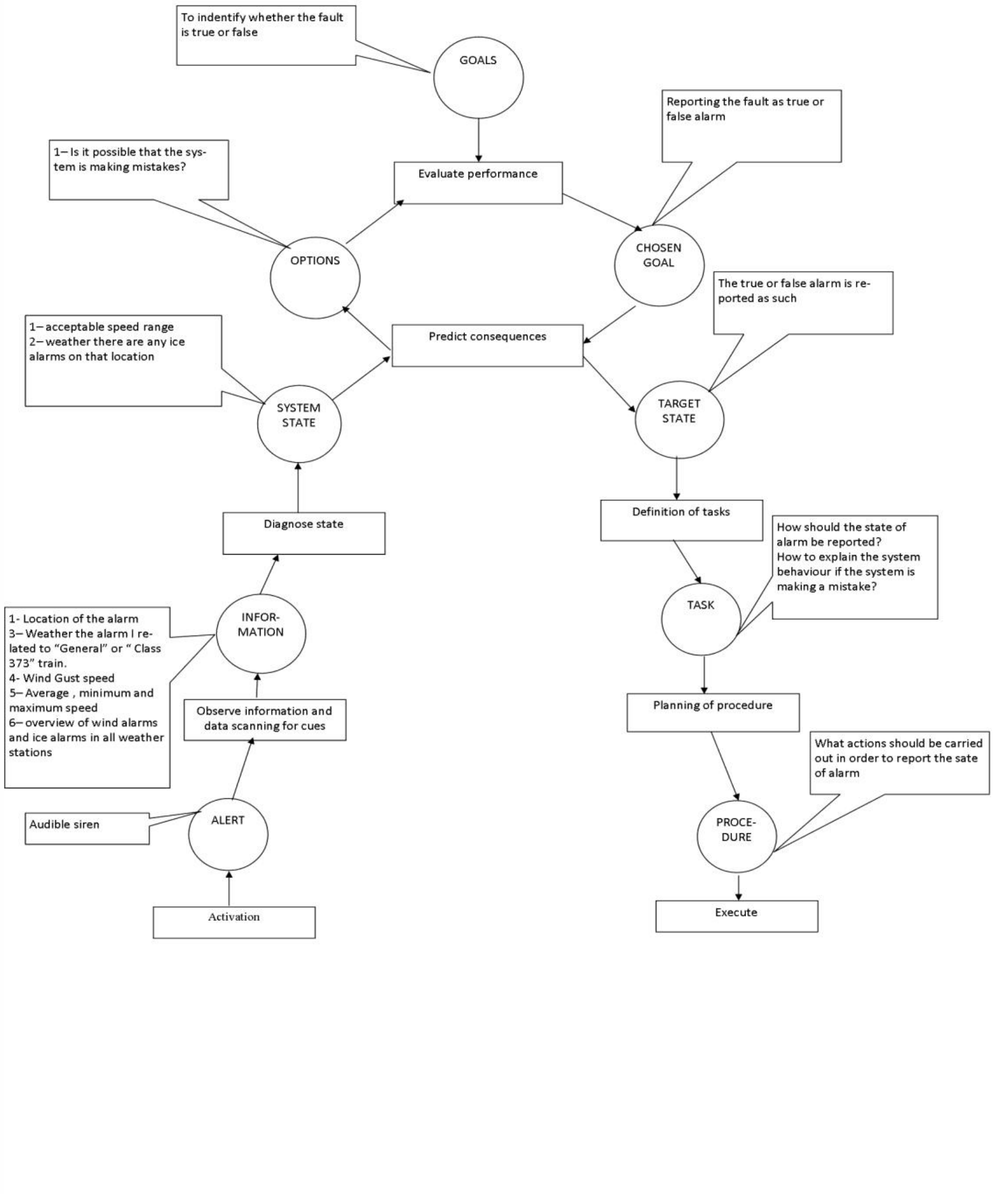



**FIGURE 8-12: DECISION LADDER OF ALARM ACCEPTANCE WHEN PRESENTED WITH THE SECOND LEVEL OF INFORMATION**

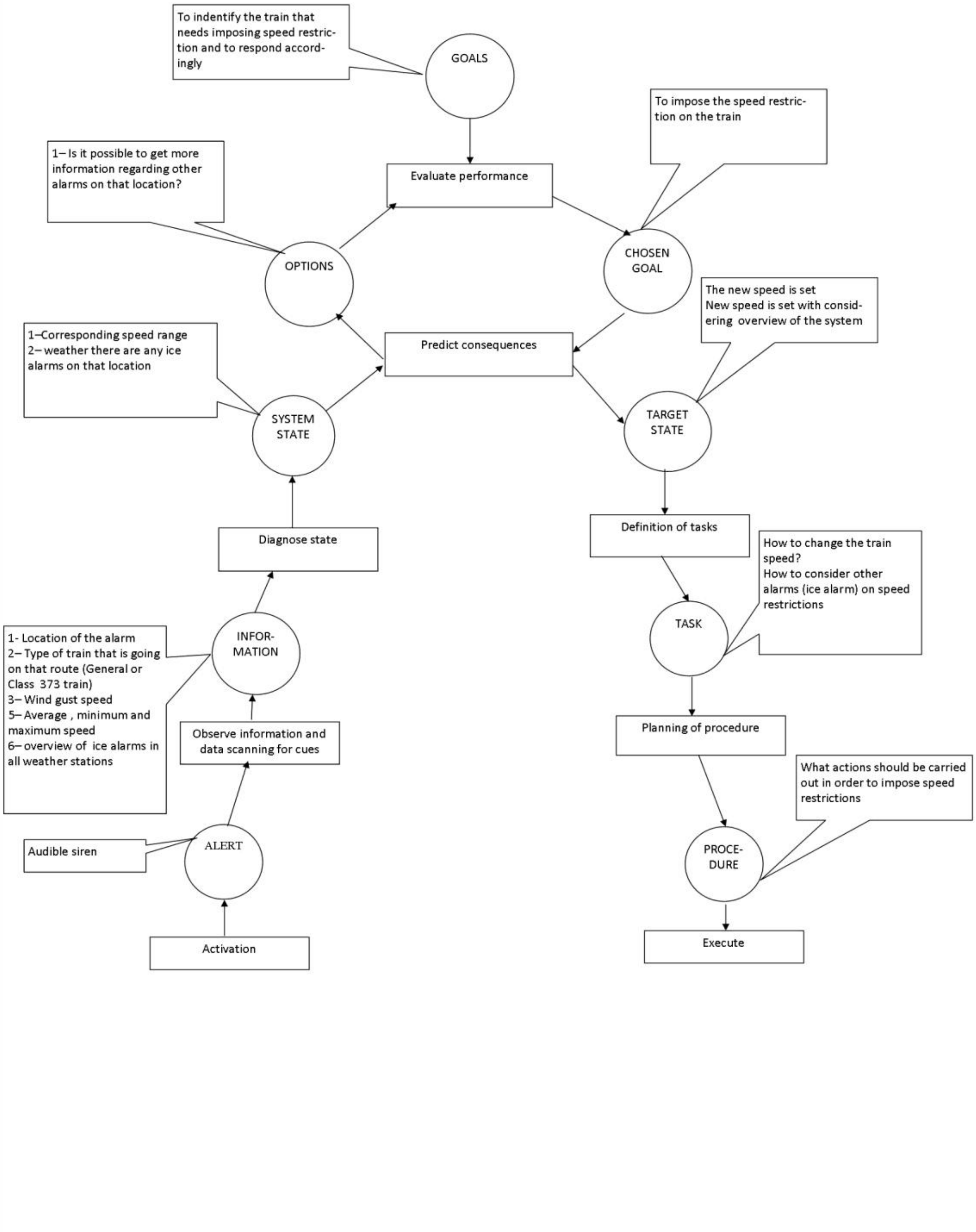



**FIGURE 8-13: DECISION LADDER OF ALARM CLEARANCE WHEN PRESENTED WITH THE SECOND LEVEL OF INFORMATION**

#### 8.3.2.3. Level three

The third level of information provides participants with information that enables them to predict future states of the system by applying their knowledge to make a more informed decision. In this experiment, participants were provided with information that enabled them to predict potential future wind alarms.

Figure 8-14 shows the experimental prototype at level 3, when participants had to conduct the alarm acceptance task. A table of wind gusts in the neighbouring weather stations was provided. Depending on the type of train, locations with a wind gust speed close to 35 mph and 45 mph are likely to generate an alarm fairly soon and operators can therefore expect alarms in those locations.

Figure 8-15 shows the experimental prototype for level 3, when participants had to conduct alarm clearance. In this case, participants know the route the train will be following and also know that the location in which the train is heading will be alarming soon. They have to re-set (increase or decrease) the speed restriction for the train entering the new location as the speed restriction applies only to the current location.

Decision ladders of both alarm acceptance and alarm clearance tasks in condition three are shown in Figure 8-16 and Figure 8-17. The decision ladder at this level is similar to the decision ladders of alarm acceptance and alarm clearance tasks at level 2; similar states and processes are supported. However, more information is available to participants.

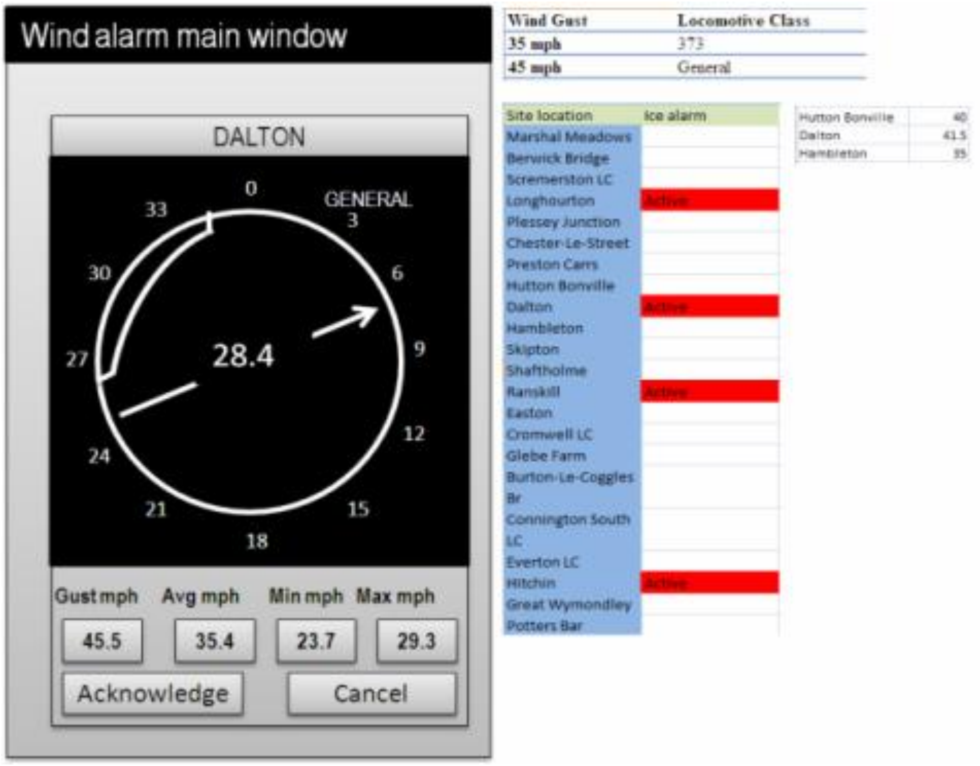



**FIGURE 8-14: PROTOTYPE OF LEVEL 3 TO CONDUCT ALARM ACCEPTANCE**

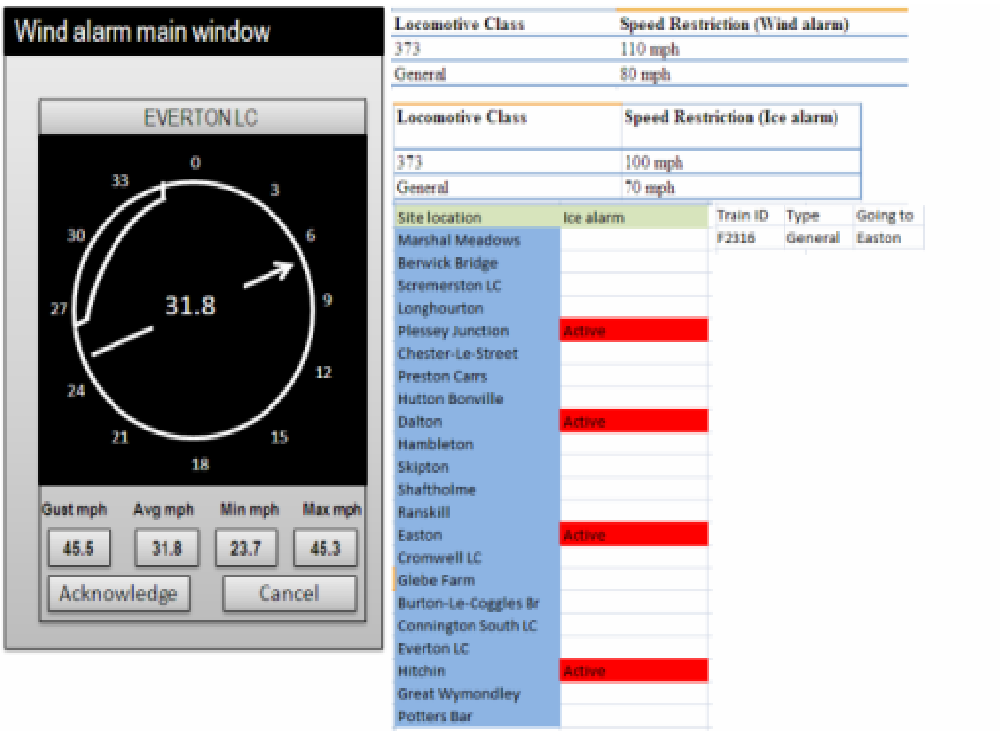



**FIGURE 8-15: PROTOTYPE OF LEVEL 3 TO CONDUCT ALARM CLEARANCE**

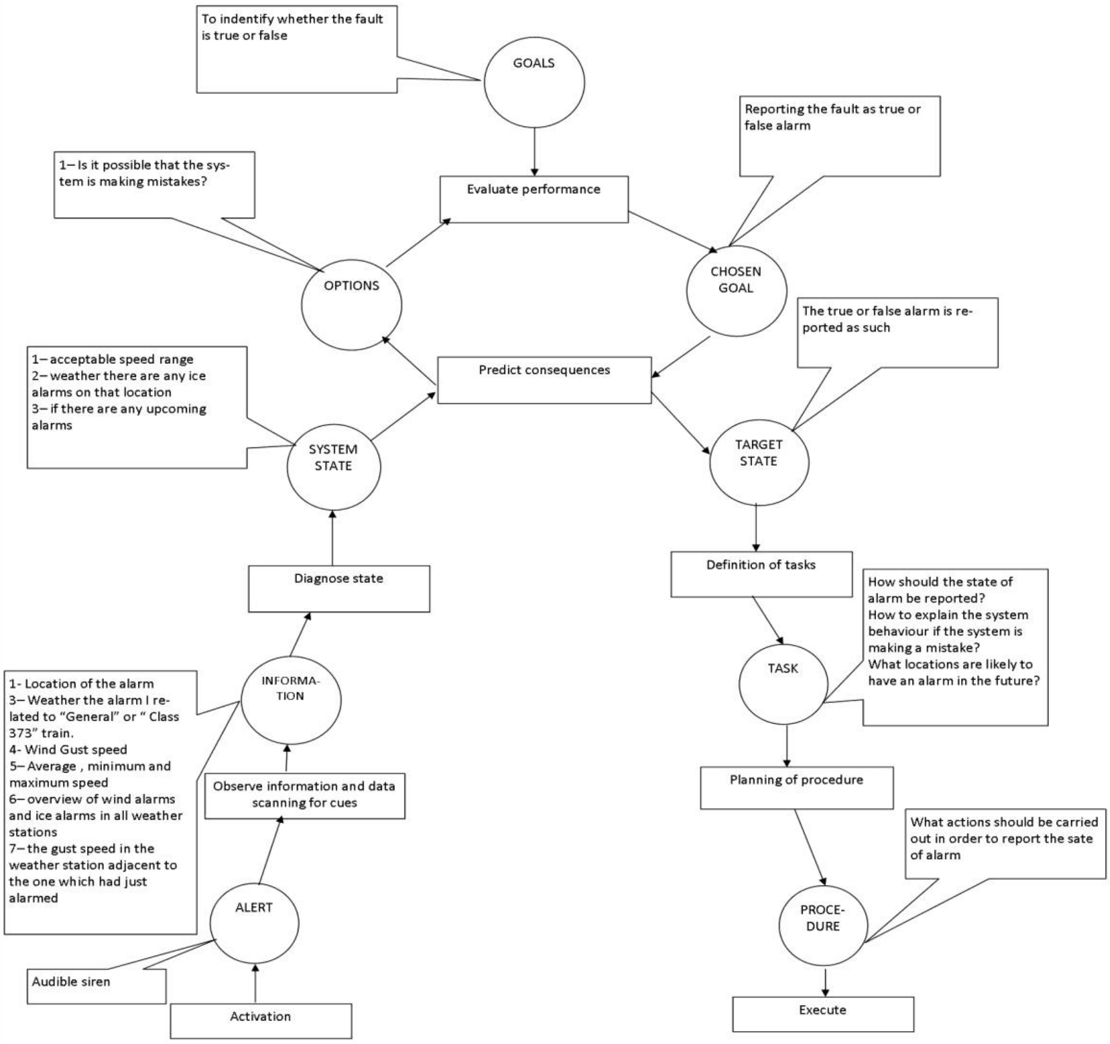



**FIGURE 8-16: DECISION LADDER OF ALARM ACCEPTANCE WHEN PRESENTED WITH THE THIRD LEVEL OF INFORMATION**

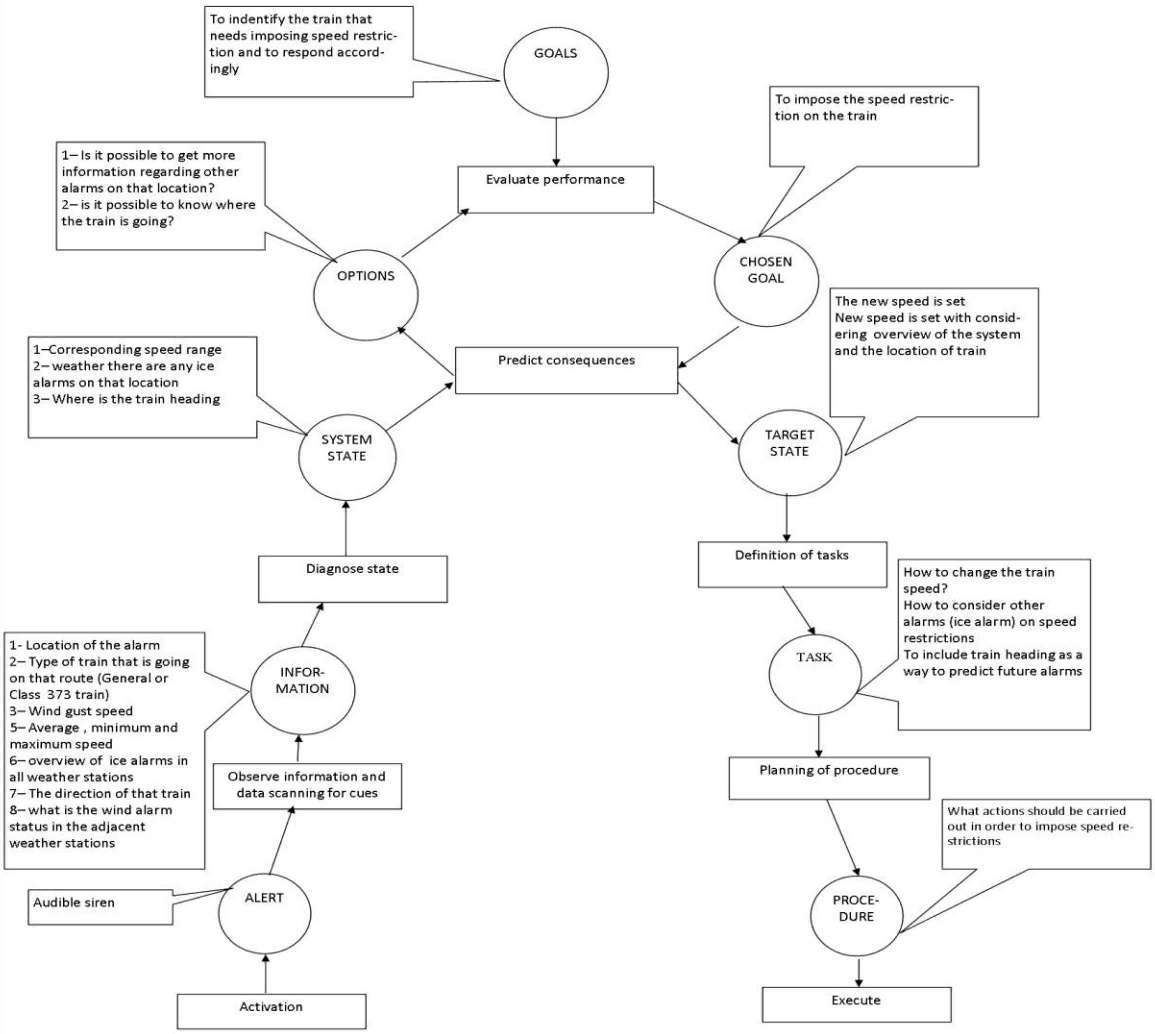



**FIGURE 8-17: DECISION LADDER OF ALARM CLEARANCE WHEN PRESENTED WITH THE THIRD LEVEL OF INFORMATION**

### *8.3.3. Relationship between performance and levels of information*

The decision ladders reported earlier enabled the prediction of participants' performance when presented with various levels of information. As shown in Figure 8-18, the alarm acceptance completion time is expected to increase from level 1 to level 3. The first level of information provides the participants with only a basic understanding of the problem by giving tables of train speeds and train types. The second level of information provides the wind alarm status in the neighbouring weather stations to give them an overview of the domain and the third level of information provides information regarding future potential wind alarms.

The increase in the completion time can simply relate to the increase in the amount of information presented to the participants. Moreover, the information at levels 2 and 3 is not necessarily useful for the alarm acceptance task. Although the second level of information can provide participants with an overview (status of wind alarm in the neighbouring weather station) of their choice ('accept' or 'cancel'), it is not a necessary piece of information.

Similarly, errors are also expected to increase from level 1 to level 2, but will decrease when participants are presented with the third level of information. The errors in the second level increase possibly because operators become confused and their task does not really need an overview to aid their understanding. However, giving information to participants about future alarms means that, when those alarms occur, they are expecting them and therefore their errors decrease.

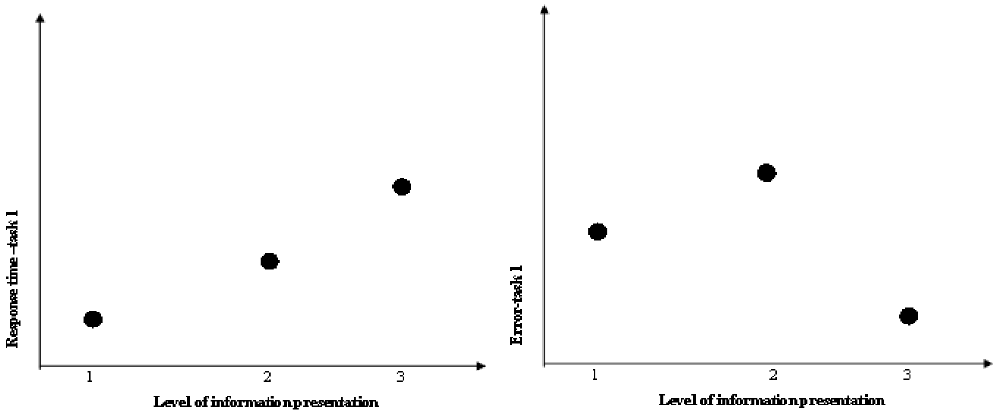



**FIGURE 8-18: HYPOTHESISED PERFORMANCE OF PARTICIPANTS WHILE CONDUCTING TASK 1: ACCEPTING THE ALARM**

In terms of the intelligent infrastructure roles, assuming that track workers' main tasks are to notice and accept faults, this hypothesis means that track workers do not need/want an overview of the domain if the system is reliable enough to provide them with an accurate binary indication of assets' status. This corresponds to the findings from the data processing framework (Figure 8-19).

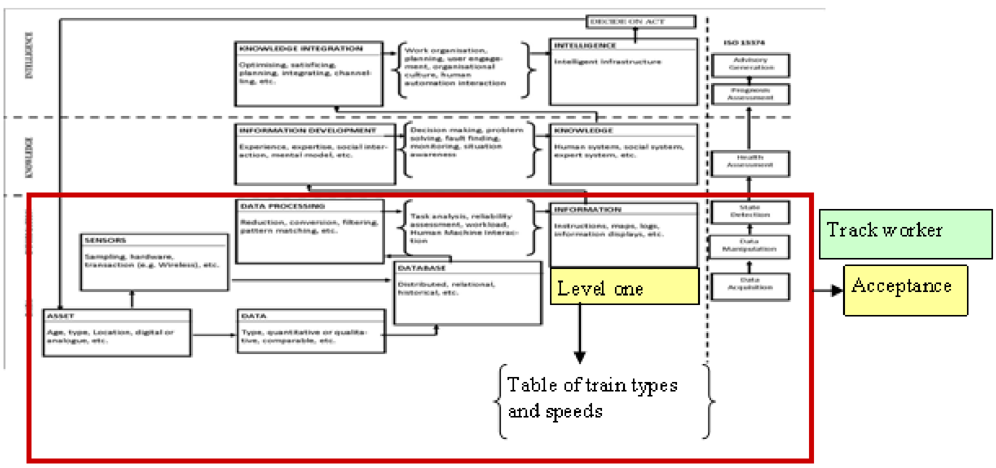
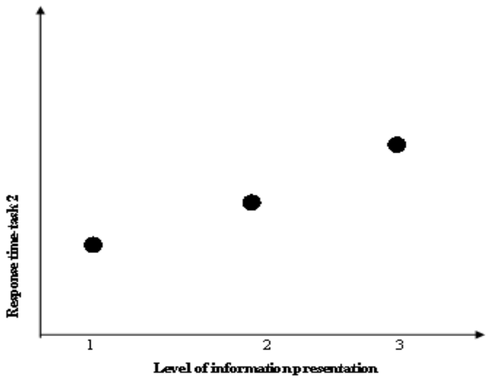



**FIGURE 8-19: HYPOTHETICAL OPTIAMAL LEVEL OF INFORMATION FOR ALARM ACCPETANCE**

The decision ladders led to hypotheses about the performance of alarm handling tasks at each level of information. Figure 8-20 shows the completion time and errors associated with alarm clearance while presented with the three levels of information. Task completion time will hypothetically increase. The increase in the task completion time is due to an increase in the amount of information presented to the operators.

The errors would probably decrease when operators are presented with the second level of information, as this information will give them a better overview of the problem. When presented with the third level of information, errors would probably increase due to the fact that the information is not directly related to operators' task at hand. Instead, it provides information about future alarms, but does not add much in terms of the existing situation; such irrelevant information can confuse operators.



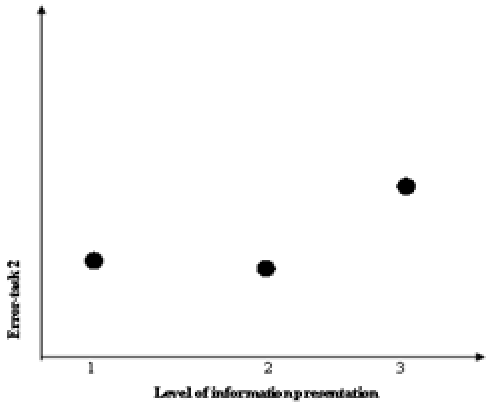




**FIGURE 8-20: HYPOTHESISED PERFORMANCE OF PARTICIPANTS WHILE CONDUCTING TASK 2: CORRECTING THE ALARM**

Assuming that, within an intelligent infrastructure system, the core function of control room operators is to analyse and clear faults, the provision of information regarding the future state of assets will only confuse them. However, they do benefit from overview information (Figure 8-20).

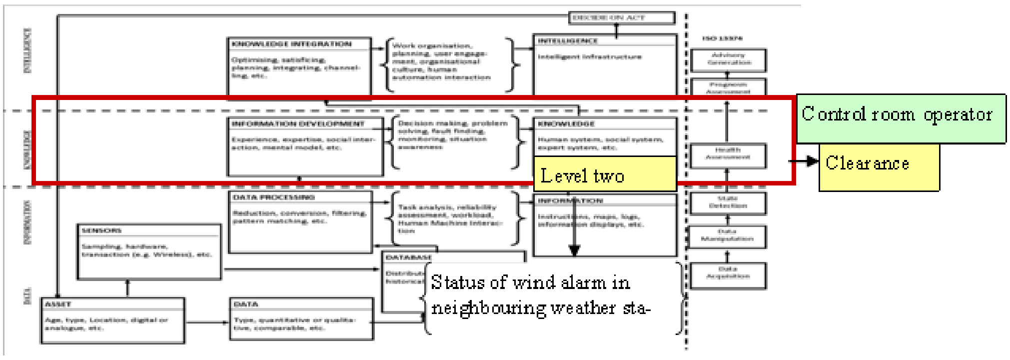



**FIGURE 8-21: HYPOTHETICAL OPTIAMAL LEVEL OF INFORMATION FOR ALARM CLEARANCE**

The laboratory study presented in the next section investigated these hypotheses in a simulated environment.

## *8.4. Method*

### *8.4.1. Design*

Three groups of participants (group A, group B and group C) were instructed to conduct both alarm acceptance and alarm clearance tasks. The experimental conditions are summarised in Table 8-5 below.

**TABLE 8-5: EXPERIMENTAL CONDITIONS**

| Participants / Tasks | Group A | Group B | Group C |
|---|---|---|---|
| Accepting | Level 1 | Level2 | Level 3 |
| Clearing | Level 1 | Level2 | Level 3 |

A between subject study was designed: each group of participants was presented with only one of the levels of information. Both tasks were examined and participants' response times and the number of errors they made while conducting the tasks were recorded.

Participants were asked to take note of specific faults that were logged on paper on the fault management system (Figure 8-22). This secondary task was used to keep the participants occupied between the occurrences of the alarms.

The hypothesis and the dependent and independent variables investigated in this laboratory study are listed in Table 8-6.

**TABLE 8-6: HYPOTHESIS AND VARIABLES INVESTIGATED IN THE LABORATORY STUDY**

| Hypothesis | Independent variables | Dependent variables |
|---|---|---|
| There is an effect of the information provided on the performance of alarm handling tasks. | Information available→3 levels<br>Alarm handling tasks→ clearance and acceptance | Alarm handling performance<br>Secondary task performance |

### *8.4.2. Participants*

The sample consisted of 31 students (14 male and 17 female, with a mean age of 22 years) from the University of Nottingham. They were recruited through an advertisement on the University of Nottingham's portal. None of the participants had any prior experience of alarm handling systems. Ethical guidelines of the University of Nottingham were followed throughout this laboratory study. The information sheet of this study can be found in appendix 12.9.

### *8.4.3. Apparatus*

A 15" Sony VAIO™ laptop was used for displaying the screenshots of the wind alarm prototype. A 15" Dell™ laptop was used to display the maintenance control fault log (Figure 8-22) to participants when they were not handling alarms. A fault log recording form (Figure 8-23) was filled in by participants while monitoring the fault log. Finally, an Olympus™ audio recorder was used to record participants' comments after the completion of the trial.

| Log | Date | Tech. | FMS No | Location | Equipment Type | Equipment ID | Controller Unit Ty | Field Uni | Common Fault | Common Fix | | Cleared / Fixed |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 18/10/2008 | NP | 390206 | PL42 | AWS | AWS.3892I/3892S | N/A | N/A | Feedback Discordance | VIO Replaced | Feedback Discordance, Missing checking Bit from 3892 (SUPP) IR<br>Poor Voltage from VIO 30v only going to relay. | Fixed |
| 2 | 25.10.2008 | PE | 391130 | PL01 | Point Machine | WM.5251 | N/A | N/A | Point Heaters Faulty | Sacda Issue (Plant) | Point Heaters not working | Fixed |
| 3 | 25/10/2008 | PE | 391131 | DPL101RB | Point Machine | WM.5175 | N/A | N/A | Point Heaters Faulty | Sacda Issue (Plant) | Point Heaters not working | Fixed |
| 4 | 06/11/2008 | GH | 392679 | DPL43RB | Area Controller Normal | CdAN-21 | N/A | N/A | Normal Unit Dead | Area Controller Reset | Area Controller failure | Fixed |
| 5 | 06/11/2008 | JJ | 392722 | PL01 | OFF Indicator | OFF.391(2) | POT | CLAM | Lamp Failure | Lamp Replaced | Awaiting lamp replacement | Fixed |
| 6 | 16/11/2008 | PE | 393969 | DPL91LA | Area Controller Normal | CdAN-58 | N/A | N/A | Normal Unit Dead | Area Controller Reset | Area Controller failure | Fixed |
| 7 | 16/11/2008 | PE | 393985 | PL01 | Insulation Monitor | N/A | N/A | N/A | Earth Alarm | Dry Weather | TX6 Earth alarm | Cleared on own |
| 8 | 21/11/2008 | NP | 394791 | PL43 | RAPL | RAR.3877/3878/3882 | POT | CLAM | Failed to Light | ROA / NFF | Right Away indicator failed to light with key turn. | Unknown |
| 9 | 22/11/2008 | PE | 394898 | PL01 | Point Machine | WM.5252 | DEV | CDEV | Failed to get Normal | Slidechairs cleaned | No normal/Slidechairs cleaned. | Fixed |
| 10 | 23/11/2008 | PE | 395048 | PL47 | Point Machine | WM.5182 | DEV | CDEV | Lost Normal Detection | ROA / NFF | Lost normal /restored on IPS. | Unknown |
| 11 | 28/11/2008 | NP | 395708 | PL47 | TPWS | TPWS.4076 | VIO | N/A | Failed to Power | TPWS Module Reset | TPWS Failed to power, TSS Module reset | Fixed |
| 12 | 29/11/2008 | GH | 395814 | PL45 | Main Signal | S.3864 I | POT | CLAM | Failed to Light | PSU/Filter Replaced | replaced psu/filter | Fixed |
| 13 | 01/12/2008 | NP | 396036 | PL45 | Not Applicable | Not Applicable | N/A | N/A | REC Failure | ROA / NFF | Point Heating: Mains Failed | Cleared on own |
| 14 | 01/12/2008 | NP | 396085 | PL43 | Not Applicable | Not Applicable | N/A | N/A | REC Failure | REC Restored | Point Heating: Mains Failed | Cleared on own |
| 15 | 01/12/2008 | NP | 396062 | PL43 | Point Machine | WM.5225 | DEV | CDEV | Failed to get Normal | Back Drive Adjusted | 5225 Points failed to obtain Normal | Fixed |
| 16 | 01/12/2008 | PE | 396199 | PL101 | Point Machine | WM.5165 | DEV | CDEV | Failed to get Reverse | ROA / NFF | No reverse 5165 points | Unknown |
| 17 | 01/12/2008 | PE | 396226 | DPL43RB | Point Machine | WM.5234 | DEV | CDEV | Failed to get Normal | ROA / NFF | No normal 5234 points | Unknown |
| 18 | 01/12/2008 | PE | 396228 | PL43 | Wilmslow North Points Heating | 5233 | N/A | N/A | Point Heaters in Manual | Sacda Issue (Plant) | North cubicle point heaters in manual. | Fixed |
| 19 | 04/12/2008 | SL | 396668 | PL43 | Point Machine | WM.5224 | DEV | CDEV | Failed to get Reverse | ROA / NFF | Fault team suspects interlocking issue | Unknown |
| 20 | 04/12/2008 | NP | 396693 | PL47 | TPWS | TPWS.4067 | VIO | N/A | Failed to Power | TPWS Module Replaced | TPWS Failed to power TSS Replaced | Fixed |
| 21 | 04/12/2008 | NP | 396708 | DPL43RB | Area Controller Reserve | CdAR-20 | N/A | N/A | Reserve Unit Dead | Area Controller Reset | Reserve Area Controller dead | Fixed |
| 22 | 05/12/2008 | NP | 396862 | PL41 | Area Controller Reserve | CdAR-07 | N/A | N/A | Reserve Unit Dead | Area Controller Replaced | Reserve Area Controller dead | Fixed |
| 23 | 06/12/2008 | PE | 397012 | DPL43RB | Point Machine | WM.5234 | DEV | CDEV | Lost Normal Detection | ROA / NFF | Lost normal /restored on IPS. | Unknown |

**FIGURE 8-22: MAINTENANCE CONTROL FAULT LOG**

Fualt details :
Log No:
Equipment type: Point Machine
Date :

Common fault :

Common Fix : Reported By :

**FIGURE 8-23: FAULT LOG RECORDING FORM**

### *8.4.4. Procedure*

Participants were briefed and asked to review the information sheet before agreeing to take part in the study. In all of the experimental trials participants had to perform task 1 (alarm acceptance) prior to task 2 (alarm clearance) and they received training for each of the tasks. Participants were guided through a 7 to 10 minute training session for task 1 and then performed a practice run with the experimental prototype. Next they were asked to attend to 24 cases of alarm episodes. After the completion of task 1, they were briefed and trained on task 2 for another 7 to 10 minutes. They then practised with the experimental prototype, after which they were asked to attend to 16 cases of alarms.

There was a 30 second interval between each of the alarm cases, during which participants were asked to monitor and find 'point machine' faults on the fault log (Figure 8-22) and fill in the fault log recording form (Figure 8-23).

Finally, participants were asked to comment on the alarm episodes and to describe their reasons for the decisions made. Their comments about the experimental prototype and the tasks were recorded using an audio recorder. This led to approximately two hours of audio recording. The procedure for this experiment is summarised in Figure 8-24 below.

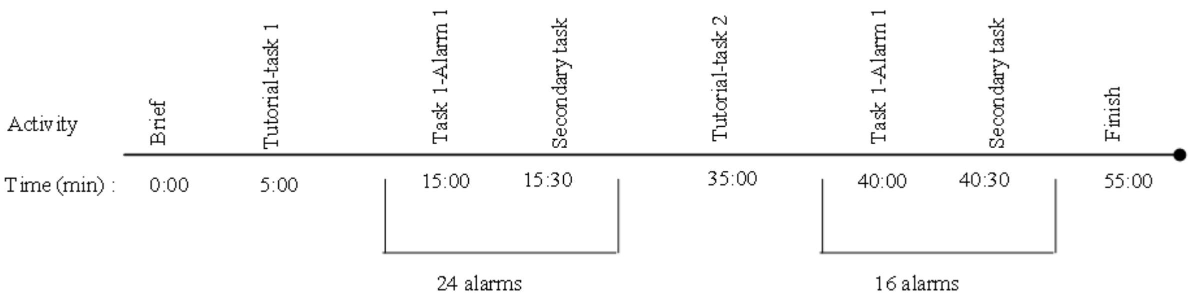



**FIGURE 8-24: EXPERIMENTAL PROCEDURE**

## *8.5. Results*

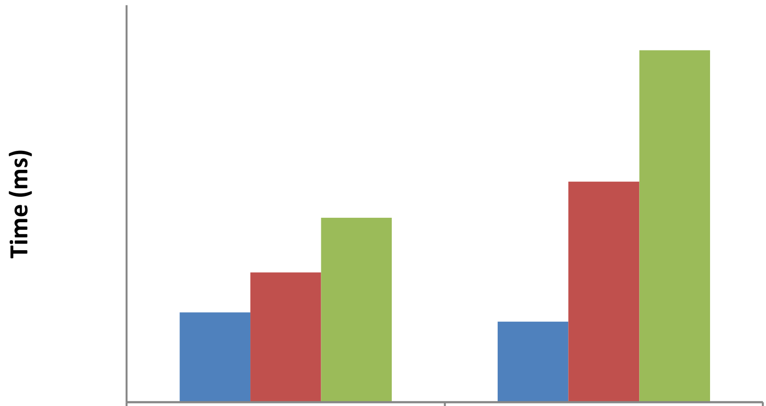
Participants' completion times and errors during the trials were recorded through E-prime 2.0™. A 2X3 between subjects ANOVA was conducted. The results have been analysed statistically using SPSS™ Version 18.0. Participants' comments were reviewed and the main themes mentioned by participants were identified.

### *8.5.1. Completion time*

For both alarm acceptance and clearance, a linear increase in response was visible from level 1 to 3. Means of the response times associated with alarm acceptance and alarm clearance tasks while presented with three levels of information are shown in Figure 8-25. Despite the existence of this trend, this increase is not significant for alarm acceptance; $F(2, 28) = 2.94$, $p>0.05$.

Multiple comparisons between different levels of information show significant differences between completion times of alarm acceptance with level 1 information, compared with alarm clearance with level 3 information ($p<0.05$).

Unlike alarm acceptance, when participants were clearing alarms, the completion time were significantly different depending on the level of information: $F(2, 28) = 11.73$, $p<0.001$. Multiple comparison shows significant difference between all the levels ($p<0.001$).




| | Alarm acceptance | Alarm clearance |
|---|---|---|
| Level 1 | 4076.29 | 3654.85 |
| level 1 | 5881.39 | 10001.32 |
| level 3 | 8365.44 | 15948.68 |

**FIGURE 8-25: MEAN OF COMPLETION TIME FOR TWO TASKS AT THREE DIFFERENT LEVELS (MS)**

### *8.5.2. Error*

The mean of the number of errors while performing both tasks and when participants were presented with the three levels of information is shown in Figure 8-26. Although the third level generates the least number of errors while accepting alarms (task 1), this was not significant: F (2, 28) = 0.73, p>0.05. Multiple comparisons of various levels also do not show any significant difference among levels.

On the other hand, when participants were clearing alarms, depending on the level of information available to them, their errors were significantly different: F (2, 28) = 5.871, p<0.05. Multiple comparison between different levels of information shows significant difference between levels 1 and 2 (p<0.05) and levels 1 and 3 (p<0.01).

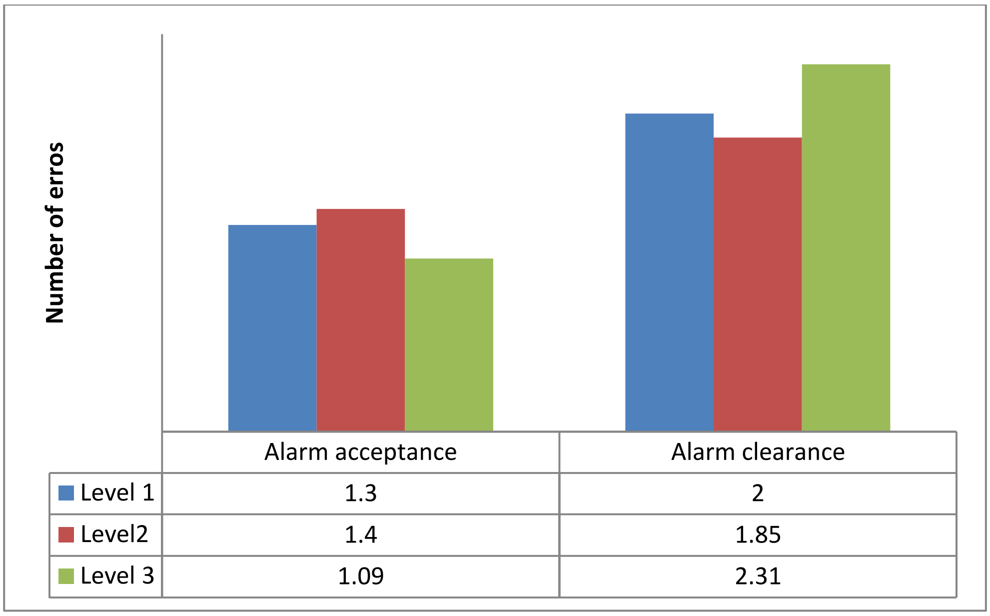
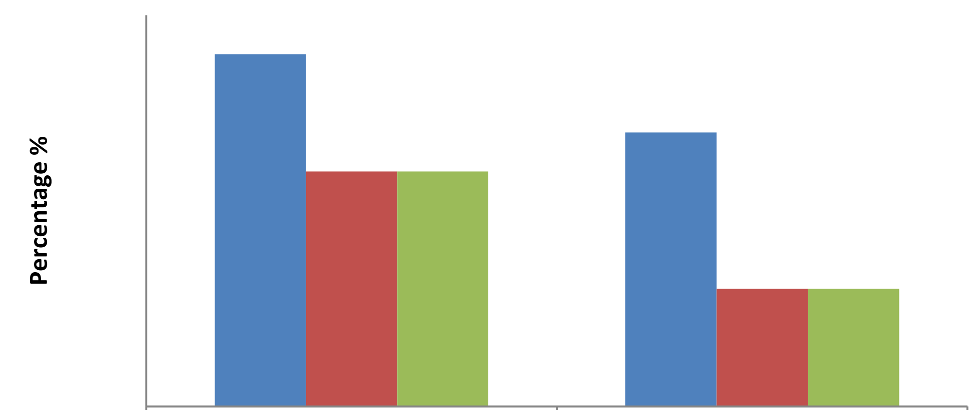



**FIGURE 8-26: ERRORS MADE DURING ALARM ACCEPTANCE AND ALARM ANALYSIS IN THREE CONDITIONS**

### *8.5.3. Secondary task performance*

Secondary task performance refers to the percentage of faults logged correctly. The secondary task was designed to keep participants occupied when there was no alarm and it did not target any specific research questions.

There was no significant difference between secondary task performance in both alarm acceptance and alarm clearance tasks when presented with various levels of information. Figure 8-27 shows the mean percentage of secondary task performance while presented with the three levels of information for both alarm acceptance and alarm clearance tasks. The highest percentage, 97%, was associated with the first level when participants were accepting the alarm.  The lowest percentage, 93%, was associated with levels 2 and 3, when participants were clearing alarms. With the increase in the conditions, this percentage shows a decreasing trend. Although not significant, the drop in the percentage from level 1 to 2 and 3 while performing task 1 (from 99% to 96%) was smaller compared to the drop in the percentage while performing task 2 (from 97% to 93%). Moreover, the percentage of secondary tasks in two of the levels (2 and 3) is identical for both tasks.




| | Alarm acceptance | Alarm clearance |
|---|---|---|
| Level 1 | 0.99 | 0.97 |
| Level2 | 0.96 | 0.93 |
| Level 3 | 0.96 | 0.93 |

**FIGURE 8-27: PERCENTAGE OF SECONDARY TASK PERFORMANCE WHILE CONDUCTING TASKS 1 AND 2 IN THREE CONDITIONS**

### *8.5.4. Participants' comments*

When participants were presented with the first level of information, they found alarm clearance easier than alarm acceptance. One participant mentioned that "*task 2 (alarm clearance) was easier because I only had to look at one thing*". In other words, the perceived difficulty was associated with the amount of information available, which explains the higher response time for alarm acceptance tasks in comparison with alarm clearance. Out of the 10 participants presented with the first level of information, only one participant said that alarm acceptance was easier than alarm clearance and the reason mentioned was*:" the location of information was more organised on the screen than in task 2"*. Although the presentation of information on the screen was not the focus of this study, this participant's comment suggests that presenting the information on a display affects the user's perception of task difficulty.

When presented with the second level of information, participants had the option of reviewing location information and using this data for decision making, if they wanted to. Although this was an optional piece of information, all 10 participants in this condition considered it. One of the participants mentioned*:" well there is an option there and you just want to* *use it"*. Unlike the first group (first level of information), 7 of the 10 participants in the second group found alarm clearance more difficult. This was due to the increase in the amount of information that they felt obliged to review and analyse. This difficulty is reflected in the quantitative data as well: errors and response times are higher for the alarm clearance task than for alarm acceptance. The 3 participants who found task 2 easier under the second condition gave different reasons. One participant said that the second task was easier because they were familiar with the system after performing alarm acceptance. Another participant made a mistake when accepting alarms due to distractions caused by monitoring the fault log and therefore found the task more difficult.

All 11 participants performing the tasks under the third condition attended to location information for the alarm clearance task but mostly ignored it when accepting alarms. One of the participants said that, during alarm acceptance, "*I got quite stressed and I could not attend to any additional information regarding the location, I just wanted to deal with the absolute minimum*". However, five participants used the information regarding the gust speed in the neighbouring location as a clue to predict future alarms. This explains the reason for the lower number of errors when performing the alarm acceptance in the third group (information level 3) in comparison with the other two groups. Participants mainly used these extra pieces of information to investigate a false alarm; if the alarm was true, participants were unlikely to consult any of these sources of information. Other participants chose not to refer to the wind speed in the neighbouring station as they wanted to handle alarms as quickly as possible and therefore did not want to attend to information believed to be beneficial in the future. One of the participants mentioned that: "*I was not sure when these alarms would happen, so I thought by the time they are generated I might have forgotten them already*".

In the third group, only one participant used the route information to predict future alarms when clearing alarms; the rest chose not to use that information. One participants mentioned that, " I felt it was too much", another said that " *because there were too many pieces of information I* *knew I would not remember that route anyway, so it was better to deal with them when they were generated".*

In the third group, 7 out of 11 participants found the alarm acceptance task easier than the alarm clearance task. One participant thought that alarm acceptance was more difficult because, in alarm clearance, the user felt more engaged and felt that they had control over the situation. The participant said: *"Task 1 (alarm acceptance) is too boring for the operator and should be done by a machine, not a human"*. A number of participants reported confusion when they had to deal with various pieces of information when clearing alarms and admitted that they might have made some mistakes.

## *8.6. Discussion*

The main goal of intelligent infrastructure system is to: *"provide the right information at the right time to the right person"* (NR Intelligent Infrastructure project manager). Currently, with the aid of advanced technologies, sophisticated pieces of information are being collected. However, the question remains as to whether the provision of all of these pieces of information to users with different responsibilities would enhance performance or not.

The study presented in this chapter has attempted to address this question in a simplified simulated environment. Different activities (alarm acceptance and clearance tasks), thought to be relevant to the roles of a future intelligent infrastructure system (track worker, control room operator and strategic analyst), were assessed when participants were presented with different levels of information.

There were two reasons for using the simulated environment in this study. Firstly, it was not possible to use real-life settings due to the safety criticality of the maintenance technicians' role. Secondly, a simulated environment enabled the experimental tasks to be isolated from each other and addressed the objectives of this study more effectively.

Novice participants (trained students in this case) were selected in this study. This was to avoid bias imposed on the experiment by experts.

Expert operators would automatically accept and clear the alarms and the presentation of different levels of information would not have much effect on their performance. This is because the type of the fault prototyped in this study was a simple and straightforward scenario.

Power analysis was conducted after performing the study with 4 participants within each of the groups. This was to get an idea of the effect size of various conditions, as well as the optimum sample size. The recommended sample size was found to be 45 (15 in each group). However, this study did not aim to identify significant differences between various conditions; it was mainly to explore the trend that was hypothesised (Figure 8-18).

The data processing framework presented in chapter 5 of this thesis identified three categories of data processing: data & information, knowledge, and intelligence. These corresponded to the three levels of information investigated in the present study. The findings of the laboratory study in admittedly limited conditions confirmed the impact of presenting various levels of information to operators at different stages of problem solving. As mentioned in chapter 5, it is reasonable to assume that each of the roles of the future intelligent infrastructure system will benefit from one of these categories. Track workers would require only basic understanding of the system (level 1), control room operators need to be able to interpret the system (level 2) and strategic analysts need to be able to predict the future state of the system (level 3).

According to the data processing framework, control room operators' performance is best when they are presented with the second level of information (knowledge). Findings of the study confirmed that alarm clearance errors were fewest when operators were presented with level 2 information. However, while accepting alarms, the least number of the errors related to the third level of information This is potentially due to the fact that, during alarm acceptance, operators had enough time to attend to extra pieces of information to predict future alarms and consequently to expect when they would be generated.

The performance of the participants with different levels of information was predicted through the decision ladders that had been drawn during the fault finding study (Chapter 7). These predictions were mostly confirmed. This highlights the benefit and necessity of using field studies to understand cognitive activities and, in particular, the use of decision ladders to obtain a clear understanding of the system behaviour.

## *8.7. Chapter summary*

This chapter reports a laboratory study conducted to explore the hypotheses derived from different studies in the PhD about the optimal level of information for problem solving. A simplified scenario was simulated within E-prime 2.0 ™ and trained students were asked to conduct separate stages of problem solving (alarm acceptance and alarm clearance). Participants' completion times and errors were measured. The results confirmed the trend that was hypothesised. For each of the tasks, the best performance was associated with the level of information that had been hypothesised within previous studies.

# 9. Discussion

The overall aim of this thesis has been to investigate and to understand the relevant human factors for a future intelligent infrastructure on the GB railway. This has involved studies of behaviour, cognitive performance and knowledge requirements for current relevant work functions and, in prospect, for the future intelligent infrastructure.

The nature, use, and future requirements of information management in a railway intelligent infrastructure were studied through a variety of paradigms and methodological approaches. The implementation of intelligent infrastructure systems in the rail industry is still in its infancy, and despite optimistic voices at the outset of the research in 2008 it was not until 2011 that Network Rail (NR), where the research study has been based, made considerable strides towards intelligent infrastructure implementation. Therefore a considerable amount of the empirical work in this thesis was focussed on similar types of systems in today's railway, especially alarm handling and fault finding systems. This has had the beneficial effect of allowing in-depth study of railway alarm handling and fault finding – both somewhat under-studies until this work – as well as allowing the first in-depth prospective study of intelligent infrastructure human factors.

This discussion chapter is built around the original thesis objectives, and opens with a re-statement of them. A particular aspect of the discussion not covered in-depth elsewhere comprises the provision of guidance on design for and implementation of intelligent infrastructure, produced to meet objective three. Finally, a review of the application and extent of use of several paradigms and methodological approaches as well as limitations of the work are identified and their potential consequences for the findings of this work are addressed.

## *9.1. Overall contribution*

This PhD examines the needs for and delivery of information and knowledge management for railway intelligent infrastructure systems from a human factors viewpoint. In doing this, and certainly at the time when work from this PhD has been more widely published (Dadashi et al, 2011), it is believed that the research makes the first substantial human factors contribution to the application field. In addition, the key findings of the work have facilitated a deeper understanding of the roles and needs of operators in electrical control alarm handling and fault finding, considered to be key functions of the future railway intelligent infrastructure.

The objectives of this PhD thesis are to:

I. Develop a data processing framework that guide and support effective implementation of railway intelligent infrastructure from a human factors perspective
II. Establish an understanding of operators' strategies for human supervisory control tasks in alarm handling and fault finding.
III. Produce human factors guidance for the future development and implementation of intelligent infrastructure systems in the railway to match and complement human capabilities and needs.

As a result of this work, a number of major contributions have been delivered, and are briefly described here. Further on in this chapter the value of these contributions are further discussed in the context of the objectives of this PhD.

- The first contribution is the establishment of a data processing framework that identified the scope of and activities within the railway intelligent infrastructure

A data processing framework was developed which structured activities related to information within a potential intelligent infrastructure system. This framework is a combination of processes that are performed by technical equipment (e.g. sensors, data bases) and it moves up to processes performed by the human operator to handle and clear the problem. In other words, the data processing framework shows the structure within which data are manipulated (either by the human operator or technology). This provides the starting point, in an abstract view, for guidance of developers and implementers. A joint technological and human operator view of the work matches a cognitive system engineering approach whereby system performance is the result of joint collaboration amongst various agents (human and machine).

- The second major contribution is the identification of human factors issues of most importance to a successful implementation of railway intelligent infrastructure.

Although it is arguable that the study as a whole explores and investigates intelligent infrastructure from a human factors perspective, this deliverable is specifically reported to highlight the most relevant human factors issues that might challenge the effective implementation of intelligent infrastructure systems. The human factors issues identified through the interview studies from rail experts involved with the project were later confirmed and reviewed within the field studies and provided a list of most important issues that designers and developers should be aware of. It should be pointed out that, in order to carry out a rational programme of empirical work, the work function central to producing this advice was control room work, rather than, say, track workers or systems analysts.

- The third contribution was an understanding of the activities carried out, artefacts used and coping strategies prevalent during railway alarm-handling and fault-finding

Field studies conducted in electrical control and maintenance control led to a detailed understanding of the activities involved in problem solving as well as the artefacts used by operators. Moreover, studying these work domains in their real setting enabled the researcher to understand what comprises a challenging situation (i.e. information deficiency) and has guided the identification of the strategies that operators use to cope with information shortcomings.

- The fourth contribution has been guidance for the effective implementation of railway intelligent infrastructure

All the studies reported in this PhD have led to an understanding of how designers and developers can effectively implement intelligent infrastructure systems. Chapter 5 identified the human factors issues, chapter 6 and 7 developed an understanding of alarm handling and fault finding which are potential functions of the future intelligent infrastructure systems and chapter 8 investigated the hypothesis regarding the optimal levels of information for different roles within the intelligent infrastructure system. The outcomes from this work should not be mistaken for detailed design guidelines; the strategies identified should be studied further for developing detailed guidelines. This PhD does however provide high level guidance as to what strategies should be investigated and how knowing about them prior to the design process starting can aid developers in building more effective and less confusing systems. The guidance which is collated from the studies conducted in the PhD is contained at the end of this chapter.

- A fifth contribution has been the demonstration of the value of applying a combination of human factors and cognitive engineering study methods in investigating cognitive processes within socio-technical systems.

A combination of qualitative and quantitative methods was adopted to address the objectives of this study. Selecting and applying these methods faced the investigator with different challenges, including the fact that there were no existing intelligent infrastructure systems in Network Rail, and collecting data from real-life control rooms while these are in operation which can impose extra challenges in data collection. The paradigms and approaches in this PhD study were used so as to best handle these limitations and can be used in studying similar complex socio-technical environments, discussed in the following section.

## *9.2. Objective one: Identify the human factors of most relevance to railway intelligent infrastructure and, in so doing, develop a framework that focuses on data processing requirements to support informed decision making.*

Indentifying and investigating human factors issues in large and complex control settings is not new, but as noted by Noy (1997), they have often been studied in isolation; a few of the many examples from rail include workload studies (Pickup, Wilson, & Clarke, 2003), situation awareness (Golightly et al., 2010), and automation (Balfe, 2010). Moreover, Wilson and Norris (2005) emphasise the need to consider human factor issues in the railway since this domain is, and will be, facing tremendous technical and organisational changes. For the foreseeable future it will consist of various legacy systems as well as advanced technologies. Furthermore, in addition to operators' roles and their interactions with the systems, there are always concerns about passenger safety and comfort, both of which need to be taken into account. Therefore, a thorough understanding of human factor issues for future intelligent infrastructure was considered necessary.

The human factor issues identified in the interview study (Chapter 5) are summarised in Table 9-1 below.

**TABLE 9-1 : HUMAN FACTORS ISSUES IDENTIFIED FROM THE INTERVIEW STUDY**

| Human factor issues | % | Relevance to the intelligent infrastructure |
|---|---|---|
| **Planning** | 15 | To plan the optimal course of action to keep the balance between safety and operation of the service |
| **Safety and human reliability** | 14 | To understand potential sources of error and to mitigate the risks associated with them. |
| **Organisational culture** | 13 | To involve various roles and different attitudes towards technical advancements, role changes, business change, etc. with the project. |
| **Decision making** | 11 | To understand the process involved with current and future railway decision making, ultimately to inform optimal decision aids. |
| **Situation awareness** | 10 | To determine knowledge in the head and knowledge in the world that is or |

| | | |
|---|---|---|
| | | will be required by the railway operators. |
| **Workload** | 9 | To determine the effect of the introduction of the new technology on the current workload. |
| **User engagement** | 8 | To engage end users with the project and facilitate a participatory design. |
| **Monitoring** | 7 | To identify issues affecting the performance of monitoring and how this will be changed. |
| **Automation** | 5 | To determine an appropriate level of automation that is practical to the nature of the roles. |
| **System reliability** | 5 | To design and develop reliable systems and issues associated with users' reliance on and trust in the systems. |
| **Human-Machine interaction** | 3 | To identify and address usability issues in order to design effective systems. |

From the twenty interviewees, only two were ergonomists and therefore intimately aware of the potential human factor issues. However, other participants referred, both directly and indirectly, to various issues connected with people and social systems. The researcher's interpretations of any indirect references to human factors were confirmed through informal discussions with the ergonomists.

As mentioned in chapter 5, the interview transcriptions were coded three times: first to address general issues and produce a definition of the concept of intelligent infrastructure, second to identify the data processing associated with various activities within the intelligent infrastructure systems, and finally, to identify the human relevant factors. Merging of these coding groups led to a categorisation of the human factors within the data processing framework and linking them to intelligent infrastructure activities. The human factors are presented in the frequency order in which interviewees mentioned them within the different levels of the data processing framework. This understanding was also incorporated in the guidance (Objective three).Therefore, a designer or a developer would know which of these issues should be considered and which phases of the project would benefit from an assessment of them. For example, issues associated with system reliability should be considered in the early stages of the design of intelligent infrastructure systems.

The strategies applied by operators in coping with information deficiencies during problem solving (filtering, categorising, similarity matching and extrapolation) can also inform the most relevant human factors that should be considered. Filtering and categorising, while a fault is being noticed and accepted, refer mainly to the issues associated with the presentation of information in a reliable and perceptual form. Therefore, they are directly related to system reliability and monitoring. Furthermore, when operators use similarity matching to analyse and clear, it implies that historical information and obtaining a wider picture of the problem should be provided. This is directly related to operators' expertise. Finally, when operators extrapolate the existing information to facilitate analysis and clearance of faults, they use their expertise. In order to extrapolate the correct information they should have a clear understanding of the organisation of the work.

Table 9-1 above presents the human factor issues relevant to intelligent infrastructure identified from the interview studies (Chapter 5). Moreover, the field studies conducted in this PhD have led to the identification of the issues of most relevance by exploring potential intelligent infrastructure functions (alarm handling and fault finding). Table 9-2 below lists these human factors and reports their relevance to the intelligent infrastructure.

**TABLE 9-2: HUMAN FACTORS ISSUES OF MOST RELEVANCE TO INTELLIGENT INFRASTRUCTURE**

| Human factors | Relevance to the intelligent infrastructure |
|---|---|
| **System reliability** | To provide reliable and consistent information to the operators. |
| **Expertise** | 'what is missing from the algorithms is understanding how operators deal with existing problems, (NR intelligent infrastructure project manager) |
| **Monitoring** | There are many information displays on any of the control rooms workstations studied in this PhD. It is important to support operators in monitoring these screens so that they don't miss important features. |
| **Planning** | To plan the optimum course of action by allocating a knowledgeable maintenance team and sending them on track at the time that will cause least delay. |
| **Work organsiation** | Various organisations are involved with intelligent infrastructure; either they use it (e.g. TOC), provide it (e.g. Westinghouse), monitor it (e.g. ANSALDO) or apply it (e.g. NR). It is important to understand the relationship between these organisations and how they can or should inform each other. |

Identification of human factors of Intelligent infrastructure systems have been fed by understanding the scope and concept of railway intelligent infrastructure and to model the data processing associated with various activities within intelligent infrastructure. Intelligent infrastructure systems have been used and explained in conceptual terms, but scientists or practitioners have mainly modelled the relationships between various technical elements. For example the elements in the intelligent information infrastructure modelled by Lau et al., (2002) consist of a common internet interface and other layers of a computer network. Although Lau et al., (2002) noted the details of the technical layout required for recording and transferring information within the database, they have not discussed what information should be collected and presented to achieve this expert system.

Another example is shown in Figure 9-1 below. This is a framework of intelligent infrastructure for a sustainable potable water system developed by Adriaens et al., (2003). It includes various information sources such as remote sensing or coastal urban centres as well as various forms of data coding. There are two boxes allocated to modelling water quality and to strategic decision making. It seems as if these are "magic boxes" and it is supposed that they would automatically generate intelligent information that can be fed into various components of the system.

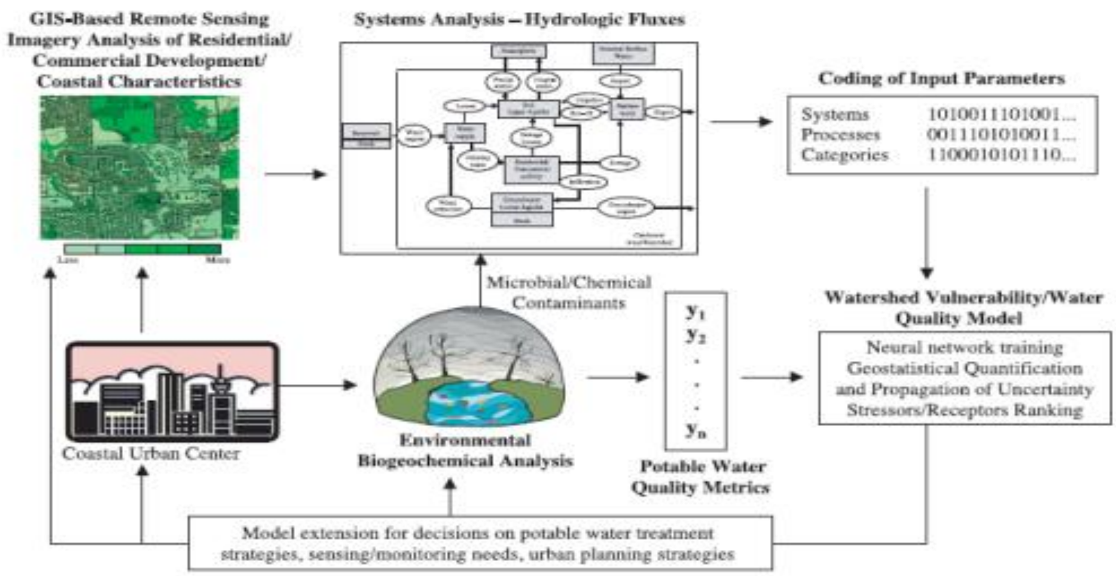


**FIGURE 9-1: CONCEPTUAL FRAMEWORK FOR AN INTERACTIVE DECISION SUPPORT SYSTEM TAKEN FROM ADRIAENS ET AL., 2003, PP. 122**

Network Rail's high level model of remote condition monitoring is shown in Figure 9-2 below (a modified version of this model was developed in NR in 2010). Like the two previous examples, this is also a very simple high level work flow; it shows the data sources, transformation links, a strategic intelligent infrastructure solution (i.e., the magic box!), and end user interfaces.

A standard that is used to direct phases of developing remote condition monitoring systems is ISO 13374 (Network Rail, 2010). This model is shown on the right hand side of Figure 9-3. ISO 13374 consists of six stages but it does not provide information on how to conduct those stages. The data processing framework can inform the activities required to achieve the various stages of ISO 13374.

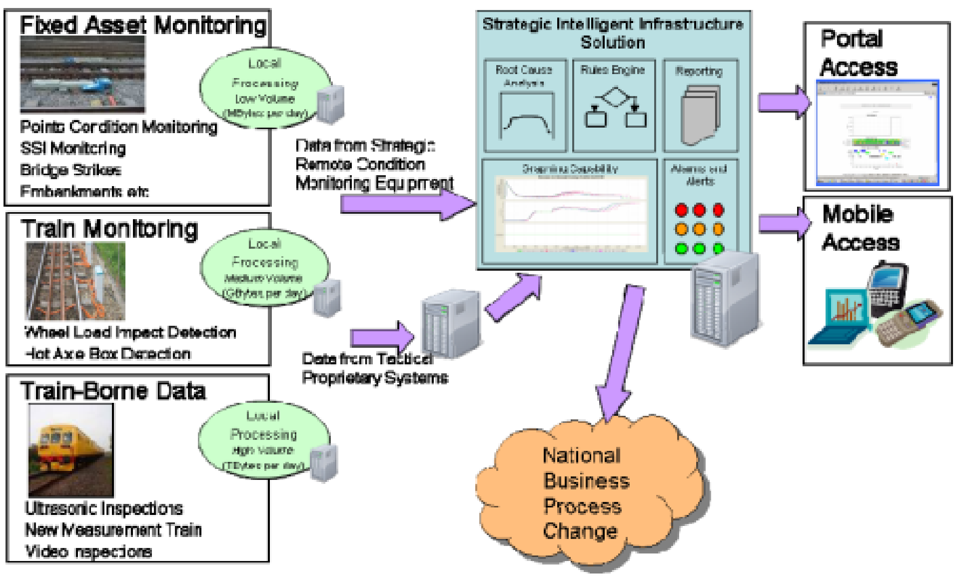



**FIGURE 9-2: HIGH LEVEL MODEL OF THE RCM INTERNAL NETWORK RAIL COMMUNICATION**

The question explored within the data processing framework of this PhD attempts to inform these 'magic boxes'. Exploring the functions of potential intelligent systems currently conducted by operators and studying their strategies for a safe and efficient decision in their complex systems will allow identification of the features these “magic boxes” should have.

In this PhD, a data processing framework was developed to move beyond a purely technical description of intelligent infrastructure to one that addressed the role of cognition (automated or human), and to describe how data generated by the system will be turned into intelligence to meet overall system objectives.

Therefore, the data processing framework looks at the transition of data during a problem solving activity that is going to feature in the future intelligent infrastructure. By looking at the manipulation of data the different roles involved with the tasks can be clarified and the data relevant to these roles can be identified. These aspects are further investigated in this PhD.

The data processing framework is the product of a series of studies. It was first drafted in a workshop held by NR and then explored in detail through the interview study with 20 key organisation decision makers reported in chapter 5. The sequences of  data processing and the content of the framework, as well the relevant human factor issues, were then reviewed and refined through the two field studies reported in chapters 6 and 7.

In addition to the various studies to identify the content and sequence of the data processing framework, a controlled knowledge elicitation exercise was performed in the ECR to support some verification of the framework. ECR operators were asked to carry out an alarm handling episode and to write the information they wanted to be made available to them on a card. They were then asked to sort the cards in order of priority and to group the cards according to the various stages of the data processing framework.  In this way, various forms of information within different levels of the data processing framework were structured. Figure 9-3 below shows the final iteration of the data processing framework, as well the related and relevant human factors.

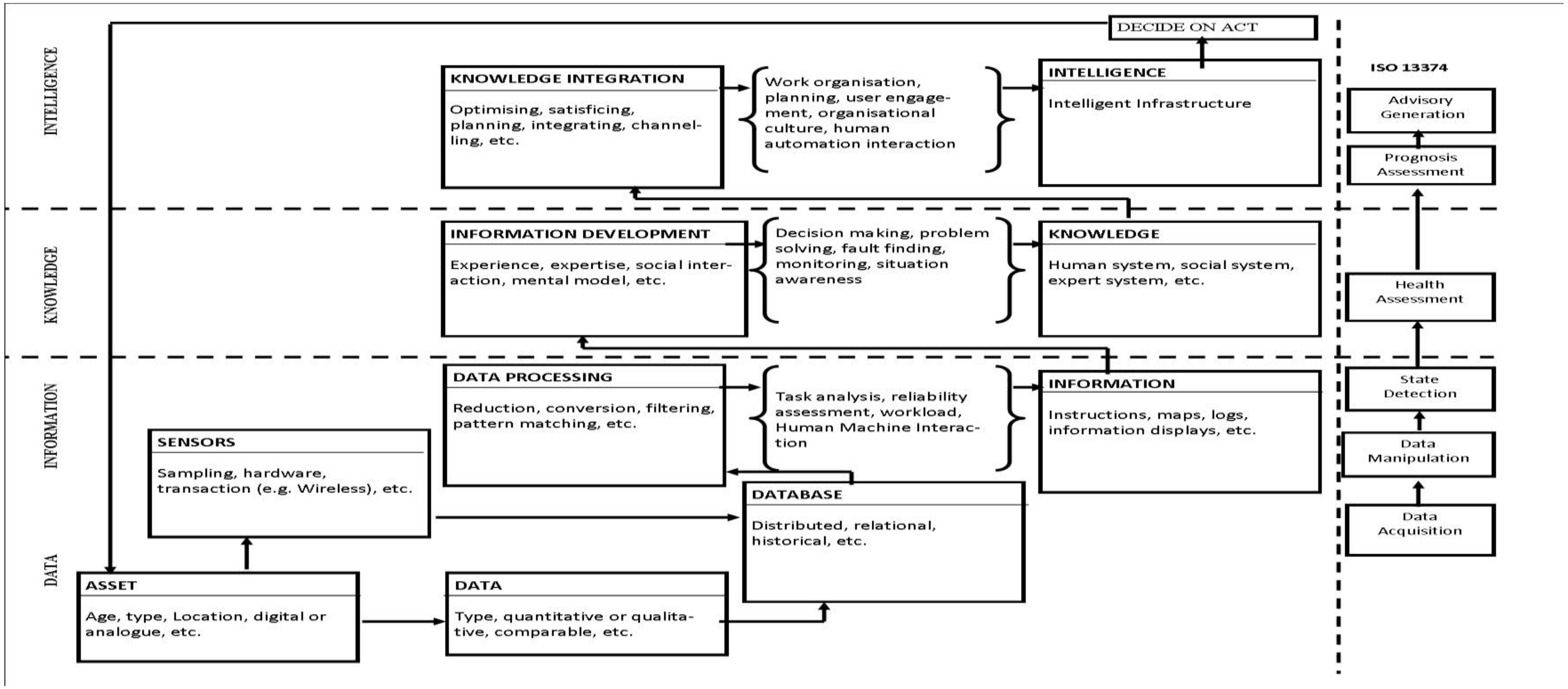



**FIGURE 9-3: DATA PROCESSING FRAMEWORK OF RAILWAY INTELLIGENT INFRASTRUCTURE SYSTEM**

An intelligent infrastructure system can be thought of as, in effect, a knowledge sharing centre in which information is collected in great quantities, processed and presented to operators to support their decision making. It is not intended to replace current systems and, therefore, users' current responsibilities and priorities will remain the same. A critical question remains as to what level of knowledge and information is required for operators to meet their responsibilities in the best way possible and what range of information level is advisory (i.e., not too much or too little).

The field studies conducted in the ECR and MCCs led to an understanding of the activities performed by operators when handling alarms and analysing faults as: receiving notifications, acceptance, diagnosis, and clearance. Revisiting the interviewees' comments showed similarities between the activities of various roles in the future intelligent infrastructure and the activities identified within the ECR and MCCs. For example, track workers and control room operators notice the failure; the control room operator investigates the fault's authenticity and accepts the fault if it is true, diagnoses potential causes for the fault and clears it. The strategic analyst then collates the historical information regarding that particular fault and derives future recommendations to avoid the fault. Therefore, it was made possible to hypothesise that different roles would benefit from different types and amounts of information (i.e., levels of information) as they are responsible for different activities (Section 8.3.3). These hypotheses were investigated in the experimental study reported in chapter 8.

The data processing framework developed and explored in this PhD attempts to inform the "magic boxes" of the other frameworks. It is indeed a starting point for human factors identification to manage the information development and presentation required for successful implementation of such intertwined knowledge sharing centres.

## *9.3. Objective two: Establish an understanding of operators' strategies for human supervisory control tasks in alarm handling and fault finding.*

The aim of the second objective of this PhD was to gain an understanding of operators' strategies while conducting problem solving tasks of relevance to the future intelligent infrastructure.

Note that the strategies explored in this PhD study refer to the tactics adopted by operators while dealing with information deficiencies (i.e. multiple sources of information) that amount to insufficient or irrelevant information. Rasmussen and Lind (1982) specified that the route to in-depth understanding of control settings is through investigation of operators' activities, rather than the system requirements. Therefore, in this PhD field studies were conducted to explore operators' activities in the control rooms.

In order to identify the constraints when handling alarms and analysing faults, real operators commented on the challenges that they face while attending to an alarm or a fault (Chapter 6 and Chapter 7).

A wide range of data collection techniques was used to ensure that an understanding of operators' activities and the associated cognitive processing was reached. These field studies are similar in approach to process tracing, which aims to identify how participants use the cues available to handle a situation within a dynamic and evolving situation (Woods, 1992). Methods typically used to facilitate such understanding include behavioural records, verbal reports, eye movements, observation, concurrent or retrospective probes, interviews, etc. (Patrick, James, & Ahmed, 2006). A similar range of methods of data collection was used in the present PhD study.

Within the ECR, video recordings of alarm handling episodes enabled timing of the activities, collecting information about the duration and sequence of interactions with different artefacts. Furthermore, a time stamped observational checklist was designed to structure the data in terms of the use of the artefacts and whether operators considered these alarms to be of 'high information' or 'low information'. Finally, operators' verbal protocols provided the basis for an understanding of their thinking processes and an explanation of their actions. These extensive data collection were led to Cognitive Work Analysis (CWA).

CWA explores the work setting by understanding the domain, its functions and available artefacts (Abstraction Hierarchy). The activities that are required to facilitate domain functions (Contextual Activity Matrix) and their sequence are elaborated (Cognitive transformation analysis) and it leads to understanding the strategies adopted by operator to deal with the problems raised within their context (Strategy analysis).

It was not possible to conduct a video recording in the MCCs as the technicians did not agree to be recorded. Moreover, maintenance technicians do not respond to faults as soon as they are generated. The faults are recorded in a fault log and the technicians attend to them in their own time. Therefore, a semi-structured interview was designed to capture operators' activities, cues, and strategies when analysing a fault. The probes used in this interview were similar to the probes used within a CDM.

The CDM interview technique facilitated an understanding of activities and their sequence. The cues used by operators and the reasons for seeking out those cues were discussed. The reasoning behind the selection of cues guided the strategies adopted in the control rooms. The cues used by operators are rooted in the characteristics of their context and the information available to them.

Findings on the alarm and fault initiated activities show some correspondence with the stages of alarm initiated activities identified by Stanton (2006): observe, accept, analyse, investigate, correct, monitor, and reset. The difference between the work here and Stanton's is that, although his findings develop an understanding of the activities associated with alarm handling, his model is mainly focused on physical actions performed on one system (SCADA). The four activities identified in the present study - notification, acceptance, diagnosis, and clearance - refer mainly to domain functions and do not depend on specific artefacts (Note that the artefacts within ECR and MCC as well as the three MCCs varied).

Therefore, it is reasonable to assume that the activities associated with problem solving identified in this PhD can correspond to those in railway intelligent infrastructure, in which the artefacts are yet to be specified.

Operators in both domains, ECR and MCC, confirmed that information deficiencies, i.e., being presented with redundant information or not having enough information, comprise the most important challenges to their duties. Railway control workstations consist of various forms and types of information displays, there are cases where two or more displays refer to a particular alarm, with the result that there may be too many channels of information. In this study the terms 'high information' and 'low information' are used.

Throughout the field study in the ECR, alarms with 'high information' took twice as long to handle in comparison to alarms with 'low information'. This confirms participants' concern and suggests a major source of difficulty as information deficiencies and highlights the risks of presenting too much information in future intelligent infrastructure systems, just because the sensor systems can generate it. This finding concurs with that of Omodei et al., (2005), where alarm handling performance worsened as the operators felt obligated to attend to every single piece of information simply because it was available.

In addition to the lessons learned for human factors of future intelligent infrastructure systems, the two domains addressed in this study- electrical control rooms and maintenance control centres- have not previously been the focus of much rail human factors study, compared to say signalling or rail traffic control. Therefore, the findings from this thesis can inform the industry with regard to these two domains. Indeed, the findings from this study so far have fed into the flagship GB railway Thameslink project as well as the future railway Operation Strategy.

The Thameslink project used the ECR alarm handling findings to inform the design of the ECR system of the future with the ultimate goal of combining AC and DC control rooms. Similarly, the detailed understanding gained from the ECR alarm handling was used to facilitate the standardisation of Electrical Control Operators in different control rooms, as part of the railway Operation Strategy for future network control.

## 9.4. *Objective three: Produce Human Factors guidance for the future development and implementation of intelligent infrastructure systems in the railway to match and complement human capabilities and needs.*

The third objective of this PhD was to collate the findings from all of the studies and inform the industry about effective implementation and development of railway intelligent infrastructure from a human factors perspective. The studies reported in the previous chapters led to specific guidance regarding the roles, activities, strategies and human factor issues associated with a potential future intelligent infrastructure system (Table 6-6 and Table 7-4). The guidance for an effective approach to the design of intelligent infrastructure to best meet human and social needs is, not surprisingly, compatible with traditional ergonomics design guidance (Network Rail, 2004) and is summarised in Table 9-3 below. Note that the intelligent infrastructure system in this table refers the overall system rather than the interface to be used, for example, by the control room operator.

**TABLE 9-3: HIGH LEVEL CONSIDERATIONS IN DEVELOPING AND IMPLEMENTING INTELLIGENT INFRASTRUCTURE SYSTEMS**

| Guidance | Relevance to rail Intelligent Infrastructure |
|---|---|
| **Clearly specify the scope, priorities and stakeholders of the project.** | Having a clear view of the values of the project will lead to an accurate understanding of the requirements and priorities of the system. Currently the main value residing in the intelligent infrastructure project is to reduce the delays and improve safety. Furthermore, identifying the stakeholders of the project (people who are involved or affected in any form by the project) can determine various phases of work that needs to be considered. |
| **Identify the stages that are necessary to facilitate successful implementation of each of the phases of the project** | Currently, NR is using ISO 13374 to guide the development phases of intelligent infrastructure project. It seems feasible to use the data processing framework developed and described in this thesis to guide successful implementation of each of these phases. This can be achieved by including human factor considerations presented in the data processing framework. |
| **Identify the roles of potential users early on in the project** | Since 2006, when the intelligent infrastructure project was launched, there has apparently been no clear view of the potential users and their roles within the project. The interview study, as well as the case studies, conducted in this PhD confirmed that an understanding of the various future user roles (track worker, control room operator and strategic analyst) is essential in terms of what information and functions should be embedded within the interface. Therefore it is essential to develop this understanding early on in the project. |
| **Engage the users early on the project** | Engage users, not just to achieve a participatory design but to encourage a sense of ownership. Whilst this is important for all human factors contributions to systems design, it is particularly important when the new system will change ways of working for whole networks of operators, including changes in the balance of responsibilities between them. |

| | |
|---|---|
| **Reduce the numbers of alarms and faults alerted within the control centres** | In the MCC study, a huge number of alarms were logged, many of which were false and nuisance alarms. Occasionally they were misleading and caused the operator to miss the real alarm. Since the events to be logged in future intelligent infrastructure systems are likely to be very numerous, some considerable effort in intelligent screening and sorting will be required (although the history of alarm mismanagement from human factors literature shows that this is easier said than done). This will mean that the priorities and stregies of user groups must be thoroughly understood. |
| **Avoid presenting too much information to the operators.** | In the alarm handling study in the ECR, alarms categorised as 'high information' took twice as long to be handled compared to those categorised as 'low information'. It is important to identify and design for a necessary and sufficient level of information to the operators. Moreover, transferring a huge amount of data from sensors and loggers to information displays in control rooms can be very costly, and any reduction in this will help project cost effectiveness. |
| **Provide a reminder facility on the interface.** | In both case studies (ECR alarm handling and MCC fault finding) operators used paper based reminders to make sure they will attend to the important faults. It is important to assess the optimal format of the reminder facility (i.e., on paper or on the interface), and given systems change generally in this (eg the change from paper strips to computer interfaces in air traffic control), it is likely that insightful work analysis and interface design will be needed to develop computer based reminders. |
| **Ensure that support facilities are available.** | One of the issues identified by the maintenance technicians in the MCCs was that the legacy systems in control rooms are not sufficiently maintained and when things go wrong there is not enough support available. |

From the studies performed throughout this PhD, specific design guidance for HMI within intelligent infrastructure was made available, which is summarised in Table 9-4 below. This guidance assumes that alarm handling and fault finding are two core functions of intelligent infrastructure (Chapter 5) and therefore refer to the field studies (Chapter 6 and chapter 7) as well as the experimental study (Chapter 8).

**TABLE 9-4: DESIGN GUIDANCE FOR SUPPORTING THE THREE ROLES WITHIN INTELLIGENT INFRASTRUCTURE (HMI RECOMMENDATIONS)**

| Findings | Enablers/barriers | Design guidance |
|---|---|---|
| Three roles involved with future intelligent infrastructure are track worker, control room operator and strategic analyst. | Unlike strategic analyst, track worker and control room operator are existing roles and have a number of responsibilities within their job specification which should be considered when assigning them to intelligent infrastructure related activities. | Clear job specification for the roles is required. |
| Different roles would benefit from various levels of understanding, depending on their values and priorities. | Track workers' priority is to access the track in order to conduct its maintenance, whereas control room operators' priority is to access the track for running the train. | In designing job specification ensure that one role does not have conflicting values and priorities. |
| **Guidance for the track worker** | | |
| The sources of information should be reliable | Track workers have no or limited access to interfaces on site (e.g. handheld devices) and therefore they cannot investigate the accuracy of the information | System reliability should be ensured |

| | | |
|---|---|---|
| | available to them. | |
| Track workers need binary indication of the state of the asset | In order to notice and accept the fault on track, a track worker is only interested to know whether the asset is in working condition or has failed since they don't have the authority to plan the maintenance and have to feedback the information to the control room operator. | Provide information regarding the state of the asset |
| The information can be accompanied with local knowledge (e.g. recent engineering work in the location) | Although knowing detailed information about the type of fault or historical information for a particular fault is not useful, situational information can help track workers to assess the authenticity of fault with more confidence | Update track workers with the situational information |
| Track workers do not need information associated with potential future faults | Track workers are sent out on track to deal with operational failure at hand; some information is associated with what is going to happen next. | Provide information only related to comprehending the task at hand. |

| **Guidance for the Control Room Operator Role** | | |
|---|---|---|
| The information required for noticing and accepting alarms: 1-type of alarm 2-general temporal and spatial information 3- the geographical characteristics | Type of alarm and temporal aspect is usually available but knowing the characteristics of the location is very much dependent on the operators' expertise. However, ignoring a true alarm only based on the fact that the location has high false alarm rate is dangerous. | Provide geographical characteristics (e.g. existing engineering work, number of the failed assets in the last month, etc.). |
| Telephone is the most used artefact while attending 'expected' alarms | In cases of emergency, use of the telephone can be distracting. Furthermore other operators in the vicinity cannot share the information as they are not privy to the other end of the phone call. | The other operators might find it useful to share phone conversations through a party line or open call. |
| Paper is the most used artefact while attending 'unexpected' alarms | Possibly due to the limitations of the computer display which cannot provide alarm indications on one page. Hence operators are required to write indication codes from, for example, an event log and switch back to the display area to complete the alarm assessment on other display pages. | Key information (e.g. codes, history, etc) to be presented on the display on request (maybe with a mouse rollover) |

| | | |
|---|---|---|
| If the information about the alarm is presented through more than two sources (phone, display, etc) it takes nearly twice as long to handle compared to the alarms where information is presented through no more than two sources. | Redundancy in information load can cause confusion. Operators need to consider these features, if they are being informed through different types of media. | Minimise information redundancy. An integrated information display might assist reduction of information redundancy. |
| Operators do attend to multiple sources of information for the fear of missing some important information | Almost all of the participants in the experimental study attended to the optional piece of information. This is very important; usually one of the design strategies is to allow the operators to customise the information they want. This finding suggests that operators are not very good at ignoring irrelevant information for the fear of losing something important. | The interface should manage the information that is being presented to the operator. |
| Operators conduct similar core activities (notification, acceptance, analysis and clearance) disregarding the artefacts available to them- the only difference is that some processes are only supported. | The comparison between the three MCCs showed that the activities conducted while dealing with faults remain the same. However, with more advanced RCM equipment, analysis and clearance are supported. | Identify the level of support that is to be provided by the intelligent infrastructure interface in different control rooms. |

| **Guidance for the strategic analyst role** | | |
|---|---|---|
| Strategic analysts are not interested in knowing about the operational state of the asset or the cues that will facilitate diagnosis of faults. They only want trends in the history of the behavior of the assets so that they can evaluate its performance | The findings in the interview study suggested that, since the strategic analysts' role is not of immediate relevance to the operational task, they should not be alarmed by asset failures. | Statistical analysis of the historical trends shown in graphs can be used to give operators an overview of the asset's behavior over time. |
| Strategic analyst need to have a clear understanding of the organisation of work in order to be able to advise on efficient maintenance regimes and plan future recommendations. | Different organisations are involved in the maintenance of an asset. This includes the company who developed the asset (e.g. Westinghouse), the TOC whose train is running on the asset and the railway safety board who advise on the safety requirements and standards. | Clarify the benefits and the extent of involvement for different organisations involved with the project (if any) and hence define the extent of advice generation by the strategic analyst (so that it is feasible). |

## *9.5. Paradigms in analysing system control work: a review*

In this study, several paradigms and methodological approaches have been used, and the reasons for selecting these paradigms and their relevance to the research questions of this PhD were described in Section 3.4. The paradigms include a) the information processing paradigm, used to develop an understanding of the sequence of activities and of information processing during alarm handling and fault finding, b) the supervisory control paradigm to identify the resource and function allocations associated with the different roles within the potential intelligent infrastructure system and c) the cognitive systems engineering paradigm to understand the nature of the intelligent infrastructure control context at a systems level, and to use this to understand relevant factors such as coping strategies when operators are dealing with potential challenges (such as information deficiencies). This section reviews these paradigms in light of the outputs of this PhD study and comments on their use.

The empirical work in the current research project started with a holistic view of intelligent infrastructure, facilitated by an interview study (Chapter 5), and followed by an exploration of specific problem solving tasks (i.e. alarm handling and fault finding – chapters 6 and 7) and identification of the sequence of activities within particular work contexts. It was found that particular cognitive demands existed in the context of these control settings and that these resulted from situations of information deficiency. This has led to some hypotheses about the level of information provided which were investigated further through a laboratory study.

The underlying approach of this PhD study was to understand cognition in context, hence the variations in cognitive methods and detailed field studies adopted in this study. At first it had been assumed that CSE would be an appropriate paradigm for the whole of the research work. The core requirement of the CSE paradigm is to investigate and explore the collaborations between various users and technologies in their actual dynamic forms (Woods et al., 1996). In the context of this PhD study, this would have meant exploring both the human operators' and technological interface's actions and reactions and investigating their coupling throughout the complex situation. This was not possible, however, due to limitations in the resources available in this PhD.

In other words, in order to facilitate a full use of the CSE paradigm, support for problem solving, the cognitive processing of the human operator, cognition of the machine (e.g. decision support systems) and their co-agency should all be explored. The main problem for developing such understanding in this PhD was the fact that there was no existing intelligent infrastructure system and therefore speculations about its functionalities could only be made through interviews with potential users.

This was the same approach adopted by Bisantz et al., (2003) in guiding the development of new US navy decision support systems.

Upon identifying potential functions of the future intelligent infrastructure, exploring and investigating the human cognition and operators' behaviour during problem solving were facilitated and structured through cognitive methods such as CWA and CDM. However, within these studies, an information processing paradigm was followed to develop an understanding of the sequence of activities and processing modes during problem solving. Studying in the field (or "in the wild") and observing operators in action, gave an indication of the challenges (cognitive demands) as well as the strategies they adopt to cope with these challenges. Work with key decision makers within Network Rail identified that problem solving within the future intelligent infrastructure will be distributed amongst various roles and across different control rooms. Hence, the supervisory control paradigm was used to facilitate considering these roles and their relevant cognitive processing. Beyond that, supervisory control guided the identification of the themes (i.e. resource and function allocation, strategies) that have to be addressed with future intelligent infrastructure. A simulation of a railway problem solving task was set up in order to examine problem solving performance based on the knowledge required by the operator (according to their roles) and the knowledge provided by the system. The findings suggest variance in the performance depending on the level of information provided and the tasks undertaken. In a way the final experimental study, although very simple, seeks to explore cognitive coupling in railway problem solving. This is similar to the experimental study conducted by Dalal and Kasper (1994).

In summary while it was necessary to draw on different aspects of the three different paradigms (information processing, supervisory control and CSE), in order to address the questions identified at the outset of this thesis. Some of these paradigms do have acknowledged research limitations, which are discussed in the next section.

## *9.6. Limitations of the research*

Intelligent infrastructure comprises a very large, somewhat ill-defined and complex system or even system of systems. In the planning within NR, the salient project is massive, both in terms of the quantity and variety of data that have to be collected as well as the wide range of roles and functions that will potentially be affected by it. Likewise the variety of human and social issues potentially involved is very large and inter-connected. Furthermore, since this is an on-going project within the company, it changed constantly throughout the life of this research, in terms of the strategies and priorities of the project as well as the people involved with it. For example, the project manager interviewed as part of the first study (Chapter 5) was no longer responsible for the project at the conclusion of the research. This is not only a limitation for this PhD, but it confirms a challenge to the development of large scale projects, such as intelligent infrastructure, in organisations such as Network Rail.

During the field study in the ECR, only 22 alarm episodes were generated during the course of 18 hours of the study. This number appears to be low in order to achieve the objectives of this study. It is worth taking into consideration the fact that the researcher was involved in a number of other projects related to ECR; through her additional knowledge of the domain gained from these other duties, this number of alarms and the quality of data collected (via video recording, interviews, etc.) has provided sufficient information to achieve the objectives of this study and to make the interpretations reported. Also notable is the fact that the findings from the ECR were confirmed in the study conducted in the maintenance control centres.

The number of participants (31 students) recruited for the experimental study (Chapter 8) is relatively small from a statistical point of view. The power analysis conducted prior to the study recommended the inclusion of around 45 participants to avoid any risk of missing a significant effect. In fact, this study was not established to seek a significant effect but aimed to confirm the trend in the performance of the tasks trialled as hypothesised. Therefore, the sample size is regarded as adequate for purpose.

# 10. Conclusion and recommendations for future research

## 10.1 Conclusions

The research undertaken and described in this thesis has developed a human factors understanding of likely human behaviour and cognition, as well as the knowledge and information requirements, for future users of a potential railway intelligent infrastructure system. Several paradigms and methodological approaches were used throughout this PhD, suitable for different research questions and in light of the resources available to the researcher,

The researcher was fortunate to be welcomed into a wide range of railway control settings to explore operators' cognitive processing in action (alarm handling and fault finding). Moreover, the researcher was a member of the Network Rail (NR) Ergonomics Team for three years and hence had developed a good overall understanding of the organisational culture, which enabled her to place the scientific and theoretical knowledge acquired in a realistic context. In this sense she became a participative observer of the company, the development of human factors solutions generally and the progress of the intelligent infrastructure systems development (a very slow process!).

This project was the first in NR to study the human factors of future intelligent infrastructure and one of the few in all domains that aims to understand and facilitate use of the requirements for an intelligent infrastructure system which does not yet exist. This provided opportunities to contribute to a novel idea and, at the same time, offer design guidance at both basic and more advanced levels, in comparison to the guidance developed for existing systems. The PhD took a systematic approach towards understanding the future likely work systems and workplaces so that the researcher could predict the knowledge and information requirements of a system not yet in existence.

Intelligent infrastructure has been defined in this PhD study as: an integration of existing remote condition monitoring technologies that are distributed locally and centrally and used by different operators in identifying and handling faults in the infrastructure assets in order to improve safety and efficiency of the rail service.

This definition highlights features of the work that will influence the successful implementation of intelligent infrastructure. These features are: identification of an effective method of integrating various (possibly incompatible) sources of data, retention of accuracy and reliability throughout any data cleaning and reduction techniques, identification of potential user groups, exploration of the information and knowledge requirements for each group of users and identification of the values and priorities of the overall system. The first two features relate to the technical challenges of the intelligent infrastructure system and those remaining are practical human factor issues that designers and developers need to address for successful implementation.

The methodological framework used in this study was continually assessed and evolved throughout the research. Different cognitive methods were used to facilitate the study: CWA and knowledge elicitation in the alarm handling study (chapter 6), and CDM and Decision Ladders in the fault finding study (chapter 7). Using a combination of methods to capture and structure the field-based qualitative data provided the means to understand the practicalities and limitations of the use of these methods and could be adopted as a good practice guide for future research. For instance, the outcome of understanding the practicalities and limitations associated with CWA were published in a journal of rail and rapid transit systems to inform railway practitioners (Dadashi et al, 2012 in press).

In today’s energy-aware world, the railway is appreciated more than any other mode of transportation and there is an urgent and critical need to improve the quality of the services provided by the rail industry. Thus, in the years to come, we will be witnessing more advanced technologies to address these needs. The methodological approach adopted for the purpose of this research can be used to inform the design and scoping of these future technologies.

## 10.1 Recommendations for future research

This research has been among the first attempts to study railway control settings from a cognitive systems engineering point of view. In order to implement and develop a successful intelligent infrastructure system, many aspects need to be addressed beyond those feasible within the scope of this research. Some of the proposed future research areas are listed here:

1- Investigate and critically examine the data processing framework in rail (via further verification) and in other intelligent infrastructure domains. This PhD study was focused on the exploration of various aspects of intelligent infrastructure in the rail industry, yet it is believed that the data processing framework has the potential to be generalised to other intelligent infrastructures and knowledge sharing centres. At the time of writing this thesis, system developers providing services to the water industry encountered during presentation of the research at international conferences have shown an interest in applying the data processing framework.

2- The interview study has revealed a number of cognitive functions as part of the activities of the potential intelligent infrastructure system, such as decision making, planning, regulating, problem solving, etc. The focus of the current study was problem solving. One possible future work direction is to apply a similar work analysis approach to discover and explore other cognitive functions as well.

3- The data processing framework recommends an order in which various human factors issues should be investigated at different phases of the project. Although this order is derived from an in-depth and comprehensive interview study, not all of the informants were human factors specialists. Complementary pieces of work with human factors experts could investigate these issues, particularly their order, in more detail. Ultimately the goal would be to develop a human factors practical standard that guides the development and implementation of intelligent infrastructure and knowledge sharing centres.

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# 12. Appendices

## *12.1. Information sheet for the railway intelligent infrastructure interview study*

Network Rail is making the further development of an intelligent infrastructure a key part of its future plans. Within that, remote condition monitoring is likely to play an important role. Intelligent Infrastructure will be introduced to move rail work processes from a 'find and fix' mentality to one of 'predict and prevent' and potentially to 'design and prevent' (Network Rail Intelligent Infrastructure Good Practice Guide). The objective of the Intelligent Infrastructure is essentially to integrate data obtained from different types of assets (e.g. software, hardware, points, tracks, trains, etc) and convert them to useful information and especially knowledge that can be used as a decision aid.

It is clear that there are a number of critical human factors implications of intelligent infrastructure and remote condition monitoring. What will the new functions and roles be, how will the new knowledge and decision making routines effect distributed teamwork and communications? What knowledge will people need to do their jobs? How should the data collected from the infrastructure be managed into knowledge and how should this be displayed for different functional groups on information devices and interfaces (including mobile computing)? Intelligent Infrastructure presents integrated information on a display to assist operator and hence it is essential to understand not only the information and functional requirements of an Intelligent Infrastructure information display, but also how this information should be presented to the operators.

The latest in a series of PhD projects managed by the Network Rail Ergonomics Team and University of Nottingham is examining the human factors of remote condition monitoring and of Intelligent Infrastructure generally. The very first stage in this research is to conduct an exploratory study of Intelligent Infrastructure and RCM in rail through a series of semi-structured interviews with rail staff who are potential users or those who know of Intelligent Infrastructure information displays. Below is a list of possible questions to feed into these interviews:

1. What do you understand to be the future of Intelligent Infrastructure for Network Rail?

2. What do you think is the purpose of Intelligent Infrastructure?
3. Do you consider RCM as a type of intelligent infrastructure?
4. What does 'remote' in RCM mean?
5. What does 'intelligent' in intelligent infrastructure mean?
6. How will the information required for an intelligent infrastructure be captured?
7. What do you think are the main functions of an intelligent infrastructure information display?
8. Which control rooms need to be in direct contact with intelligent infrastructure systems?
9. What are the challenges for designing an effective intelligent infrastructure system?
10. What are the main roles and responsibilities of operators working with intelligent infrastructure systems?

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### 12.2. An example of the interview study and the one of the coding schemes

| Code | Colour |
|---|---|
| Definition and purpose | |
| Benefit | |
| Current RCM situation | |
| Future plans | |
| Functions | |
| Cognitive functions | |
| Challenge | |
| Roles and responsibilities | |
| System distribution | |
| Human factors issues | |

Interview number 1:

Intelligent infrastructure is an ill defined project although it goes back to few years ago. My role is to lead Intelligent Infrastructure, I am part of the transformation team, and this team has been set up from early 2009 and to help NR achieve significant budget shortfalls due to recent economical changes. So effectively it is to inform a 4 billion gap caused by recent alterations.

The intelligence at this stage is not perceived to consider Human Machine Interface [HMI] related issues, we had not considered human interaction issues yet.

Now what do we mean by intelligent infrastructure?

The definition and the understanding of intelligent infrastructure are not consistent around the company. What I have found is:

Intelligent infrastructure is an infrastructure which in some way uses technology to provide data pertinent to its condition.

At the moment the how we look after infrastructure is completely passive, something breaks on the track, you as a technician get alerted and fix it. We are using ISO 133743 model to present intelligent infrastructure. ISO 133743 is a framework which is a standardised approach and it has six stages:

1- Data acquisition:

This is being done to some extent at the moment. For example we do measure point heating and this data is being collected every second, and the time interval setup on it is chosen due to purely arbitrary perspective. The problem of this rather arbitrary data acquisition is generating inappropriate amount of data, so we need to specify exactly what data we need. For example on a point machine you can measure various things: the time it takes to switch, force, temperature on the rail, hydraulic pressure, etc, but do we really need all of these information, part of the project is to collect the right amount of data at the right interval and also on the right asset.

2- Data Manipulation

If you acquire data you need to be able to manipulate it or that data is pointless.

3- State detection

This is to identify what state the asset is and it gives binary measures, is it working normally or is it working abnormally, currently this is the stage where network rail is. We have remote condition measurement systems places on various assets and we can determine whether the asset is operating in its normal condition or an abnormal condition.

4- Health assessment

This is a diagnostic position where we can diagnose from the data we have and say what is wrong with it. Somewhere in here between these two steps you need to inform people somehow. Today in most cases we just have an alarm and alert approach. Local operators set the limits for the assets in their area and when an abnormality occurs it will generate an alarm which is a window on their normal operating screen and they can click on it to find out what is wrong and they can look back and see plots over time. For example if you look at a point machine in Essex the guy at the control centre based in Liverpool Street is monitoring the resistance of the 650 volts of power supplies to a signalling power supply and normally for some reason the resistance value shows abnormality and there is a huge drop in the resistance which is beyond the alarm limit. So the operator had to send a fault team on track and they have found a rat which decided to feed on main power supply and ended up having a 650 volts lunch which fried him so they removed the rat and that is basically how alarms get responded to. The risk in handling them more intelligently is that we are going to end up with huge amount of data alarms and alerts being raised on different asset categories with different level of urgency and the problem is how we are going to present that data to operators in order that we get the right reaction.

In order to focus the project a number of strategic assets have been selected. The selection was conducted by two criteria: historical and criticality. Historical is due to information regarding previous delay records and what assets are the major contributors. Essentially network rail signs a contract with network operators and guarantee certain network availability to them and if this is not fulfilled then NR is subject to a fine. Critical assets are those if failed which cause major problems (if they do fail that would be a nightmare). Most of them are quite well known and what you normally find is that they get special attention and maintenance operators know that these set of points are really important so these have a higher routine maintenance schedule. A project in Network Rail entitled “Network Criticality” is responsible for this assignment and they have developed a map of critical assets which is assists intelligent infrastructure project team with identification of critical assets.

Also we do have a number of legacy systems which collect and analyse asset data, one of the requirements of the intelligent infrastructure projects is to align these various legacy systems. Today there are around 3000 RCM systems and some of our most problematic maintenance points have many RCM systems so the question would be if it worth it or not. For example in there is loads of point condition monitoring fitted on points in the Anglia region and the an off the shelf system provided for the company called CDS together with other off the shelf systems and we could just say that let's replicate those off the shelf systems but we don't think that is ideal. So one of the big pieces of work is to look at the legacy systems and provide recommendations for it. for example we do have a pilot which is an alignment of various off the shelf systems and essentially what you get in different places are different with different users.

Intelligence is when we are able to use data to prevent equipment failures. So going back to the ISO standard in these six steps the level of intelligence is increasing. The infrastructure has no level of intelligence in it, the first level of intelligence is how much information is required to reach a good decision and then on the sixth stage which is the advisory generation.

At the moment only alarms has a level of intelligence in them. So instead of having data versus time, you have data versus time versus control limits.

There are huge amount of expertise involved with the decision making and fault finding, a lot of people are being surprised by knowing what exactly is that happens to an asset. For example I was surprised to see that there are cases where fluctuations to resistance are normal, there are many contributing factors and this is where human become useful. To be honest we really want to know how an expert does this job, because that can be what it is that contributing to reduction in service.

We have drawn a conceptual benefit model with two axes benefit and time. Time has an important factor in the context of intelligent infrastructure project. A period of understanding is required for each of these steps and we try to link this to the six stages in the ISO and actually in terms of benefit you get x, y and z on each of the three steps and z< x>y and these three stages are diagnostics, prognostics and advisory generation.

I do agree with your model but the time piece is also important.

The way we are looking at our system is that we have a number of loggers that acquire data and it is then connected to an aerial via GPRS which is managed by O2 and transmitted to our central server. Up to this level it might be called as intelligent infrastructure but it is not, it is just an IM. Currently we are planning to present solutions suggested based on the aligned information by Invensys (So what is shown on the screen here is not in the scope of our project, it is mainly Invensys) and that is then connect to our internal network so we can display the output on a terminal anywhere. Part of our work is to describe this business process because at the moment we believe that we provide the wrong information to the wrong people at the wrong time. Actually I think what we do is that we over kill, we give information to everybody.

We have put some thoughts into the amount of data that we are putting on the screens so for example rather than measuring everything and then filter it later we want to be more specific and record the vital signs and then we got less to deal with later. The least we want to assign a person to look at data all day, for me the project can actually fail on the same criteria that it can succeed. So it is important how much information is beneficial to collect.

Distribution of the system is not finale yet, it can be a national RCM centre which you have one screen and one source of data but it is unlikely to have that. Probably the most realistic distribution of the system is the regional one. The distribution of the system relates to the type of work that needs to be done. Two types of actions need to be considered: interim corrective action and permanent corrective action. Interim corrective action refers to when the operator has to fix the problem quickly, for example if an error occurs and it is going to cause delay the maintenance team might decide to fix the error straight away, two options are available:

1- The maintenance supervisor will use his operational capability to avoid asset failure, for example if it is a point failure re-routing trains might be an option in order to eliminate or decrease delays. I think Network Rail is very good in this but the problem is that just after they have dealt with one occurrence they forget about it until it happens again. Partially this is due to the nature of work, we can't afford delays and if we want to make up with a permanent solution then it is going to need three months of analysis and lab work and a new deployment schedule. Well that is not possible, we need a quick way but we also need another loop which for me is called permanent corrective action.

2- Permanent corrective action: this might involve contacting suppliers with an enhanced set of information to be provided to a more strategic group. The control centres which support this feature should be more central, so for example if we have 40 local RCM control centre to deal with TCA one would be responsible for PCA. So the local centres would see the information and respond to them fairly quickly and, the central centres would receive the same information but should not be immediately responsive they can monitor and analyse the information and provide permanent corrective actions. For example the central guys say well you fixed them good but I am monitoring it and I can see that you have done 100 of times in the last year and of those 100 times 80% seems to be the same thing so what I am going to do is to focus on that 80% and I am going to try to come up with a permanent action to basically to start eliminating these faults. But it should be the same source of information probably more depth available in the central level.

The reason for separating these two roles is that we don't want to burden the local guys with unmanageable amount of work. For example we know that just with current measurements we can detect the state of the point, this might not be enough for diagnosing why the point has failed but good enough at the operational level.

What we in intelligent infrastructure team refer to is flight controller model and the analogy would be that on a plane a captain might get a red light about a fuel system and he say that I know what it is but I am busy flying the plane, the flight engineer would have pressure gauges, thermal couples and other information, so he looks into it and find the reason for the problem. So basically the pilot is the operator on the front line and the flight engineer is the central room controller.

Another note is that we do not want to measure parameters if we are not going to use those parameters. For example in the pilot in Scotland we only measure current whereas at Liverpool Street we measure current, swing time, force and temperature. They measure four parameters and at the end they only use current to do the state detection. However we don't know for the next stage on the ISO which is diagnosis do we have to step back and apply more parameters or not.

Main functions of the system are alerting at the operational level and a parametric description of asset condition in this bigger loop. On our pilot in Scotland in the control centre in Glasgow the operator has a minimised window on his control screen which flashed red when an asset condition became abnormal, he then log a fault in FMS (Fault Management System) and contact the signal box to inform them of the fault and inform the local fault team to diagnose if it is a genuine faults and if yes what has caused it. What we are aiming for in intelligent infrastructure is to give them the right information to do the right action and also tell the front line that the failure is going to happen in an specific duration and the advise would be to either fix it now and avoid the peak time or leave it for tonight also some information to the maintenance track worker regarding the causes of failure so that they can go on track prepared. So the idea is to get the right information to the right group of people and stop bothering others. For example some of the trains have some sort of RCM on them , for instance if there is a fault on the door it will contact to the server depots and order future maintenance works . These systems apparently work really well and train operating companies no longer do routine maintenance checks, moreover they don't even inform the driver about all this as long as it is not affecting the operational procedure. One of the challenges for us is to identify which information for hat task and when.

Challenges facing the project are:

1. Selecting the right assets
2. Identifying the correct parameters to measure

Too many and you overkill it and too few and you don't get the capability out of the information.

3. Identify the correct operating process

This is to do with the people. When we ask operators who do you like RCM they say it is very good but in reality they ended up doing more work.

Roles and responsibilities of the operators are going to be defined by the business process team. By December we will have a strategic plan which gives us a view on the operative model. After that we can decide on the major roles and responsibilities.

Moreover we are talking to other departments in Network Rail and ask them their requirements and view on the project. What I don't want to do is that people in the system don't give any input and say it is nothing to do with me that would be destined to failure. For example we ask customer service and ask them do you have assets that can be benefited from RCM and assist you in delivering CP4 business target. One example is information about ticket barriers, large information displays and passenger related information. We were actually going to put a questionnaire e-mail at everybody but we realised that will end up into an unmanageable responses, that is why we are targeting at key stake holders.

## *12.3. Information sheet and consent for the knowledge elicitation exercise*

Thank you for your participation in this study. I am a PhD student in Human Factors Research Group, University of Nottingham and I am funded by Network Rail. The goal of this study is to investigate the information requirement while alarm handling in railway electrical control rooms.

This study will take around 30 minutes. You will be presented with an exemplar of an alarm situation. You will be asked to diagnose the fault and suggest corrective actions. More information regarding the fault would be available to you upon request.

Information will be gathered in the form of your responses and the information that was requested during the study. The results from the study will be retained securely by University of Nottingham in accordance with data protection policies, and will be use solely for the purpose of this research, including academic publication. Data will only be accessible by people directly involved in the research. Images will not be used without your permission.

No personal information (e.g. name, contact details) will be associated with your responses; it will not be possible to identify you from response data. You will be allocated an ID number upon arrival and this will be used on your responses.

**Participation in this experiment is strictly voluntary and you may withdraw at any point. Your participation in this experiment is anonymous and the records of your participation will be kept strictly confidential**.

Thank you very much for your help. Please do not hesitate to ask any questions.

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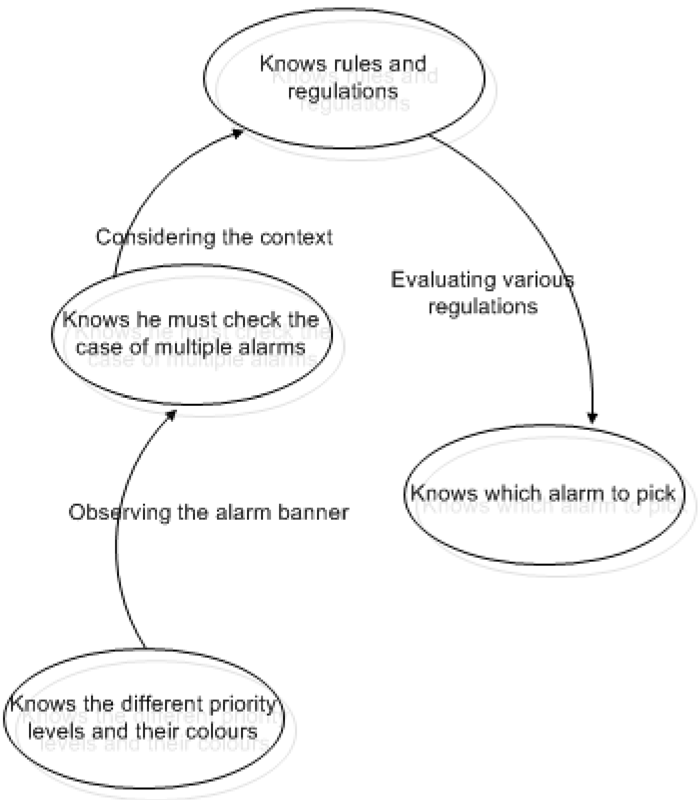
## 12.4. Alarm handling observational checklist

Date: Task No: Location: First session -spreadsheet

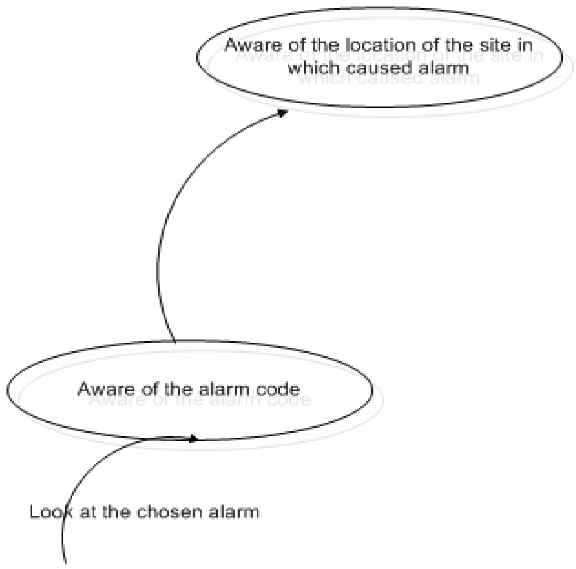
| Ti me line | Artefacts: Social (communication) | | Artefacts: technical artefacts (main display) | | | | | | | Coping with complexity | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | tell | F2F | alarm banner | Menu | Dispay area | Page button cntrl | Over view | Board | Paper | Time | Time% | Knowledge | Knowledge % | Competence | Comp% | Resources | Res% | Ommission | Reduced Precision | Queuing | Filtering | Cutting categories | Decentralisation | Escape | Frequency Gampling | Similarty matching | Extrapolation | Trial and Error | Laissez-faire | dynamic | static | ov-un | time start | time finish | total interaction | control | duration | activity | Artefact |
| 0:00:01 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 0.6667 | 9 | 1 | 9 | 1 | 6 | 0.6667 | | | | 1 | | | | | | | | | 0.17 | 0 | ov | 11.15 | 11.18 | 22 | 0.8333 | 225 | activation | 0.1111111 |
| 0:00:16 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 5 | 0.5556 | 9 | 1 | 9 | 1 | 7 | 0.7778 | | | | | | | | | 1 | | | | 0.33333 | 0 | ov | | | | 0.8333 | 225 | obs+inter+task | 0.2222222 |
| 0:00:30 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 5 | 0.5556 | 9 | 1 | 9 | 1 | 7 | 0.7778 | | | | | | | | | 1 | | | | 0.33333 | 0.33333 | un | | | | 0.8333 | 225 | task+formulate+execu | 0.3333333 |
| 0:00:45 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 9 | 1 | 9 | 1 | 9 | 1 | 8 | 0.8889 | | | | | | | | | 1 | | | | 0 | 0.33333 | un | | | | 0.9722 | 225 | formulate+exec | 0.1111111 |
| 0:01:00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 9 | 1 | 9 | 1 | 9 | 1 | 9 | 1 | | | | | | | | | 1 | | | | 0 | 0.33333 | un | | | | 1 | 225 | formulate+exec | 0.1111111 |
| 0:01:15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 9 | 1 | 9 | 1 | 9 | 1 | 9 | 1 | | | | | | | | | 1 | | | | 0 | 0.33333 | un | | | | 1 | 225 | task+formulate | 0.1111111 |
| 0:01:30 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 8 | 0.8889 | 8 | 0.8889 | 9 | 1 | 8 | 0.8889 | | | 1 | | | | | | | | | | 0 | 0.33333 | ov | | | | 0.9167 | 225 | execution | 0.1111111 |
| 0:01:45 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 8 | 0.8889 | 8 | 0.8889 | 9 | 1 | 8 | 0.8889 | | | | | 1 | | | | | | | | 0.16978 | 0 | ov | | | | 0.9167 | 225 | task def | 0.1111111 |
| 0:02:00 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 8 | 0.8889 | 8 | 0.8889 | 9 | 1 | 7 | 0.7778 | | | | 1 | | | | | | | | | 0.16978 | 0 | ov | | | | 0.8889 | 225 | obs+inter+task | 0.1111111 |
| 0:02:15 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 8 | 0.8889 | 8 | 0.8889 | 9 | 1 | 8 | 0.8889 | | | | | | 1 | | | | | | | 0 | 0.33333 | ov | | | | 0.9167 | 225 | obs+inter+task | 0.1111111 |
| 0:02:30 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 7 | 0.7778 | 8 | 0.8889 | 9 | 1 | 7 | 0.7778 | | | | | | | | | | | 1 | | 0.16978 | 0.33333 | un | | | | 0.8611 | 225 | obs+inter+task+exec | 0.2222222 |
| 0:02:45 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 8 | 0.8889 | 8 | 0.8889 | 9 | 1 | 8 | 0.8889 | | | | | | | | | 1 | | | | 0 | 0.33333 | un | | | | 0.9167 | 225 | obs | 0.1111111 |
| 0:03:00 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 7 | 0.7778 | 8 | 0.8889 | 9 | 1 | 8 | 0.8889 | | | | | 1 | | | | | | | | 0 | 0.66667 | ov | | | | 0.8889 | 225 | obs+inter+task+exec | 0.2222222 |
| 0:03:15 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 8 | 0.8889 | 8 | 0.8889 | 9 | 1 | 8 | 0.8889 | | | | | 1 | | | | | | | | 0 | 0.66667 | ov | | | | 0.9167 | 225 | obs+inter+task+exec | 0.2222222 |
| 0:03:30 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 9 | 1 | 9 | 1 | 9 | 1 | 9 | 1 | | | | | | | | | 1 | | | | 0.16978 | 0.33333 | un | | | | 1 | 225 | execution | 0.2222222 |

## *12.5. Alarm handling state and process diagrams*

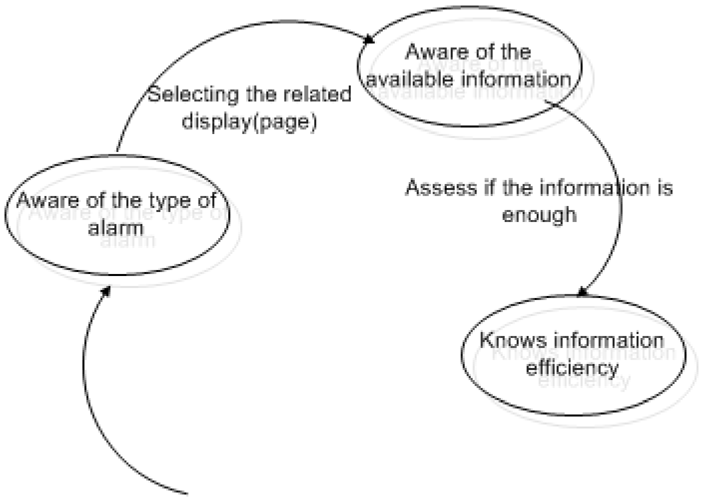
Identify priority:



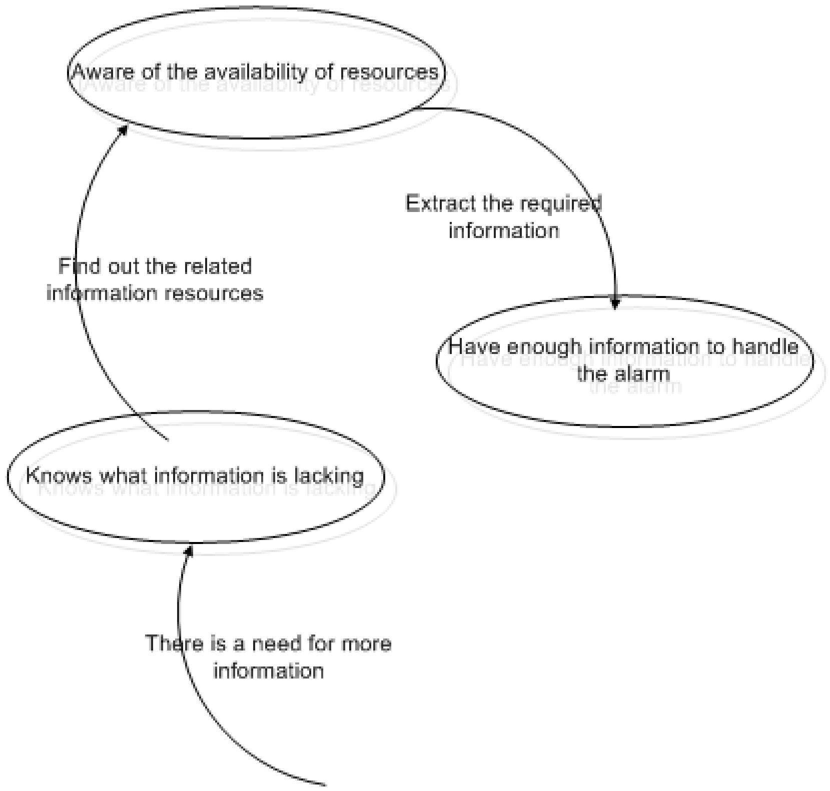

Locating alarm→ what is the alarm about? What does the code mean?



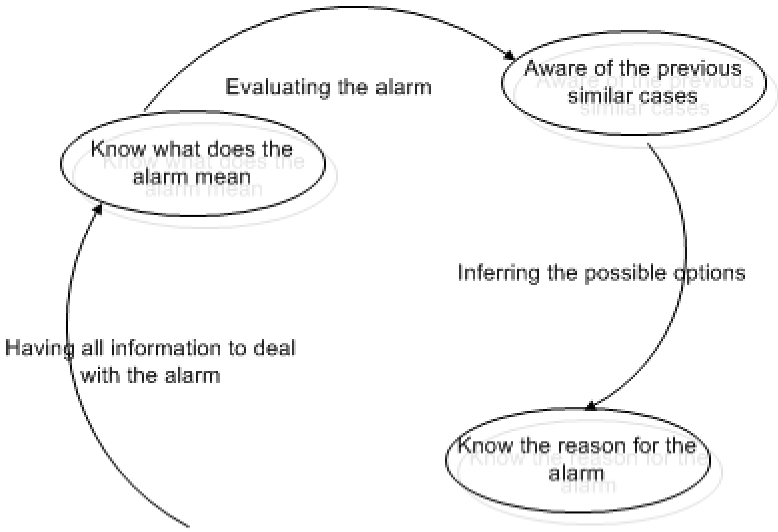
Information requirement analysis



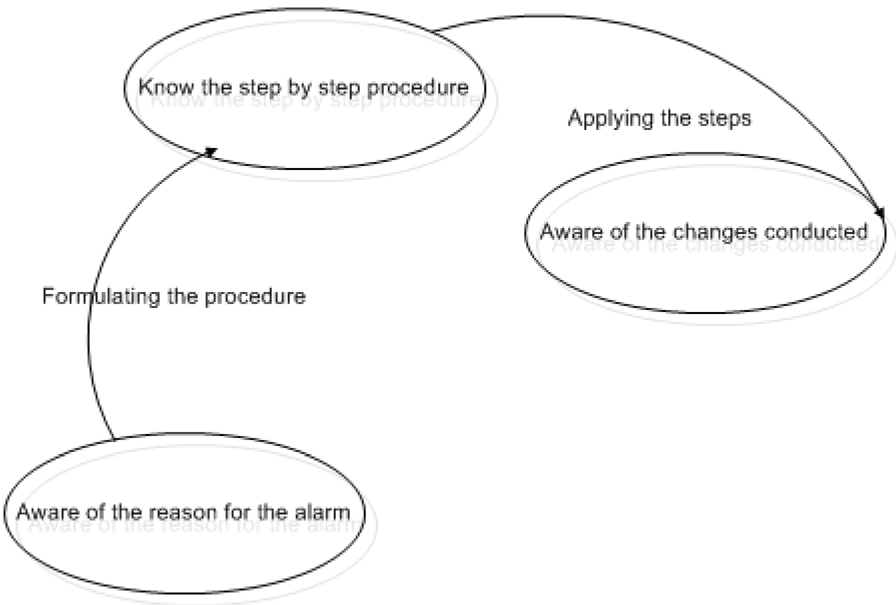

Collect the required information



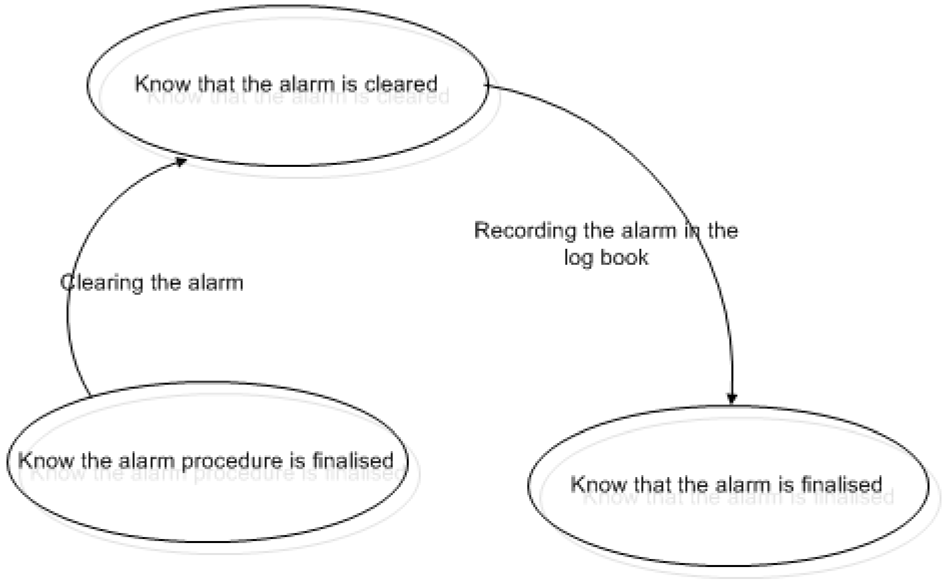
Assess the alarm




Make the appropriate changes



Finalising the alarm



## *12.6. ECRO comments after handling alarms- 2 examples*

Alarm 1: unexpected alarm

Note: It took 3 seconds for the operator to look at the alarm and grab the mouse and acknowledge it by clicking on the operational display. And another 4 second to load the new page where caused the alarm. But before the page is loaded or while it is loading O1 started to explain what he thinks this alarm is about.

Operator1: see once when get here, there could be anything at Lewisham. There is no way we can tell what the problem is. But in this case it is a trip charge. It just dropped a lot of threshold and its gone back to normal now. And now that I am on this page I see that the other one (Bloomsbury) is low as well and that is going to guide alarm so you just increase that as well.

Note: He made the changes on the screen and continues talking about the procedure and the reasons

Operator: but you do know on your mind sort of why is that, because you can see that there is no DC breakers trip or AC breakers trip. What I am saying is that you looking and you already looked into it and you sort of know what's down before you have the page up loaded. Because you look at the other two screens, because if anything of AC has tripped you see it on there and DC tripped you see it on the other and by the time the alarm related page loads up you know you have to rule out those two options. All I am saying is that you automatically do that and you already looked at both screens and you know that nothing is actually tripped, so you are already half way there.

Note: Now he is going back to the screens to show me what it is that he is scanning:

Operator: So without even looking at it you have already checked that it is not the other two so it is very likely to be the other one. Whereas if it is a AC trip you see the thing open on the screen and then you know that this is what that need taking care of and you rule out the other options.

Researcher: so this is how you realise what's wrong.

O2: yes, obviously, all we get is the alarm banner. This is the operator we call this up to do operations about accepting the alarm, we look at the overview to grab the information and decide what's wrong, it's like second nature, you think you are not thinking. When you look at the colour you think what category alarm it is and you already are half way there, because you can say what category alarm it is and you know what is the priority of each category and what are the things associated with the potential causes of the alarms based on the categories.

Note: then he generates the alarm to show me how different categories work, he does it to test an outstation but it was going to generate an alarm.

Alarm2: expected

Operator: there are multiple alarms in that because I just set them like that, as part of the testing. But the system will display only the high priority. The highest priority is category two and that's the one I am seeing, but when you go on a site, you see that we got category 2, category 3 and category 4 alarms, so it will only show you the individuals. Now what I am going to accept just the category 2 alarm and you see the banner is going to change to the pink.

Researcher: so the system do the prioritising for you in colour coding, but in this case you have 5 category 2 alarms in red, how do you know which one to chose first.

Operator: it would depend on what it is, because we have so many different category 2 alarms.

Researcher: so you do a double filtering in some sense.

Operator: yes, exactly. For example if we lost an HV supply, we get lots of category 2 alarms plus everything else. So you go to the site and you'll see. Let me show in an example:

Note: so he changes the page and goes to another one to show me what happened if a HV is lost and what he has to do in response to that:

Operator: we would have to rectify trip, that indicate opened that would remain open. We would have to battery charge of 1, 2 and 3 (Category 4 alarm) , NV1, NV2(category 3), SS1 (category 2) ... and all these would alarmed. We also get a rectifier trip as well which will be category 2. And if its is due to a fault on that feeder then that DCP would be open and we will get 61,62 (?) which will be category 2. And that would be just one of the sites. For example if we lose the feeder of 1074, everything in orange on here we would get those alarms from.

Researcher: So the branch colours are another way for you to know which branch to look.

Operator: exactly, the only problem is that it's a bit misleading because we don't get indication of any of those group points. So if it is tripped at grid supply, we wouldn't get indication of that because they never give us indication because they haven't got cables in. However we would now by losing our voltages so if we go to the tab changing page , you can still work it out because that 1704 , the Lewisham one, those voltage would be 0. So we know that it tripped the entire supply grid. After we have confirmed it we get in touch with the grid and first of you asked them has it tripped, if it's No, then what happened, they could have their equipment tripped, and also we can't put it right back on because then it will be a shock to this system, so we have to go slowly. And you can see by the size of it if this happens what huge work it is and when you are recharging them back you get all of the alarms back as well and you have to accept them before you can carry on.

## *12.7. Information sheet and consent for the fault finding study*

Thank you for your participation in this study. I am a PhD student in Human Factors Research Group, University of Nottingham and I am funded by Network Rail. The current study is to provide a conceptual understanding of fault finding within maintenance boxes. The aim of this project is to explore the activities associated with fault finding and tactics and strategies adopted by operators.

In this experiment which will take about an hour you will be asked to think of examples of recent faults they have attended with any of the following:

1- Example of fault detection which refers to the promptness of detection
2- Incipient faults: small faults that if not attended can adds up
3- False alarm rate: example of a case where the detection was difficult due to high false alarm rate.
4- Example of an incident where the fault detection get missed?
5- Example of an incident where incorrect fault identification occurs: system correctly register that there is a fault but incorrectly identifies the component which has failed.

The researcher will ask following questions for each of the cases recalled by operators, note must be taken that these questions re not fixed and might vary from case to case:

1- How you became aware of the fault? What was the cue in identification of the problem?
2- What was the most important piece of information that helped you in making that decision?
3- How did you integrate all sources of information and came to a conclusion?
4- What artefacts you used?
5- What was your level of situation awareness?

**Participation in this experiment is strictly voluntary and you may withdraw at any point. Your participation in this experiment is anonymous and the records of your participation will be kept strictly confidential**.

If you felt any inconvenience at any stage of the experiment please make sure that you inform me.

For any questions regarding the experiment please do not hesitate to contact me.

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## 12.8. CDM-like spreadsheet completed during the fault finding study

| Fault type | Activities/ goals | Cue identification | Data processing | Information Development | Knowledge Integration | Notes |
|---|---|---|---|---|---|---|
| Promptness of fault: this was a nearly saved SPAD incident on 13/01/10 | Get informed of the alarm | Signalling from Crew-Wlimsilow tell that there was a problem with the signalling- a bleep was given every 30 seconds- the alarm banner was flashing | these information and the knowledge on the relay room from their trainings: equipment for signalling with power supply+UPS system | this week work has been carried out to test the UPS batteries in each of the relay room | the power supply is lost but he wants to know from which side of the feed- how they look like on the signalling screen | main power supply was just lost, they pushed the contract in and the elctron was shut down and the UPS has to work, during the week the UPS battereis were under changing so the eintire signalling from Wilmslow to Crew was failed |
| | Diagnose | On the signalling screen all of the track seems red which implies that it is occupied- the operator knows that it is not occupied physically so there must be something else. | the fault is noted as the power supply problem- the red tracks on the signalling and it is very difficlut to miss | The information captured from the cues and the system is not enough for the diagnosis and the oprator needs to call them up right away. | Everything was alright towards manchester and everything was wrong towards crew so that is where the problem is. | |
| | Course of Action | Collecting more information was required because there is not enought infromation from the current cues | processing the data obtained from various sources : there is nothing particluarly wrong which has caused by the engineering work and there is a loss of connection towards manchester. | | | |

## 12.9. Information sheet and consent for the laboratory study

Thank you for your participation in this study. I am a PhD student in Human Factors Research Group, University of Nottingham and I am funded by Network Rail. The goal of this study is to assess the effect of information presentation on the performance of alarm handling.

This study will take up to an hour and you will be paid £12 for your time. A tutorial of the experimental procedures will be available and the required level of competency will be assessed through a test. Upon successful completion of the competency test you will be asked to assess 30 alarms presented on the experimental prototype and respond accordingly. In order to take part in this study you must successfully complete the test which will take around 15 minutes.

The study will take place in a usability laboratory, where you will be asked to perform a simple alarm handling task. The experimenter will explain the equipment being used and there will be a practice run of the system to give you the opportunity to familiarise yourself with the experimental procedures.

Information will be gathered in the form of response times, interaction with the experimental prototype and a record of eye movement while conducting the experiment. The results from the study will be retained securely by University of Nottingham in accordance with data protection policies, and will be use solely for the purpose of this research, including academic publication. Data will only be accessible by people directly involved in the research. Images will not be used without your permission.

No personal information (e.g. name, contact details) will be associated with your responses; it will not be possible to identify you from response data. You will be allocated an ID number upon arrival and this will be used on your responses.

**Participation in this experiment is strictly voluntary and you may withdraw at any point. Your participation in this experiment is anonymous and the records of your participation will be kept strictly confidential**.

Thank you very much for your help. Please do not hesitate to ask any questions.

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