Alarm handling for health monitoring: operator strategies from rail electrical control

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Abstract: Alarm management is a key component of the successful operation of a prognostic or health monitoring technology. While alarms can alert the operator to critical information, false alarms and alarm flooding can cause major difficulties for successfully diagnosing and acting upon infrastructure faults. Human factors approaches seek to design more effective alarm systems through a deep understanding of the contextual factors that influence alarm response, including strategies and heuristics used by operators. This paper presents an extensive analysis of alarm handling activity in the setting of a rail Electrical Control Room (ECR). The analysis is based on contextual observation, and the application of a time-stamped observation checklist. Functions, performance requirements and general operating conditions that influence alarm handling are presented, delineating the typical operational constraints that need to be considered in the design and deployment of asset-based alarm systems. The analysis of specific alarm handling incidents reveals the use of specific strategies that may bias operator performance. Implications for the design of health monitoring systems are discussed.

Keywords: human factors, alarm handling, strategies, joint cognitive systems, work analysis

1. INTRODUCTION

Highly sophisticated use of remote sensors has the potential to give control operators detailed, real-time understanding of the status of complex environments comprised of multiple assets. Continuous monitoring of these large asset bases is beyond the performance capabilities of any human operator. A common solution, therefore, is to use alarms to assist human operators in managing numerous sources of data by presenting audible, visual or haptic alerts to critical events. This applies to a number of rail related domains including infrastructure monitoring, vehicle asset monitoring and, the topic of this paper, monitoring of the power supply in rail Electrical Control Rooms (ECRs).

Alarms range from simple prompts for an operator to carry out further actions, including making diagnoses, through to semantically rich messages carrying verbal, textual or pictorial information about the source or cause of the abnormality. With the shift to prognostic systems, alarms will move from informing the operator of a current or recent event (e.g. failure of a piece of infrastructure) to include anticipatory alarms that warn the operator of an emerging risk (e.g. potential failure or degradation of asset performance). The use of this kind of pre-emptive alarm is likely to be highly relevant to the future, predictive asset management and health monitoring system on the railways [1].

Successful implementation of alarm display systems, however, is not straightforward. Poor alarm handling has been a contributory factor in a number of safety-critical incidents such as Three Mile Island in 1979 [2] and the Texaco refinery explosion in 1994 [3,4]. In transportation, aircraft hazard reports confirm that alarm problems contributed to about 50% of all of the incidents recorded between the years of 1984-1994 [5]. Other examples include the Ladbroke Grove train accident [6] (though see [7], for a different perspective) and the Channel Tunnel Fire [8].

Major problems associated with alarm systems include alarm flooding, poor system state indication, poor priority management, nuisance alarms and false alarms [3,5,9]. Research on alarm design suggests many instances where alarms are irrelevant or present unnecessary duplication of information [10]. Alarm problems are mainly rooted in some form of information complexity. [11] listed the sources of complexity as:

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

A significant effort has been devoted to exploring alarm design problems. Topics covered include alarm handling response times [12], direction of attention [5,13], modelling the operators' diagnostic procedures [7,13], information load [14] and assessing how informative and meaningful alarms are [9].

[15] pointed out that, despite their great potential, complex control systems are most likely to fail during emergencies. This is partially due to inconsistency between the machine 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. When faced with a high degree of information complexity, heuristics are used to reduce cognitive load in order to overcome the shortcomings and make an optimised decision [11]. [16] identified the strategies potentially applied by operators to cope with complexities due to information inefficiencies (**Error! Reference source not found.**). These are effectively shortcuts applied by operators that consequently risk making their decisions somewhat biased.

(Table 1)

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 and contextual approach is required [17]. This has also been advocated in the Cognitive Systems Engineering approach [16] which emphasises examining technology and human working together as a single unit of performance. Identifying when and why coping strategies are applied, and how they may influence subsequent operator and system performance, requires an in-depth understanding of the work domain. Furthermore, in order to reflect these understandings in future design of the system, it is important to correspond each of the strategies to its specific alarm-initiated activity.

The following paper examines the current application of alarms and the use of alarm handling strategies in the setting of rail power provision. Railway 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 equipment. It is a key strategic area for effective rail operations, necessary to ensure a continuous supply of power to the track. Therefore, it enables rail infrastructure managers (such as Network Rail) to meet their contractual obligations to provide an effective rail network for railway undertakers such as train operating companies. It is also safety critical, with electrical isolation being a key part of safe access to the track during maintenance, engineering and incident handling [18] in those parts of the rail network using electric traction.

The paper presents an in-depth analysis of alarm handling at one specific control room that provides electrical power to key urban and suburban lines in the metropolitan area of London, UK. The work presented in this paper was part of a larger project to modernise, and potentially centralise, the rail electrical control function for the UK railways and is part of a larger strategy to centralise maintenance activities and control. The project is indicative of attempts to deliver future asset management control systems (see other papers in this volume). Prior work in the project had set out a general framework for understanding the requirements of joint human-automation cooperation in rail intelligent infrastructure, based on interviews with senior stakeholders (see [1]). Alarm handling was highlighted as an area for further analysis, leading to the study presented in the rest of this paper. This study set out to capture the functions and processes of alarm handling and, in particular, the application of strategies for alarm handling, under the current ECR arrangements. While roles might change and technology might change an understanding of current behaviours is still critical and valuable. First, and pragmatically, the lessons of the past can be used in the design of new technology and, second, while responsibilities between automation and human decision making might shift with new technology, the nature of those decisions and the functional outputs of the ECR as a joint-cognitive system will remain the same.

The methods and results covered two strands of analysis. The first strand used observations and interviews to understand the underlying contextual factors – functions, performance criteria, alarm types, environment, and processes – of ECRs. This is critical to understanding the ECR environment as a joint cognitive system. The second strand used verbal protocols and an observational checklist to identify the sequence of activities as well as particular coping strategies that operators adopted during alarm handling episodes. Together, these two sets of analyses shed light on the factors that influence alarm handling in ECR, which is taken up in the discussion, and data collected went on to for form a cognitive systems analysis of rail electrical control alarm handling [19]. The contributions of this paper are (1) In-depth description of alarm functions within rail maintenance systems environments (2) mapping of alarm handling strategies to stages of alarm handling to inform alarm theory and subsequently to design guidance (3) examples of methodologies for use by others wishing to take an operator-centric view of the design and deployment of future asset management technologies.

2. METHODS

Field studies are useful for developing an understanding of the domain in a comprehensive way [20] enabling researchers to identify significant issues in complex socio-technical settings. [21] have noted that structured field studies can interconnect with exploratory observational studies to produce a deep understanding of user needs. However, 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 [22] 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 [23] but unstructured verbal protocols may not access important information regarding performance or concurrent activity.

To address these needs, a two-stage approach was taken. Familiarisation through observations and semi-structured interviews facilitated an overview of the work domain and led to development of an observational checklist. The observational checklist was developed from series of open interviews with the railway electrical operators, this led to an understanding of the activities associated with alarm handling, particular challenges and artefacts adopted by operators during alarm handling. Such checklists have been used previously in signalling control environments **Error! Reference source not found.**, [24]. A second round of observations was then conducted using the observational checklist, along with verbal protocol and video recording footage of operators handling alarms, to develop a fundamental understanding of alarm handling in the ECR.

The combination of observational checklist data and verbal protocol allows an analysis of frequencies and sequences of events, with a simplified version of the [26] Alarm Initiated Activities Model used as a basis. The model developed by Stanton and Stammers 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 [26].

2.1. DOMAIN FAMILIARISATION

The researcher visited a specific Network Rail Electrical Control Room (ECR A) for two sessions (total of four hours) 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 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 and to identify issues affecting the performance, the process, the control room specifications and regulations. Moreover, having these two sessions prior to the field study helped the researcher to build rapport with the operators and ensure that they were fully informed about the aims of the study and various stages of data collection associated with it. The familiarisation visits led to an assessment of the resources required for the field study, and the design of the observational checklist.

2.2. FORMAL FIELD STUDY

2.2.1. PARTICIPANTS

Six electrical control room operators in ECR A 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, briefed about the research 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.

2.2.2. 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 system. 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. The observational checklist was time-stamped and allowed structuring alarm related activities and use of various artefacts within specific time frames, this enabled a sequential understanding of the alarm handling process. Table 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.

(Table 2)

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 (classified as 'Face to Face'). Measurements of the occupancy of operators with each of the artefacts provided an understanding of their importance at any given time in the alarm handling process. The total use and overall time used for each artefact were recorded on the checklist. Additionally, operators were asked to comment on the amount of information presented to them and this comment was also recorded on the spreadsheet.

2.2.3. PROCEDURE

Four sessions of 4.5 hours each (two day shifts and two night shifts) 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.

When an alarm was generated the researcher started the video recording and noted the artefacts utilised during the alarm handling episode in the observational checklist (these observations were verified through the video recordings). When the alarm was cleared, the operator informed the researcher and that he is ready to answer questions (retrospective verbal protocol). The researcher then annotated the observational checklist based on this information. These questions were also addressed to explore operators coping strategies (Table 1). The strategies were defined to and discussed with operators throughout the familiarisation phase, they were then referred to further during the verbal protocol session and were directly asked to select a relevant strategy (from the list on Table 1) associated with the activities noted.

During the time when no alarms were being observed, the researcher engaged in additional discussion with the operators about their work, and made observations regarding general activities in the control room. This qualitative information from the operators help to develop a wider understanding of activities performed within the ECR.

3. FINDINGS

3.1. FUNCTIONAL OVERVIEW

ECR operators have two main responsibilities; the first 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.

Electrical Control Room Operators (ECROs) are in communication with signallers (i.e. dispatchers) and inform them that the railway tracks have electrical supplies. Moreover, they communicate with maintenance staff to ensure them that railway tracks are isolated and safe for track workers to conduct any work on site. This is conducted through a three-way communication system to assist with the accuracy of the procedure. During major incidents (e.g.

over head line failures) this communication is extended to train managers, and route managers to provide information regarding the estimated time of availability of the service and allow signallers to plan their regulating and re-routing activities.

The second function 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 status of the track and whether it is safe for track access, or operational for traffic.

Operators are usually occupied with other activities when an alarm occurs (e.g. programming isolation work, communicating with relevant in track workers regarding an on-going engineering work, etc.). The electrical control domain is highly dependent on successful alarm handling to maintain continuity of the service while at the same time identifying spurious false alarms that are either generated through testing and maintenance work, or for unknown reasons.

3.2. RAIL ECR ALARMS

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.

ECR A is a typical Electrical Control Room covering heavy rail infrastructure in the urban London area. It has three workstations (Figure 1) and similar information available to all three. The SCADA display in the ECR was developed on the basis of Network Rail’s system specification recommendations [27] and it corresponds to EEMUA standards [28].

There are four information displays on each workstation: the left screen displays the main track 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.

These information displays contain numerous duplications, which is often used as a source for confirmation for operators. For example when there is a circuit breaker failure, the operator can compare the alterations on the AC and DC information display to determine the extent of the failure (e.g. grid level). From the four displays, the operational display has the most interaction points. This is where isolations can be implemented and alarms can be explored and assessed. In other words the three remaining displays are for providing information and the operational display is for executing operational decisions.

(Figure 2)

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. 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.

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.

Any unacknowledged alarm appears on the alarm banner, which is located on the operational display. 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 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 3)

During the familiarisation phase, 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.

Not surprisingly, operators noted information deficiencies as one of the challenges associated with their alarm handling. Alarms can have ‘high information’ or ‘low information’. ‘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. It should be noted that these terms refer to operators’ subjective interpretations of the situation, since it was not possible to objectively assess the sufficiency and relevancy of the information presented to operators during real-time alarm handling.

Other usability issues that were noted by operators included system lag when they wanted to close circuit breakers in order to prepare for an isolation. If there were a number of circuit breakers they had to be modified sequentially since the SCADA would not allow synchronised switching. This was not the case with previous electro-mechanical mimic diagrams. Another usability issue related to the implementing last minute alterations to the maintenance plans, which introduced some level of cognitive demand since the operator had to reverse the existing isolation, permits and implement new ones within a pressured time frame.

3.3. ALARM-INITIATED ACTIVITIES

Review of the qualitative information collected during the verbal protocol analysis led to identification of activities associated with alarm handling. Operators comments were video recorded and transcribed (~7000 words) and were thematically analysed [29], Table 3 presents three examples (two unexpected alarms and one expected alarms) of this coding activity.

(Table 3)

Four high level activities were identified: Notification, acceptance, analysis and clearance.

The first stage of alarm handling is ‘notification’, this the first instant were the operator notices the alarm. Any unacknowledged alarm appears on the alarm banner, which is located on the operational display, shown in Figure 3. The information provided includes the colour of the banner, the category of alarm which roughly indicates the type of failure.

The second stage is ‘acceptance’. This refers to the activities that are conducted by the operator to ensure that the alarm is not a false one. 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.

Usually this is conducted by consulting other sources of information to confirm the existence of an actual failure, in case of expected alarms, because the operator is aware of the existing work going in the area, he usually does not need to consult other sources. This increases the risk of missing the unexpected alarms that are generated in the same area as other engineering works.

The third stage ‘analysis’, consists of the process that is conducted by the operator to analyse the causes of the failure, diagnose and investigate potential corrective actions. Operators consult a number of situational information including previous faults reported at the location, recent engineering work, status of the service (i.e. peak time/off peak), and availability of maintenance staff to access the faulty area and perform diagnostic investigation.

The last stage is ‘clearance’. This refers to a series of activities conducted to select the most optimum corrective action. Optimum in this context would relate to “smart” way of dealing with the faulty situation, for example to know which maintenance team is closer to the failure site or to inform the route managers with an accurate estimated time of availability and facilitate better regulation. Operators should consider the impact of the failure on safety and efficiency of the service, plan the corrective action (i.e. when to send electrical technicians on track) and to inform relevant parties (e.g. signallers) of the fault. Note must be taken that clearance does not refer to complete rectification of the failure but indicates that a plan has been established to rectify the failure.

Operators commented their key challenge was to focus on alarms while they were fully occupied with other responsibilities. This is particularly the case during the peak times when the operator felt pressured in resuming the service back to normal as soon as possible without compromising safety. Additionally, during the night shifts when alarms are generally caused by planned maintenance work, operators commented on the risk of overlooking a situation due to presuming that it is caused by the maintenance work.

3.4. USE OF ARTEFACTS DURING ALARM HANDLING

The following artefacts were utilised by operators whilst alarm handling:

- SCADA display features
    - Menu

    - Alarm banner
    - Display area
    - Page buttons
    - Overview display
- Static board
- Paper
- Phone
- Face to face communication.

Although face to face communication is more of a social activity than physical one, it has been considered as an 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.

In total, 22 alarm episodes were observed; of which 11 were unexpected and 11 were expected (e.g. triggered by testing or maintenance). Completion of the 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 2, twelve uses of different information displays and other artefacts were noted.

Furthermore, operators were subjectively asked to identify the alarm types as ‘high information’ and ‘low information’. It must be noted that only unexpected alarms were considered for this categorisation. From the total of 11 unexpected alarm episodes, six were categorised as high information and five were categorised as low information alarms.

Table 4 present the duration, mean and SD of the expected and unexpected alarms. Looking through the utilisation of various artefacts during expected and unexpected alarms (Table 5) showed that during unexpected alarm “display area” is mostly used and during expected alarm, “telephone” is the mostly used artefact. This is potentially due to the fact that during an expected alarm operator is talking to the maintenance team to confirm various issues while interacting with the SCADA, whereas during unexpected alarm, operators would consult the operational display to investigate potential causes of the alarm.

(Table 4) and (Table 5)

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.

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 with high information; t (59) = -3.63, p<0.01.

3.5. COPING STRATEGIES

Operators viewed Table 1 (the list of coping strategies) prior to the retrospective verbal protocol and were asked to identify their coping strategies during the alarm-handling episode. The coping strategies identified are:

- Queuing
- Filtering and categorising
- Similarity matching
- Extrapolation
- Trial and error

These strategies were adopted at different stages of an alarm-handling episode. The time-stamped observational checklist facilitated the correspondence of the alarm-initiated activity to the selected coping strategies.

Operators notice the alarm from various information sources. 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. Queuing often depends on the type of alarm and the location of the failed asset to identify potential impact on the service. The prioritisation is mainly based on ensuring safety and reducing delays on the railway service.

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.

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.

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*).

4. SYNTHESIS AND INPUT TO DESIGN

Integration of the time-stamped observational checklist, with the strategy analysis, facilitated an understanding of operator work process and their shortcuts, biases and artefacts. This would allow development of design guidance for similar work settings. It must be noted that the emphasis of this section is on ‘unexpected alarms’ as they need to be analysed within often a time pressured situation and could benefit from some form of design aid. It should also be noted that while the number of observed alarms was small, there was much additional discussion with operators about how representative each incident was, and reflection from the operators on other alarm handling incidents. This broader data collection, which effectively formed an information cognitive task analysis, also contributed to design.

Figure 4 shows the order and duration of activities when handling unexpected alarm episode. Not surprisingly, there is an order in occurrence of these activities: 1- notification, acceptance, analysis and clearance. An interesting point revealed that lengthy alarm handling episodes (e.g. episode 1, 4 and 10 on Figure 4) had spent longer periods on analysis and clearance and were triggered by some form of information complexity (i.e. high information in the case of alarm episode 1 and low information in the case alarm episode 4). For example during alarm handling episode 4, the operator had to investigate a number of possible causes that has led to the alarm. Once the operator identified the type and priority of the alarm and selected the appropriate operational page, he had to explore three possible routes in order to detect the affected circuit breaker that led to the alarm. Upon analysis of the alarm, the operator had to close the circuit breaker one by one and test the impact, the system did not allow simultaneous closure of the circuit breakers and it took longer than expected to clear the alarm.

Similar mapping activity across time stamped observational checklist and the selected coping strategies informed the adopted duration of each of the strategies and their order (Figure 5). Similar to the previous figure, it was observed that the order of strategies is also consistent. This would imply that coping strategies are not mutually exclusive across various activities. Therefore, it is possible to assume that for each of the activities there are certain coping strategies adopted by the operators and hence supporting/aiding/guiding that particular strategy would assist the operator in a particular phase of the alarm handling.

Integrating the findings noted in the previous sections has led to Table 6. The table summarises the most critical design guidance that emerged to inform the development of effective alarm management in future electrical control for the railways. For example to improve alarm notification, alarm banners should be designed in a way that easily facilitates 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.

5. DISCUSSION

This paper 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 effective alarm management 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.

Strategies such as similarity matching and extrapolation are related to the operator's experience and local knowledge as it was found from their comments. 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. Extrapolation is often used as the basis for clearing alarms, with the risk that an inappropriate match being made between the current case and previous experiences. Therefore, local knowledge and historical information should be available to assist operators in accepting alarms with confidence.

One particular finding of the study is the comparison between expected and unexpected alarms. 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. Having said that, operators’ expecting an alarm (due to an on-going engineering work), does not necessarily mean that the next alarm occurring is known and does not need any diagnosis. ECROs commented on situations where unexpected alarms occurred and were attributed to ongoing engineering work at the time and in the relevant area. Had they not notice the difference promptly; the misidentification would have lead to major issues.

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 future alarm displays.

One major surprise from this work was the relatively few instances of alarms that actually took place. Despite the 18 hours of field study, only 22 alarms were generated, and discussion with operators revealed that, particularly during the night shift, this kind of workload was fairly typical. This would suggest some broader human factors implications with the ECRO role, in that at periods of low workload there are probably issues around vigilance [30]. At the other extreme, managing alarms during the peak hours became one of workload in conjunction with other tasks. This suggests that future HF work in the ECRO environment could be targeted to understanding more generally the working conditions and varying cognitive demands of the role.

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 small number of alarms observed, 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 study. Also, as noted above, this left much time for discussion around the typicality of the alarms observed, and this kind of frequency, while restricting data was representative and therefore should gave an accurate context in which to observe and elicit strategies.

The relatively small number of participants can also be considered to be a limitation in this study, it must be noted that the six railway operators involved with this study were all working in ECR A and comprised 50% of the work force in that ECR. Also, this ECR was selected under guidance from senior management because of its typical nature. Furthermore, the core aim of this study was to explore the activities and strategies adopted by operators while interacting with the existing SCADA system. Finally, in identifying HMI issues with the existing SCADA system, the approach was to identify the general feel towards the role of SCADA in relation to performance and strategy over an extended period of time, rather than to compare and contrast subtle design elements (which would have required a larger participant body).

6. CONCLUDING COMMENTS

The work presented in this study indicates the complexities of alarm handling domains. While it is no doubt the aspiration of infrastructure operators to develop new environments and new working patterns for future prognostic and health monitoring systems, the reality is that many new technologies will need to be integrated with legacy technology, and / or legacy processes. This paper gives an overview of the cognitive characteristics of work in one potential health monitoring domain, railway electrical control. Importantly, the data highlights the heuristics and biases are present in all aspects of alarm handling. It is important to stress that heuristics are not shortcomings or workarounds on the part of an operator, but a fundamental characteristic of human cognition present in huge range to human activity, and should not be ignored, but acknowledged and designed for in a sensitive manner [16].

Additionally, study reported in this paper recommends a series of methodologies and approaches that facilitates understanding of complex control settings, their work domain, constraints and operational heuristics. The framework of methodologies, data collection and analysis techniques utilised during this study can potentially inform systematic reviews of alarm management system within complex control settings such as railways, nuclear, process, etc. This can ideally be part of the Human Factors integration planning activities conducted prior to commissioning alarm management systems; the advantage of this inclusion is that it incorporates knowledge of possible cognitive demands, along with physical and conditional constraints, into design and testing. Future work is required to explore this combination of sequential and contextual methods further and provide a human factors engineering program plan for design and procurement to assist them with better understanding of their complex infrastructure management environments.

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8. TABLES

TABLE 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

TABLE 2: OBSERVATIONAL CHECKLIST FILLED FOR ONE ALARM EPISODE

Time	tell	F2F	alarm banner	Menu	Display area	Page button control	overview	board	paper	Main activity	Source of complexity
0:00:01	0	0	✓	0	0	0	0	0	0	Notification & Acceptance	High information
0:00:16	0	0	✓	✓	0	0	0	0	0	Analysis	
0:00:30	0	0	0	0	✓	✓	✓	0	✓	Clearance	
Total-time of use(seconds)	0	0	22.5	7.5	3.75	3.75	3.75	0	3.75		

TABLE 3: THEMATIC ANALYSIS OF ALARM HANDLING QUALITATIVE FINDINGS

Alarm	Notification	Acceptance	Analysis	Clearance
Unexpected 5	It took 3 seconds for the operator to look at the alarm and grab the mouse and acknowledge the alarm by clicking on the operational display.	And another 4 second to load the new page where caused the alarm. Operator explains that: all we get is the alarm banner, we then look at the overview and grab the information and decide what is wrong, it's like second nature. When you are looking at the colour, you think 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	Operator noted that once you get here it could be anything. 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 I am checking another page to check the threshold on another location and when I see that is also lo, it confirms my hypothesis.	I increase the threshold and rectify the problem and then ensure that the area is covered and safe.

		based on the categories.		
Unexpected 7	Audible siren is activated. 4 seconds after that operator clicks on the alarm banner.	He says: looks like one of the breakers has failed, he accept and silence the alarm.	4 seconds after and he conclude that both of the breakers have failed, he spent another 15 seconds looking at the alarm and its indication to work out what is the problem He opens the event log and try to find the breakers on the screen and then go through the events. He reviews the facts presented on	And then tries to close the circuit breaker, but the system is not very responsive and he use a shortcut on the system to shut down breakers.

			the event log.	
Expected 1	There are multiple alarms, but that is just because I set the testing like that.	Then because I know what it is, I accept the alarm.	I know exactly what has caused this alarm, but also from reviewing of the alarm categories my expectation is confirmed.	I correct the fault through SCADA and log the event.

TABLE 4: DURATION OF 11 UNEXPECTED AND 11 EXPECTED ALARMS

												Total	Mean	SD
Unexpected Alarm ID	1	2	3	4	5	6	7	8	9	10	11			
Duration	152	67.5	30	134.55	29.85	60	89.7	59.7	74.7	104.9	60	862.7	78.42727	39.07759
Expected Alarm ID	1	2	3	4	5	6	7	8	9	10	11			
Duration	15	44.9	15	39.75	15	15	15	15	15	29.85	30	249.45	41.575	11.40509

TABLE 5: ALARM ARTEFACTS UTILISED DURING EXPECTED AND UNEXPECTED ALARM

Unexpected	tell	F2F	alarm banner	Menu	Display area	Page button cntrl	overview	board	paper
Mean	0.906818	0.302273	13.21818	14.31818	29.23409	10.7	6.022727	0	3.956818
Expected	tell	F2F	alarm banner	Menu	Display area	Page button cntrl	overview	board	paper
Mean	7.015909	0	7.038068	2.243182	1.924431818	0.73125	2.243182	0	0.085227

TABLE 6: ALARM INITIATED ACTIVITIES AND THEIR CORRESPONDING ARTEFACTS AND STARTEGIES

Activity	Main artefact	Strategies	Design guidance
Notification	Alarm banner	Filtering Categorising	-The information presented on the alarm banner should be coded so that it is easy to filter. -Codify the types of alarm to facilitate categorising.
Acceptance	Alarm banner Display area	Categorising Similarity matching	-On the alarm banner, mark the alarm to tell the operator that there are similar previous cases. -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 Menu Overview	Extrapolation Similarity matching	-On the display area provide details of previous cases and also facilitate playing back the alarm situation.
Clearance	Menu Display area Overview	Provide clearance	-Provide clearance options and ultimately potential outcomes of these courses of action according to previous cases (e.g. their delay contribution, etc.)

9. FIGURES

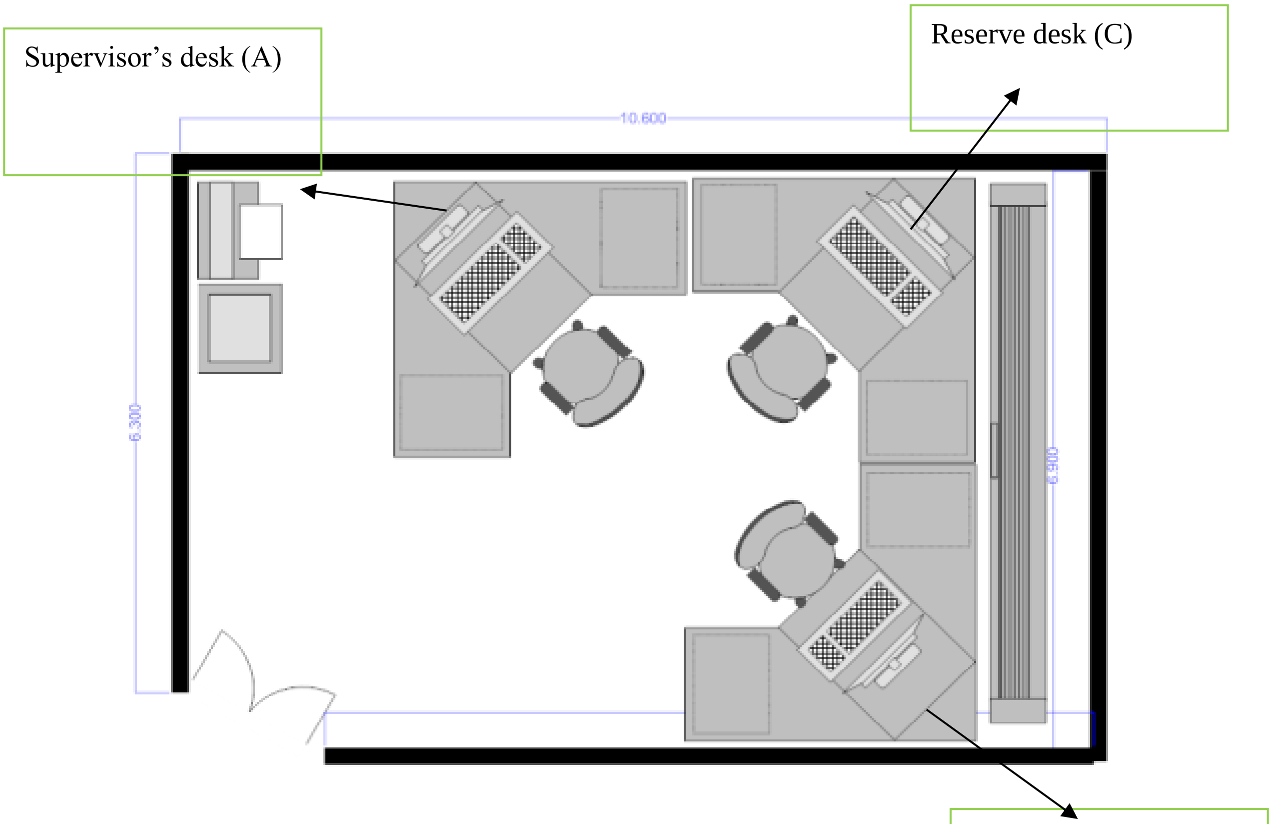

FIGURE 1: LAYOUT OF ECR A

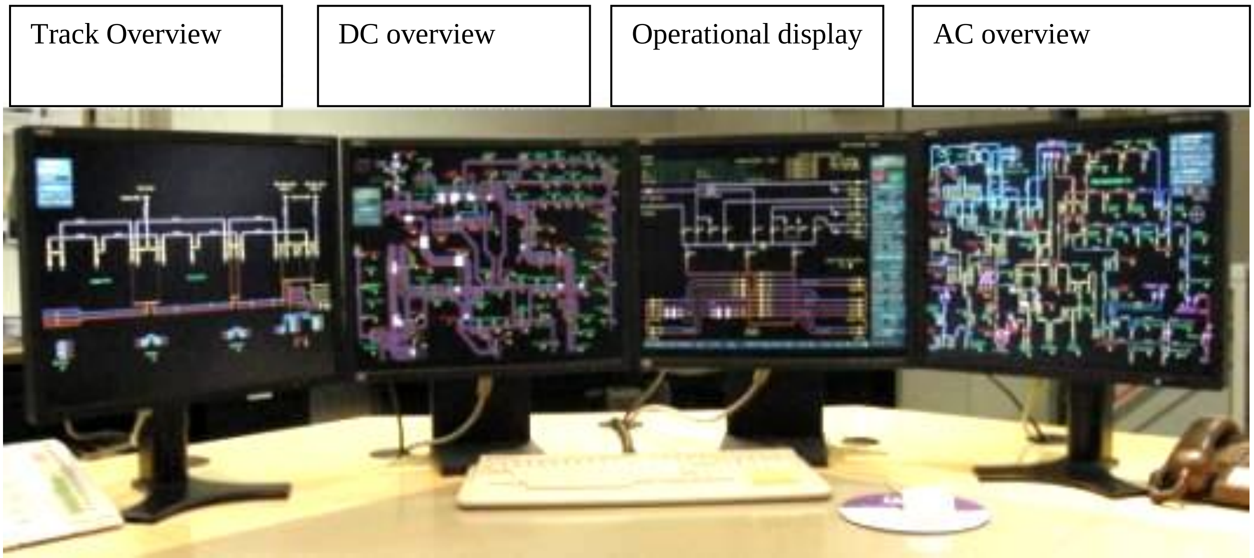

FIGURE 2: ECR WORKSTATION IN ECR A (UK)

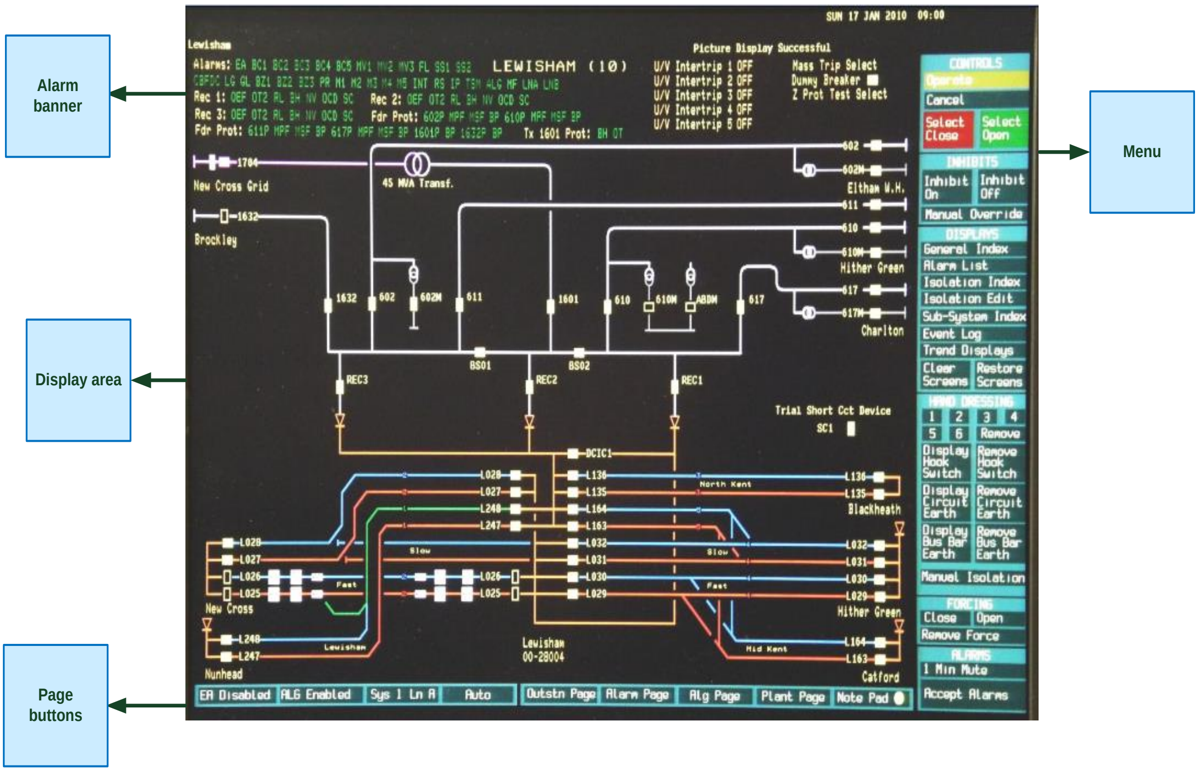

FIGURE 3: OPERATIONAL DISPLAY

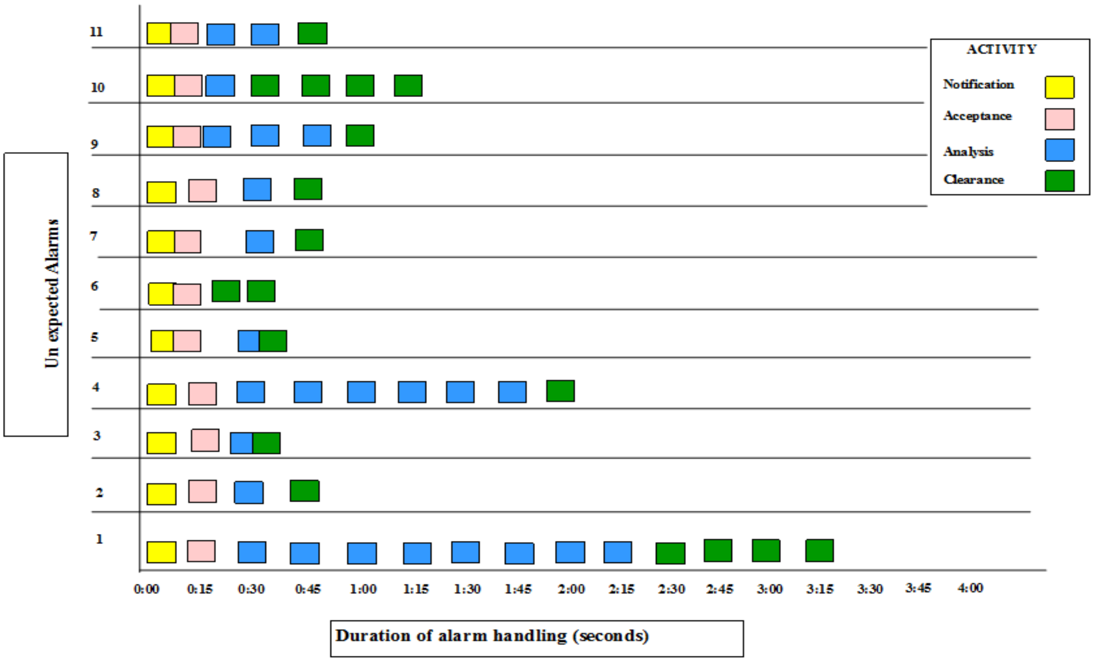

FIGURE 4: ORDER OF ALARM HANDLING ACTIVITIES FOR UNEXPECTED ALARMS

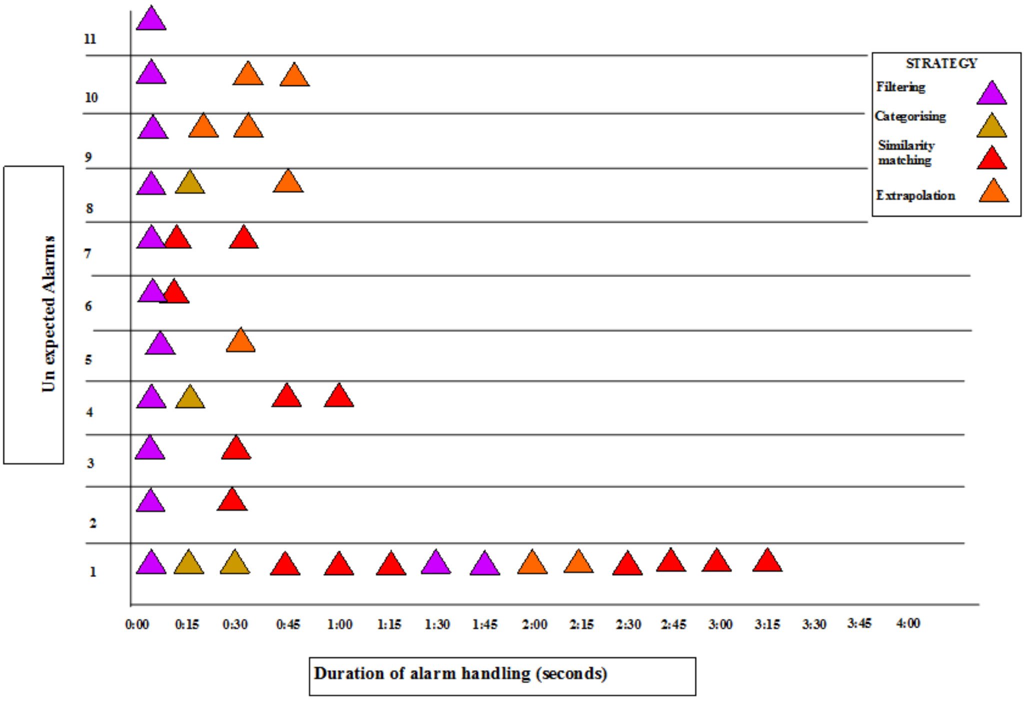

FIGURE 5: ORDER OF ALARM HANDLING STRATEGIES FOR UNEXPECTED ALARMS