Computers and Chemical Engineering 67 (2014) 1–12

Contents lists available at ScienceDirect

Computers and Chemical Engineering

journal homepage: www.elsevier.com/locate/compchemeng

Quantifying the effectiveness of an alarm management system through human factors studies

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ARTICLE INFO

Article history:
Received 9 December 2013
Received in revised form 13 March 2014
Accepted 25 March 2014
Available online 3 April 2014

Keywords:
Alarm management
Process monitoring
Prediction
Process operators

ABSTRACT

Alarm systems in chemical plants alert process operators to deviations in process variables beyond predetermined limits. Despite more than 30 years of research in developing various methods and tools for better alarm management, the human aspect has received relatively less attention. The real benefit of such systems can only be identified through human factors experiments that evaluate how the operators interact with these decision support systems. In this paper, we report on a study that quantifies the benefits of a decision support scheme called Early Warning, which predicts the time of occurrence of critical alarms before they are actually triggered. Results indicate that Early Warning is helpful in reaching a diagnosis more quickly; however it does not improve the accuracy of correctly diagnosing the root cause. Implications of these findings for human factors in process control and monitoring are discussed.

1. Introduction

Modern chemical plants consist of a large number of integrated and interlinked process units. To optimize production, process operators and engineers depend on automation systems to extract information (e.g. through thousands of sensors) and to assist them in the management of operations (e.g. through built-in controllers). Abnormal situations result in process variables moving away from their desired ranges and potentially lead to undesired outcomes. Automation systems will alert the operators of such occurrences through alarms. As process units are highly interlinked, deviations due to an abnormal situation could propagate through various process units and numerous variables. This may lead to many alarms occurring at the same time (Liu et al., 2003, 2004). The operators have to make sense of the barrage of alarms, quickly and accurately identify the root cause of the abnormal situation, and take corrective actions to rectify the root cause and bring the process back under control.

An abnormal situation can sometimes have serious repercussions, including considerable economic impact on plant profitability due to unacceptable product quality, plant downtime, or even the loss of life. Thus, there is a need to develop a dependable system that enables the operators to quickly and correctly diagnose the root cause of the abnormal situation and design and implement suitable corrective action. With early intervention, losses resulting from abnormal situations can be minimized by avoiding the worst case scenario of a catastrophic loss (Burns, 2006). A number of decision support systems have been developed to enable the operators to diagnose the root cause of the abnormal situation.

In order to ensure that the potential offered by such tools are in fact translated to operational benefits, one needs to consider the complementary aspect of human factors. Human factors is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system in order to optimize overall system performance (International Ergonomics Association, 2014). Process control typically entails working in a complex, interactive system involving hardware, software, and humans. The human aspect is widely considered to be very important but paradoxically has received significantly less attention, especially in the process systems engineering (PSE) community. We seek to address this issue in this paper. Specifically, we seek to understand how operators would interact with decision support systems for alarm management and quantify the real benefits through human factors experiments. Section 2 presents a review of alarm management systems and the pivotal role of operators in chemical plants. This is followed in Section 3 by the human factors

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http://dx.doi.org/10.1016/j.compchemeng.2014.03.013
0098-1354/

experimental methodology adopted in this research. Results of the human factors study are presented in Section 4. Section 5 concludes with suggestions on future research work.

2. Literature review

Complexity has been increasing as a result of increased sophistication in chemical processes to allow for larger amounts of material and energy integration, environmental regulation, and the greater need for optimization and efficiency (Chu et al., 1994; Wall, 2009). With this increased pressure to 'do more with less' (Jamieson and Vicente, 2001), effective process control systems are all the more critical to ensure safe and smooth operations. This is often achieved by the application of modern digital technology and increasing automation. However, an unintended consequence of increased sophistication is the greater challenges faced by operators, especially when managing abnormal situations (Chu et al., 1994).

During abnormal situations, there are real risks of operators not receiving important alarm information to take corrective actions in time, which could have potentially serious repercussions. One such incident occurred at Texaco's Oil Refinery, Milford Haven, United Kingdom (UK) and led to the explosion that took place on 24 July 1994, in which 26 people sustained minor injuries. Financial losses resulting from this explosion included 48 million pounds in reparation and substantial losses in production (Bransby and Jenkinson, 1998). It has been reported that in the 10.7 min prior to the explosion, the two operators on duty were flooded by 275 alarms. Apart from this alarm barrage, the UK Health and Safety Executive (HSE) cited poorly designed control display and inefficient alarm prioritization as two of the main contributing factors for this incident. The UK HSE has estimated that a typical oil refinery can avoid three to ten million pounds losses per year through proficient alarm management and better operator support system (Bransby and Jenkinson, 1998).

A number of guidelines have been developed to improve alarm management systems, e.g. by International Society of Automation (2009) and the ASM consortium (2009). Various algorithms and techniques have been developed to reduce the total number of alarms that will be activated (Liu et al., 2003; Srinivasan et al., 2004). Foong et al. (2009) developed a fuzzy-logic based alarm prioritization (ALAP) system to prioritize alarms during alarm floods so as to reduce the burden of operators from meaningless or false alarms. A novel alarm reduction method that involves data-mining to spot the statistical similarities among operations and alarms has been reported by Higuchi et al. (2009). Brooks et al. (2004) deemed the root cause of poor performance of alarm systems to be the single-variable and empirical methods of setting alarm limits. They examined multi-variable alarms and proposed a geometric process control method. These demonstrated a substantial reduction in false alarms in field trials conducted in chemical plants in the UK. Cheng et al. (2013) identified similarities between alarm flooding situations by employing a modified Smith–Waterman algorithm to analyze the alarm flood pattern and cluster similar ones.

Even with automation and improved alarm management systems, human operators still remain irreplaceable in the control of chemical plants, especially during abnormal situations (Parasuraman and Wickens, 2008). The human operator has different roles and responsibilities in the chemical plant that is largely dependent on the plant states (Brown and O'Donnell, 1997; Emigholz, 1996). Under normal operating conditions, the operator is able to assume a relatively passive role in supervising the unit operation with a focus on maximizing efficiency of the process unit by making minor adjustments to the process variables. However, when an abnormality occurs, the operator would need to proactively manage the situation by taking corrective actions to manipulate the process unit back to the normal operating conditions. Automation is less error-prone and can be relied on to produce repeatable actions, but generally fails to address abnormal situations which are likely to be unforeseeable. Nachtwei (2011) noted that in contrast with automated systems, humans have the ability to be flexible and to produce creative solutions in response to unanticipated situations. This ability of the operators to effectively devise solutions for abnormal situations is contingent on their situation awareness.

Situation awareness and human factors have been widely studied in a variety of domains including process control (Endsley, 1988, 1995; Stanton et al., 2001), plant design (Kariuki et al., 2007; Widiputri et al., 2009; Cullen, 2007), and process risk analysis (Kariuki and Lowe, 2006). The key steps in situation awareness are perception of the environment, comprehension of the current situation, and prediction of future status. To support situation awareness, the human factors community has developed experimental techniques for user interface design and evaluation (Kontogiannis and Embrey, 1997; Spenkelink, 1990; Tharanathan et al., 2012; Nishitani et al., 2000). In this paper, we adopt such experimental techniques to study the human factors that affect alarm management. Specifically, we seek to understand and quantify the benefits of decision support tools and evaluate their effectiveness. Although a variety of alarm management tools and techniques have been proposed in literature, their effectiveness has not been systematically studied. The interaction between operators and a decision support tool can only be closely examined through experiments involving human participation as described next.

3. Experimental methods to study human factors

The cognitive tasks performed by an operator during abnormal situations generally follow three steps: orientation, diagnosis and execution (Chu et al., 1994). When faced with an abnormal situation, the operator would first need to orient himself and focus on understanding the particular situation through the search for relevant information. The next step involves diagnosing and evaluating the situation by interpreting the information and relating the data to possible causes of abnormality. This may result in one or many postulated root causes. The execution step refers to the actions taken to verify the malfunction postulations, as well as the corrective actions taken in the attempt to bring the process back to normal. An alarm management system could make the operators more effective in the orientation and diagnosis tasks. We have developed an experimental scheme to evaluate if a decision support tool is effective in improving operators' performance in these tasks. Although the general strategy is broadly applicable to any process monitoring and diagnosis decision support system, we have applied it in the context of early alarm warnings.

Early Warning predicts the time of occurrence of critical alarms before they are actually triggered (Xu et al., 2012). Predictive aids that help users anticipate future system states have been widely used in various domains, e.g. the cockpit display in modern aircrafts that predicts the trajectories of other aircrafts in the proximity and alerts the pilots of any potential conflicts, or hurricane forecast that predicts where an oncoming hurricane will and will not strike. However, predictive aid is still not practiced in the area of alarm management in chemical plants. Early Warning provides control room operators with anticipatory information on incipient alarms that could happen within a certain time window (e.g. the next 60 s). This allows the operators to be more proactive as they are alerted early on potential problems so that they can anticipate, evaluate, and start taking corrective actions even before alarm thresholds are breached.