SITUATION AWARENESS IN PROCESS CONTROL: A FRESH LOOK

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ABSTRACT

We explore the question of how SA would be described if the notion originated from the process control domain. We seek an answer to this question in the literature on the challenges faced, and behaviors taken, by control room operators in relation to situation assessment in process facilities. The literature classifies situation assessment in terms of monitoring activities and reasoning/diagnosis activities with frequent indications of self-regulation. Monitoring leads to the recognition of deviating processes that require dedicated operator attention; reasoning leads to the recognition of the need for operator action as well as the explanation of the process anomalies; and self-regulation leads to the recognition of the need for operators to adapt their situation assessment and control strategies. These three classes of situation assessment activities and resulting awareness could be taken as a new description of SA in process control; one that is unencumbered by prevailing descriptions of a notion borrowed from a different domain. Further, taken as a whole, situation assessment and awareness in process control resembles creative problem solving, which contrasts with the resemblance between Endsley's description of SA and information processing models.

Key Words: Situation awareness, situation assessment, monitoring, reasoning, diagnosis, metacognition, problem solving

1 INTRODUCTION

Situation Awareness (SA) has been a central focus of human factors research and application for nearly two decades. Much of that work draws on Endsley's three levels of SA, which were derived from research in the military aviation domain [1]. Endsley posits three levels of SA: (i) the perception of the elements in the environment within a volume of time and space, (ii) the comprehension of their meaning, and (iii) the projection of their status in the near future. This description is particularly appealing, as perception, comprehension, and projection appear to be integral parts of the information processing model and intuitively necessary for effective decision-making and control actions. While Endsley's description has become the basis for SA research and application in many domains, the interpretation of each SA level – and the anecdotes used to describe SA - vary from domain to domain. SA is referred to as “the picture” in air traffic control (e.g., [2, 3]), “the plot” in rail traffic control (e.g., [4]), and “the overview” in process control (e.g., [5]). The variations in SA interpretations and anecdotes raise an interesting hypothetical question: If the SA notion had originated in the process control domain (as opposed to military aviation), how might it have been described?

We explore this question by reviewing (i) the system and control properties of process plants that frame the discussion about the cognitive work of process operators, and (ii) the literature on the challenges faced and behaviors taken by control room operators related to situation assessment (i.e., activities conducted to acquire situation awareness). By examining the domain properties and operator behaviours, we hope to conceptualize SA in domain-relevant terms that can guide practitioners and researchers towards the most pertinent challenges faced by process operators.

2 PROCESS PLANTS AND PROCESS CONTROL

The properties of process plants and the types of control action available to operators are critical to understanding situation assessment in process control. Examining system properties illustrates the ecology or problem space managed by the operators; whereas, reviewing the types of control actions highlights the solution space available to the operators (e.g., [6]). In essence, SA characteristics are necessarily dependent on system properties and control actions available to operators.

2.1 Process Plants

The properties of process plants are the source of many work demands on operators, thereby shaping their behaviour and defining the SA needed to operate the plants. (For a brief overview on process control, also see [7, 8] and Chapter 13 of [9]).

Process plants are *causal* systems that convert raw materials into products in large quantities continuously[1], through coordinated processes. Thus, central to the design of process plants are the causal relationships upon which the engineered components and processes are based to produce desired effects on the raw materials and intermediate products.

The engineered processes (e.g., condensation, heat transfer) are typically represented in *abstract* forms such as scientific principles and equations (e.g., thermodynamics, conservation of mass), or in *analogies* to the physical phenomena (e.g., spring-and-ball model of chemistry; also see [10]). In contrast, other domains may permit more concrete representational forms such as the spatial-temporal representation in air traffic control.

The *scale* of process systems is typically very large, containing thousands of inter-connected hardware components arranged to support dozens of engineered processes. At this scale, even highly reliable equipment cannot eliminate occasional component failures. Most process plants continue to operate through component failures safely and efficiently because of redundant safety features. However, failures still lead to safety and efficiency implications, or even accidents.

Automation plays a significant and active role in process systems. There are many automation components installed throughout the plants, many of which are complicated and hidden (e.g. [11]). These components act on the system continuously to maintain or optimize steady state operations seamlessly for intended/expected circumstances. Many components are based on complex algorithms that integrate numerical data and issue control signals at speeds and levels of precision beyond the computational capability of human operators. However, automation may not adequately handle some transient and abnormal operations that are not part of the design considerations. Moreover, automation components can

[1] Discrete and batch processing plants are excluded from the present discussion.

fail; sometimes gracefully in circumstances within the design basis, and sometimes catastrophically in circumstances beyond the design basis.

The many different equipment and automation components are *tightly coupled* (or inter-connected) in process plants. Changes or impacts to any component almost always affect other parts of the system. The tight coupling between many hardware and software components results in a very high level of complexity for process plants. For the purpose of the dissertation, *complexity* refers to the integral effect of scale, automation and tight coupling.

Given their complexity, process plants are substantial capital investments and typically have a *lifespan* of several decades to be economically viable. Long time spans, compounded by complexity, impose a limit on designers and engineers identifying and planning for possible events. For example, some nuclear power plants have recently been licensed to increase power production (i.e., uprates) and extend service-life beyond the initial regulatory approval [12]. Such significant changes to the expected plant operations and life-cycles were not considered by engineers at the design stage over three decades ago.

Process control systems possess two other notable technical characteristics. First, the process changes and control responses are typically *slow* in comparison to other domains (e.g., aviation) because many of the engineering processes, such as mass transfer energy exchange, are unstable or inefficient under fast conditions. Second, all processes and instruments fluctuate to some degree, sometimes in very complex manner, generating nuisance variations or *noise*.

Process plants operate *continuously*, resulting in two operational characteristics. First, many activities including testing and maintenance must occur while plants are in operation. For example, operations continue if component failures do not pose risks to safety or product quality. Second, operational states (e.g., production level as a result of demand) and other activities (e.g., maintenance) can vary on both regular and irregular bases. Because of varying operational states and parallel activities, "normal" or expected values of many instrument readings can vary significantly. For example, values of some process parameters considered normal during full capacity, steady state operations might be considered emergency values during start-up. In essence, operating states are rarely fully pre-defined.

Process plants are *designed as closed systems*[2] for full capacity and steady state operation, leading to another key operational characteristic. The joint functioning of equipment and automation within the plants governs the safety and productivity of the process. Full capacity and steady state operation are safest and most productive. Disturbances to process plant operations are most commonly internally driven, whereas stresses on comparatively open systems (e.g., air traffic control) are mostly externally driven. In air traffic control, for example, productivity and safety depends very much on varying traffic loads and patterns that are dictated (at least in part) by external factors such as weather.

The properties of process systems yield insight into the characteristics of situations faced by process operators. In brief, operators must cope with large numbers of tightly coupled components and automation. They need to manage closed (but large-scale), causal systems with plant processes that are mainly represented by abstract scientific principles or concepts analogical to the physical phenomena in the processes. The operators must account for the slow, noisy and continuous nature of process dynamics. They must also adapt to operate the plants in events or circumstances that are unexpected by the designers. Thus, SA in process control must reflect operator adaptation to the properties of process plants.

[2] Process plants are not completely closed systems. For instance, significant changes in the environment such as temperature of the natural cooling sources for a power plant do affect operations. However, environmental shielding is generally incorporated into system design to minimize external effect on steady–state operations. Process plants are also designed to contain the process as much as possible for preventing release of substances, which are typically harmful to the environment (such as radiation and toxic materials).

2.2 Process Control

Performing control actions that optimize safety and productivity is the most critical role of process operators[3]. From this perspective, process operators may be considered as control components with human as opposed to engineered characteristics (see e.g., [13-15]). Thus, the control behaviours undertaken by operators to ensure safe and efficient operations can be illustrative of work demands in process plants, thereby revealing characteristics of SA in process control. Multiple schemes may be suitable to classify operator control behaviours. For the purpose of understanding situation assessment and awareness in process control, operator actions are classified into three types according to the control needs of process plants. (For general reviews, see [9, 16, 17].)

Production control actions are taken to change system states (e.g., start-up to full capacity) and optimize productivity and safety during normal and expected operations. Major changes to system states are generally carried out according to procedures and/or carefully considered plans developed by operators and engineers together. Optimization is typically carried out by minor set-point adjustments according to operator judgment.

Compensatory control actions are taken to compensate for process faults or anomalies such that any deterioration of plant production, safety and equipment is minimized. Compensatory control does not eliminate the process faults themselves. For many complex process faults, operators must react without a complete understanding of the fault causes.

Corrective control actions are taken to eliminate process faults or anomalies such that the plant returns to normal operations. Corrective control, therefore, occurs after identifying the causes of the process faults and anomalies.

The types of control actions illustrate the potential contribution of operators towards safety and productivity of plant operations in various situations. In summary, during normal operations, process operators execute control actions according to plans or procedures and to optimize plant safety and production. At the same time, they must be capable of switching to compensatory and corrective controls. During abnormal or unexpected operations, process operators must compensate for the process faults and perform corrective actions that eventually transition plants from abnormal to normal operations.

2.3 Summary

The properties of process systems and types of control form the basis of interactions between the plants and operators. The properties of process systems are indicative of the system influences on the operators, whereas the types of control are illustrative of operator influences on the system. Therefore, the situation assessment activities are performed in response to the properties of process systems and the types of control action available to the operators.

3 SITUATION ASSESSMENT IN PROCESS CONTROL

The properties of process plants allude to the substantial challenge of acquiring situation awareness to support operator control behaviours. Nevertheless, operators establish a set of activities to acquire awareness of plant operating conditions. The publications on process control tends to organize research into three classes of situation assessment activities – (i) monitoring, (ii) reasoning and diagnosis, and (iii) self-regulation – that lead to effective control actions. Examining these activities illustrates the challenges faced, and cognitive solutions developed, by process operators to acquire SA that guides their control actions given the problem space (i.e., domain properties) and solution space (i.e., available controls). Therefore, SA for process control needs to reflect the characteristics of operator situation assessment.

[3] Process operators have other responsibilities that do not involve control actions. For instance, operators often participate in planning of maintenance activities. Also, the relative importance of safety and production goals varies by type of process facility,

3.1 Monitoring

Monitoring is a set of activities performed by operators to acquire information about the operating states for the purposes of initiating further cognitive processes and control actions. Process operators rely on a diverse set of activities and information sources to acquire knowledge about the plant operating states (e.g., [9, 18-22]). Operators begin their shifts by conducting a shift turnover – a briefing on plant operating conditions between operators coming on duty and those being relieved. The shift turnover communicates the plant status, activities completed and outstanding, and other special circumstances. In addition to shift turnovers, operators review logs – chronological records of significant activities (e.g., tests completed, component failures) – to gain knowledge of recent plant status. Operators conduct panel walkthroughs surveying process parameters to gain a "process feeling" in addition to making observation on specific process parameters and alarm displays at their workstations. Operators often communicate with field operators and occasionally conduct field tours to collect information about the operating states outside the control room. Operators also participate in maintenance and testing work that requires proactive information gathering and processing. In summary, *active search for information*, as opposed to passive discovery of deviations, dominates much of process plant monitoring.

The literature highlights three aspects of process monitoring that illustrate active search for information. First, operators engage in myriad set-up activities before and during a shift (e.g., shift-turn overs) to build and maintain operating contexts in order to facilitate sampling and observation of process parameters and alarms. The need for building operating context for monitoring is evident from the technical and operational properties of process plants. Complexity, lengthy life spans and continuous operations of process plants limit control room interface design from capturing the knowledge of context (c.f., cognitive underspecification [23]). As mentioned, instrument readings considered appropriate for one operating state can be deemed dangerous for another and thus can only be interpreted in context. Furthermore, process plants often operate through component failures. Some of these failures may lead to plant operations that are unanticipated or even unintended in the system design (c.f., [24]). Lengthy lifespan further contends that operational circumstances could gradually depart from the expectation of system designers. For instance, some systems may undergo testing in a manner unaccounted for by designers; hence, control room panels sometimes present abnormal instrument readings. However, these abnormal instrument readings and alarms do not indicate emergency situations but rather the status of testing activities [20]. In other words, operational circumstances in practice are not identical to those postulated during system design, typically to the extent that engineers often cannot operate process plants without substantial operational training like professional operators [25]. For this reason, rarely can interface designers specify - and process displays present - all necessary information in any given operating circumstances. Consequently, process operators take the initiative to obtain the contextual information that supports the interpretation of process parameters and alarms (and to organize other operational activities such as equipment testing). In summary, building operational contexts is an adaptive behaviour to cope with the limitations of control room information system and interface, some of which cannot be anticipated during the design stage due to the lack of operational knowledge.

Second, operators habitually employ a top-down approach to sampling process parameters and automation indicators based on the operating contexts [19, 26]. Bainbridge et al. [27] further argue that self-directed sampling is an inherent part of expertise. The scale of process plants prohibits continuous, comprehensive and reliable sampling of all process parameters [7]. In addition, effective monitoring must account for the effects of automation that are constantly acting on the process. For instance, experienced operators not only inspect process parameters with respect to set points but also check for the possibilities of masking by attending to behaviours of the slave devices governed by automation [28]. Finally, tight coupling between components further necessitates interpreting any process parameter in relation to several others. Nevertheless, process operators can also rely on tight coupling to sample a subset of process parameters that could be sufficiently indicative of process states. In essence, operators are always deciding what process areas should be prioritized for closer observation and how one observation made in relation to the operating contexts could inform subsequent monitoring behaviours.

Finally, operators perform substantial information processing to account for the behaviours of plant processes, instrumentation and automation in the given operating context. Noise in instrumentation implies that some changes in process parameters are not significant (e.g., [29, 30]). Furthermore, the dynamics of the process (as depicted by various parameters displayed in the operating panels) complicate the differentiation between nuance fluctuations and true deviations. For instance, many processes respond slowly to control actions and some parameters change in complex manners (e.g., stepwise function) obscuring the true states or behaviours of processes. The unique operating contexts (e.g., maintenance activities) often shape part of the parameter behaviours at a given time. For these reasons, normative values or actions satisfying all circumstances rarely exist, and both normal or abnormal parameter changes could be difficult to determine [9]. The complex process dynamics also imply that precise prediction of individual process parameter values is unrealistic. Alarms in process plants exemplify the challenges in managing process dynamics across varying contexts. Some alarms alert operators to real hazards of the process while others only to nuisance fluctuations. These alarms are conventionally classified as true and false/nuisance alarms, respectively, according to signal detection theory [31]. In some contexts, certain alarms provide information that cannot be classified as either true or false alarms [32, 33]. For example, maintenance or testing activities could lead to alarms that inform operators about the progress of certain activities rather than hazards of certain processes (see [34]). Hence, viewing alarms that are intended to identify “known” hazards requires considerable operator judgment. Monitoring of process parameters is, therefore, not a vigilance task of checking whether variables are within some predefined limits that directly lead to conclusions about plant states (also see [35]).

Field and representative simulator studies illustrate that operators engage in many activities to manage the challenges of monitoring process plants. Operators constantly build and update operating contexts to direct their sampling and interpretation of process parameters and alarms; they apply a top-down approach to actively search for relevant information in order to cope with the complexity; and they exhibit considerable information processing and judgment in deciphering meaningful parameter changes or deviations according to characteristics of plant processes. Taken together, the fundamental challenge of monitoring is “not how to pick up subtle abnormal indication against a quiescent background; rather it is how to identify and pursue relevant findings against a cognitively noisy background” [20].

3.2 Reasoning & Diagnosis

Reasoning (and diagnosis) is a set of situation assessment activities performed by operators to establish the rationale or basis for engaging in certain control behaviours. Process operators employ a wide range of cognitive mechanisms to reason about control needs of process plants (e.g., [17, 19, 21, 36-38]). Many of the findings on process operator reasoning are drawn from verbal protocol studies, accident investigations and control actions. This contrasts with findings about monitoring, which includes primarily observable information gathering activities (e.g., panel walkthrough). The significant reliance on self-reported information about reasoning is inevitable because both the inputs and outputs of reasoning are mental representations (i.e., information or knowledge) and the cognitive processes are unobservable. Despite methodological limitations, there is substantial convergence on many aspects of operator reasoning, providing a basis to conceptualize situation awareness in relation to the design properties and operator controls of process plants. In the literature, the dominant theme for reasoning in process control is the *creative application of system knowledge or mental representations*, as opposed to mechanistic processing of plant indicators.

The literature highlights five characteristics in reasoning about control needs of process plants that illustrate creative application of mental representations. First, operators rely extensively on domain/system knowledge – more specifically, a priori internal (mental) and external representations of the process plants. Process operators develop mental representations about the plants through training and experience [e.g., 38]. These system knowledge and mental representations may range from simple heuristics to formal scientific principles governing cause-and-effect relationships between variables [e.g., 39]. Further, external representations or artifacts of the plant such as procedures are common aids in operating process plants. Internal and external representations of the process plants are useful for reasoning about control needs because process plants are closed, causal systems (see Section 2) in which events and behaviours are internally rather than externally driven. These representations are also employed for top-down approach to monitoring. Furthermore, the physical designs of process plants and engineering principles governing the coordinated processes are (almost) static while operators have full control over the equipment set-points. For instance, operators frequently employ detailed procedures and carefully developed plans for any major changes to operations. Such procedures and plans are more practical for closed systems than open systems (which may fluctuate due to external influences). Procedures and plans can reduce cognitive demands on operators during operations as control needs are reasoned and specified a priori. In summary, representations of process plants are useful for interpreting system events and assessing intervention needs during plant operations.

Second, process operators maintain many plant representations to fully characterize the coordinated engineered processes but only employ subsets of those representations to characterize the situations (e.g., [17, 40]). As mentioned, a process plant typically involves many coordinated engineering processes, which are governed by different scientific principles and depicted by different representations. For instance, in a NPP, operators may analogically represent the fission process as splitting physical objects and the heat exchange process as transferring fluids. Conceptually, there is no single representation that is useful for reasoning about process states or anomalies in all situations. For instance, [41] applies the abstraction hierarchy, a multi-level knowledge representation modeling tool, to explain the utilities of different system structural perspectives in his observation of operators performing troubleshooting. Further, the scale of process plants prohibits process operators from maintaining a mental representation that covers the entire plant [40, 42]. Thus, operators select amongst representations of the process plants that are relevant for the situations. Note that the reasoning space is very large due to the scale of process plants even though they are closed systems. In summary, process operators rely on many plant representations to account for the diverse set of engineered processes but employ only a subset during operations.

Third, process operators exhibit multiple modes of information processing using different representational forms when reasoning about control needs of a process plant[4]. In the context of process control, the Skills, Rules, and Knowledge (SRK) taxonomy [43] is a fitting description of different forms of knowledge representation and corresponding types of cognitive processing (or, to be precise, levels of cognitive control). In familiar circumstances, operators tend to engage in Skills-based (SBB) and Rule-based behaviours (RBB), which are more automatic and less cognitively effortful than Knowledge-based behaviours (KBB). In relation to reduced cognitive effort, SBB (e.g., pattern matching) and RBB (e.g., heuristics, procedures) are necessary to manage the complexity (i.e., scale, coupling and automation as described in Section 2.1) of process plants [17]. Though efficient, SBB and RBB are bounded by the repertoires built from training and experience, and therefore, less effective during unfamiliar situations. In such circumstances, operators engage in KBB, which involves conscious and analytical thinking, to maintain or return the plant to a normal operating state [16, 42]. In brief, operators exercise multiple modes of information processing to reason the control needs of process plants. The cognitive work may vary from being (relatively) effortless as in following familiar procedures during expected operating cognitions to being strenuous as in analyzing causal and topographical relationships between equipment during unanticipated events.

Fourth, process operators often exhibit non-linear, even convoluted, reasoning frequented by errors and error recoveries. Due to the complexity of process plants, the exact nature of the operating situations,

[4] For instance, the characteristics of a process may be expressed as a mathematical equation for symbolic processing but also as a graph for visual processing.

especially abnormal ones, is often not apparent to operators (e.g., [20, 44-46]). Consequently, operators often need to correct or refine their selection and combination of plant representations to support interpretation of process states or observations (see above). Verbal protocol and knowledge elicitation studies indicate that operators often switch between multiple sequences of thoughts or thought streams [27]. Operators are also inclined to revise their diagnostic heuristics once verbalized [28]. Further, the propensity to engage in SBB and RBB is conducive to mis-application of expertise as operators try to circumvent KBB [47, 48] In effect, operators often need to correct their use of plant representations during reasoning. From a normative perspective, these detours from the "ideal" reasoning route are considered "errors" but are frequently compensated by the "error recovery" capability of operators (e.g., [49, 50]). Given this error recovery ability, operator error is difficult to define [51, 52]. [17] further argues that some errors are means to learning, adaptation and eventual solutions. From this perspective, errors themselves are less of a threat to reasoning than the failure of error recoveries. In essence, reasoning in process control often involves iterative refinement of the initial selection and combination of plant representations for interpreting process states or indicators.

Finally, process operators orient their reasoning according to *different, and sometimes competing, control needs of the plant* (see [16, 17, 53] and types of controls in Section 2). To support production control, operator reasoning involves predicting potential production outcomes and anticipating familiar process events. This allows them to gain awareness about the transitioning stages of the process that are ready for planned control actions (e.g., next step in procedures) and suboptimal parts of the process that require intervention. To support compensatory control, operator reasoning involves interpreting operating conditions to gain an awareness of any threats to plant health, safety and productivity that need immediate interventions. Often, operators perform compensatory controls without full understanding or knowledge of the situation (i.e., diagnosis of process anomalies) because diagnosis takes time that could lead to violation of safety or operational limits unless intervention is made. Further, many faults (e.g., a stuck valve) in process plants are not predictable. To support corrective control, operator reasoning involves investigating past process events to gain awareness about the process faults that must be eliminated to reinstate steady-state operations. For complicated process faults, reasoning to support compensatory control to stabilize the system could either complement or compete with reasoning to support corrective control [16]. There appear to be no clear criteria for directing orientation of operator reasoning towards any particular type of control, probably because of the dependency on the unique situation and operator interactions [47]. For instance, some operators prefer a conservative approach of engaging in compensatory prior to corrective control to stabilize the systems until corrective control actions can be determined (i.e., so-called "safe-park" strategies). However, other operators may proceed to corrective controls directly. Both or either approach may be appropriate depending on the competence of the operators as well as the situation. In essence, the control needs of the process plants mandate different orientations of operator reasoning and thus different awareness contents.

In summary, qualitative research and representative simulator studies elucidate the nature of operator reasoning in process control. To manage the complexity of closed and causal systems, operators rely extensively on a large repertoire of internal and external plant representations (i.e., system knowledge) to support reasoning. Given the complexity, operators use multiple modes of reasoning to trade off between efficiency and accuracy. Though many representations characterizing the entire process plant may be available to support reasoning, operators can only employ a subset at a given moment due to cognitive limitations and plant complexity. Finally, reasoning most likely proceeds in a non-linear fashion in order to meet multiple, and sometimes competing, control needs of process plants. Taken together, the fundamental challenge of reasoning is not how to process a large quantity of indicators given a finite set of predefined functions that determine their meanings; but rather how to simulate the operating situation using plant representations for interpreting a set of relevant process indicators and identifying control needs of the plant.

3.3 Self-regulation

Self-regulation is a set of situation assessment activities performed by operators to determine their own contribution to, and control of, the situation. Process operators demonstrate self-regulating cognitive activities to be part of managing challenging situations; however, research on regulating cognitive activities or metacognition in process control is very limited [54]. The literature on situation assessment chiefly attends to monitoring and diagnosis with respect to engineered components and processes of the process plants. From a systems perspective, operators are in fact a control component, and thus, a part of the situation that requires monitoring and regulation. Despite the lack of research attention, accident investigations, field studies and research discussions (e.g., [46, 47, 55, 56]) repeatedly allude to various self-regulating activities (or failure there of) indicating that *operators include themselves as part of their situation assessment*.

The literature contains successes and failures in managing novel and evolving situations that illustrate the need for operators to determine and regulate their own cognition. Operators frequently adapt their cognitive activities to control the plants effectively. Two prime examples are workload and procedure adaptations. When the process enters into disturbance or transient, operators defer tasks that do not have immediate safety or productivity impact and, thereby, moderate their workload (e.g., [20]). In representative experiments that intentionally introduced multiple simultaneous faults, operators prioritize their attention towards parts of the process posing greatest threats to the plant [56, 57]. To moderate workload, process operators assess their control ability as part of the situation to support decision-making and control actions. When procedures and plans are employed to transition or stabilize the plant, operators often deviate from some pre-defined steps in adaptations to the situations (e.g., [6, 46]). Some of these deviations reflect shifts in work strategy from executing specified control actions (RBB) to developing untried solutions (KBB). To adapt procedures, operators assess their performance while executing the procedural steps and altering their cognitive strategy appropriately for the situation. In essence, process operators monitor and reason not only about the conditions of the engineered process and equipment but also about their control ability and effects on the system.

Process operators, on occasion, fail to adapt to novel situations. Inadequate self-regulation is one of the many factors leading up to major incidents. In the Three-Mile Island [45], the operators were fixated on possible “pipe-bursts” from excess coolant in the primary system that were to be avoided according to their training [58]. Thus, they reduced coolant flow to the reactor, when, in reality, the reactor was experiencing a loss of coolant (an unanticipated event) as a result of a stuck-opened valve. This course of reasoning and control actions continued for approximately three hours until a shift supervisor coming on duty diagnosed the problem. In this accident, the operators did not acknowledge any failures in their plant monitoring and diagnosis (i.e., their own cognitive performance) that would have prompted them to alter their information processing. In essence, operators must monitor and regulate their cognitive work to detect and recover from their own “errors” that could undermine their goals and further jeopardize plant safety.

Field research and accident investigations suggest that self-regulating activities are an essential part of situation assessment in process control, especially in challenging operating conditions. The juxtaposition of successful and unsuccessful adaptive behaviors illustrates how operators are part of the system dynamics. Like automation, they can either stabilize or disturb the process. Operators must assess their control ability to avoid circumstances that could result in high uncertainty of their control performance. Operators also assess their work strategy periodically to detect cognitive and control errors that could prompt for correction and error recovery. In essence, situation assessment is incomplete without consideration of the dynamics introduced by the operators who monitor and regulate their own cognitive activities as well as plant equipment and processes.

4 IMPLICATIONS FOR SITUATION AWARENESS IN PROCESS CONTROL

Research in the process control domain generally examines situation assessment in terms of monitoring and reasoning/diagnosis that directly connect to self-regulation. When monitoring, operators build operating contexts, perform top-down sampling of process parameters, and engage in information processing to identify the plant processes that require operator reasoning and/or control action. Monitoring, therefore, has more to do with active exploration of plant operating integrity than sampling and vigilance of process parameters. When reasoning, operators apply a subset of plant representations in their repertoire, switch levels of cognitive control, and amend their initial applications of plant representations to identify need for operator intervention to achieve steady-state operation. Reasoning, therefore, is more about problem representations of process operations or faults than laborious computation of process parameters. When self-regulating, operators examine the interaction between their strategies for plant control and the operating conditions (from monitoring and reasoning) to identify their own behaviors that require modification in resolving the process events. Self-regulation, therefore, indicates that operator behaviors are as integral to the situation as process and equipment operations. Taken as a whole, the literature illustrates that situation assessment in process control resembles creative problem solving.

The three classes of situation assessment activities in process control have two implications for studying situation awareness. First, the three classes of situation assessment activities could become the basis for formulating SA components from the perspective of a domain operator as opposed to an abstract psychological perspective. From the former perspective, the SA component conceptualized according to monitoring could be defined as the recognition of deviating processes that require operator attention. The SA component conceptualized according to diagnosis could be defined as the recognition of control needs of the process plant as well as the explanation of the process anomalies. Finally, the SA component conceptualized according to self-regulation could be defined as the recognition of the need for adapting situation assessment and control strategies. The main advantage of this approach is that such SA components are defined according to specific domain properties and work challenges that resonate with operators as opposed to abstract environmental and psychological constraints that are conceived in research. SA components attending to domain-specific properties and challenges are expected to provide concrete guidance for the design of operations centers and the assessment of operator performance. Future work is necessary to describe and test such SA components in detail.

Second, the three classes of situation assessment activities indicate that SA in process control is driven by creative problem solving rather than information processing, which contrasts with Endsley's model of SA at the conceptual level. Problem solving research attends to the identification of structural properties and integrity, iterative representation of problem spaces (based on structural properties), and regulation of cognition that characterizes the biggest challenges faced by process operators in situation assessment. The information processing model does not account for these challenges well, favoring other cognitive issues. A cursory explanation for problem solving research to be particularly suitable for process control is that process plants are designed according to control theory; thus, the cognitive task is the representation of control-loops to inform control actions. On the other hand, information processing research appears suitable for systems driven by external demands in a well-defined problem space, such as air traffic control, where the cognitive task is sampling and computation in order to attend to fluctuating demands. The difference between the problem solving and information processing perspectives in supporting SA and human factors research warrants further investigation.

5 CONCLUSION

We have explored the question of how would SA be described if the notion originated from the process control domain by reviewing (i) the system and control properties of process plants that form a basis for the discussion about the cognitive work of process operators, and (ii) the literature on the challenges faced, and behaviors taken, by control room operators related to situation assessment. The literature classifies situation assessment activities in terms of monitoring and reasoning/diagnosis with frequent indications of self-regulation. Monitoring involves gathering contextual information, top-down sampling of process parameters, and substantial information processing. Reasoning involves application of plant representations, switching levels of cognitive control, and amending initial applications of plant representations. Self-regulation involves examining the interaction between an operator's own operating strategies and the operating conditions. The descriptions of these three classes of situation assessment activities provide a new basis to formulate components of SA in process control. Formulated with respect to the situation assessment activities, the awareness acquired through monitoring is the recognition of deviating processes that require dedicated operator attention; awareness acquired through reasoning is the recognition of control needs of the process plant as well as the explanation of the process anomalies; and the awareness acquired through self-regulation is the recognition of the need to adapt their situation assessment and control strategies. *These three classes of situation assessment activities and resulting awareness could be taken as a new description of SA in process control that is unencumbered by prevailing descriptions of a notion borrowed from a different domain.* Taken as a whole, situation assessment and awareness in process control resembles creative problem solving that involves active exploration of structural properties and integrity, iterative representation of problem spaces (based on structural properties), and self-regulation of these cognitive activities. This stands in contrast to the resemblance between Endsley's description of SA and information processing models, and thereby presents a new perspective to explore SA across similarly characterized domains. It remains to be demonstrated that the alternative description described here yields insight into the design of operations centers and the assessment of operator performance.

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