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Operator Decision Strategies in Nuclear Control Centres: A Domain-Specific Information Flow Map

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Nuclear power plant control room operators respond to accidents by following detailed emergency procedures. At the same time they ensure the procedures match the accidental situation, especially with unanticipated conditions due to multiple failures, automation disturbances, or unreliable indications. Operator adaptation thus allows the system to respond to unanticipated conditions. The engineering problem with adaptation is how to design and evaluate technology, training and work processes that support the decision strategies people may use when acting adaptively. Designs that do not consider flexible strategy choice will not support operator cognitive demands for the complex tasks that are not automated. Human reliability analyses that do not identify the strategies used in unanticipated conditions will not correctly assess the risks. Operators' strategies can be discovered through cognitive task analysis (CTA), for instance by performing a formative strategy analysis. Yet to date formative strategy analyses have been relatively neglected and are not often applied. Without CTA the task analysis will provide normative support for "the one right way to accomplish the task", instead of tailored support to several viable and effective strategies for context-specific, unanticipated situations. This paper proposes an information flow map for emergency operation in nuclear control centres. This may facilitate the performance of CTA and thereby the ability to design systems capable of supporting operators' adaptation to unanticipated situations.

Keywords: Decision-making, strategies, flow-map, emergency, procedures, nuclear, adaptation.

1. Introduction

Discretionary decisions are observed in all professional fields, including safety-critical industries like nuclear power plants. Multiple failures, automation disturbances, unreliable indications and human errors are almost always part of the causal explanation of industrial accidents. Safety critical systems are designed against these factors as long as their estimated likelihood of occurrence exceeds given thresholds. Beyond that there are operators and other emergency decision makers that 'complete' the design. Operator adaptation, that is, on the fly diagnosis and decision-making "outside the books", allows systems to respond to unanticipated conditions. The more a human-technology system is affected by external factors, or by internal factors not accounted for at design, the more necessary it will be to adapt or to deviate from "the one best way" embedded in procedures and work orders. A task for designers of modern safety-critical systems is therefore to support workers' adaptation to unanticipated situations.

Designing for adaptation is about technology, training and work processes that support the decision strategies people normally use, or may use, when acting adaptively. It includes supporting flexible strategy choice for cognitive demanding tasks that are not, and should not, be automated. Likewise, decision strategies used in unanticipated conditions need to be identified if risks are to be correctly assessed.

While we are quite good at solving the classical human factors problem of identifying "the one right way to accomplish the task" and supporting the operators performing it, our methods for providing tailored support to several viable and effective strategies that workers may need in context-specific and unanticipated situations are far less developed.

2. Cognitive Task Analysis

Cognitive task analysis (CTA) is the main tool for identifying the decision strategies operators use, or may use, in their work.

CTAs are observation, interviews, or simulation techniques for obtaining descriptive characterizations of how practitioners perform their work tasks and achieve their goals. They reveal the knowledge, the skills, and the cues attended to by the practitioners, as well as their challenges, suboptimal practices, and potential vulnerabilities (Crandall & Hoffman, 2013). CTA is most often used for analysing existing systems. For future systems the strategies need to be identified analytically. Formative strategy analysis (Rasmussen et al., 1994; Vicente, 1999) for instance, discovers the decision-making strategies and how control tasks can be performed by "activity analysis in work domain terms", "heuristic decision making" and "mental strategies" analyses.

Although formative strategy analyses have been conducted for design of interfaces, teams, training, and automation in different domains (Austin et al., 2022; Hilliard & Jamieson, 2017; Naikar, 2017; Burns & Bisantz, 2016; Bisantz & Burns, 2009; Kim & Seong, 2006; Burns & Hajdukiewicz, 2004) it remains relatively neglected and it is not often applied (Cornelissen et al., 2011). Without these stages one risks ending up the analysis with normative support for "the one right way to accomplish the task", instead of providing tailored support to several viable and effective strategies that workers may need in context-specific, unanticipated situations (Vicente, 1999).

CTA, and particularly formative task analysis, is not often performed because it requires multidisciplinary resources that are not always available to system engineering or risk assessments projects. In addition, key aspects of the methodology as the information flow maps (Rasmussen, 1986) are not widely understood and used, even by the methods' practitioners.

This paper proposes an information flow map that is specific to the domain of nuclear control room operation. The domain specificity of this information flow maps can facilitate the performance of CTA in similar domains, and thereby the ability to design systems capable of supporting nuclear control room operators' adaptation to unanticipated situations.

3. Cognitive System Engineering

Information flow map is a concept introduced by Cognitive Systems Engineering (CSE) to describe mental strategies in a way that could be used for design of operator support systems (Rasmussen, 1986). CSE stems from research at the Risø National Laboratory (Denmark) during the 1960s' and 1970s' when the Electronics Department worked at the human-machine aspects of the planned Danish nuclear reactors' instrumentations and controls. Apparently, it was not until the early 1980s' that CSE was first described in a publication (Rasmussen, 1986). However, since then the CSE group was already diverging towards two independent leads. The one headed by Eric Hollnagel and David Woods emphasised foundational themes and insisted on a joint system perspective, that is, the view that contemporary human-machine systems were to be designed and analysed in terms of joint cognitive systems, systems of humans and machines acting in common to achieve common ends, rather than in terms of the interactions between humans and machine components (like in human-interface interaction or usability engineering) (Hollnagel & Woods, 2005; Woods & Hollnagel, 2006).

The other school was represented by Jens Rasmussen, L. P. Goodstein, and other at Risø (Rasmussen, 1986; Rasmussen et al., 1994), and was later renamed as Cognitive Work Analysis (CWA) by Kim Vicente (Vicente, 1999). They presented CSE more as a "cross-disciplinary market place", where "engineering, psychology, and the cognitive, management, information, and computer sciences" meet for analysing and designing usable and acceptable work systems (Rasmussen et al., 1994), rather than a distinct research discipline. This paper refers to the latter "school" of CSE, not as result of a theoretical difference between the two (if any of substantial degree do exist) but simply because it is aimed at improving stages of the approach and representations (techniques) that belong to the second formulation.

3.1.1. Task analysis for decision-making

For CSE task analysis in the traditional, normative form, is no longer an adequate approach for analysis and design of modern work. In contrast to the pre-industrial age and up to the second industrial revolutions, the computer age has automatized elementary work routines such that individual work have moved to higher cognitive levels.

Human work has evolved towards greater demands for decision-making, communication and coordination, and tasks have become more discretionary and dependant on the workers' ability to adapt to situational characteristics and system disturbances. The more a human-technology system is affected by external factors, or by internal factors not accounted for at design, the more necessary it will be to adapt or to deviate from "the one best way" embedded in the procedures. And the more discretionary the work, the less amenable it is for analysis in terms of normative standards, i.e., "the only right way to do the job" (Vicente, 1999). Indeed, designers do not foresee all local contingencies for the work context and "a work procedure is often designed separately for a particular task in isolation whereas, in the actual situation, several tasks are active in a time sharing mode, which pose additional constraints on the actually effective procedures that were not known to the designer or work planner" (Rasmussen et al., 1994, p. 141).

For tasks that are extremely proceduralized (e.g., assembly line operations) normative task analyses can still discover the cognitive task demands in a satisfactory way. Written instructions and procedures are also a very convenient way for an analyst to familiarize with the work domain and the specific tasks assigned to the operators, also for complex work (Kirwan & Ainsworth, 1992). However, for designing for the adaptations that are necessary in contemporary open-systems one needs further instruments than those provided by task analyses techniques (Rasmussen et al., 1994, p. 58). CSE provides a methodology with specific techniques for this: the "activity analysis in work domain terms", the "heuristic decision making", and the "mental strategies analysis" that follows the domain work analysis are CSE's alternatives to normative task analysis.

4. Decision making in nuclear control centres

Decision-making in a nuclear power plant control centre is about teams of experts largely interacting with procedures and guidelines. When an emergency arises at a nuclear power plant, control room operators open the emergency operating procedures (EOPs).

Procedures support the operators in diagnosing events, identifying the probable causes, and in taking the appropriate response action (e.g., by maintaining the critical safety functions). Under emergencies the operators control the plant largely, if not entirely, through the procedures. The emergency procedures are comprehensive with regards to the accidental situations they address and detailed with regards to the specific actions to be followed.

Despite the EOPs completeness and level of detail, they still are pre-designed plans that need to be matched to the actual situation. The operators are responsible for this matching.

Jeffroy and Charron (1997) explain that in the nuclear field even when following step-by-step EOPs that “appears simple at first glance, the operator can introduce interpretations and retain a certain degree of independence”. According to Suchman (Suchman, 1987) this is always necessary as the procedures underspecify the ‘world’ as the object and actions described cannot be the object and actions in situ. Roth (Roth, 1997) explains that the operators build a mental model of the situation and plan their course of action semi-independently of the procedures. The operators use the procedures to support autonomous thinking while formulating goals, and deciding when and how to accomplish these. O’Hara, Higgins, Stubler, & Kramer (O’Hara et al., 2000) describe the operator’s role as a supervisory controller whose primary task is to monitor and control the performance of the plant through manipulation of the human-system interface and the procedures. In their view the operator’s primary tasks is controlling the plant, which includes the secondary tasks of monitoring the performance of the procedures, in the same manner as they “monitor the performance of the automatic systems and intervene when the systems fail or perform at unacceptable levels” (id.). Hence, operators interpret the procedures and form mental models and plans by comparing the procedures with the situation at hand. They also intervene when the procedures do not perform well.

Examples of operators interpretations and decisions when following EOPs are: assessing entry conditions, tracking and evaluating procedure paths, assessing the conditions of applicability of steps, dealing with problems not addressed in the procedures, anticipating diagnosis and action steps, leaving a less optimal procedure before an explicit exit step is reached, and evaluating the achievements of the overall plant safety and procedures goals (Roth et al, 1994; Jeffroy & Charron, 1997; Massaiu & Holmgren, 2014).

That procedure following is not only step-by-step, mechanic implementation of the prewritten “plan” or “program” contained is also illustrated by ‘secondary’ uses of the procedures. Paper based procedures, for instance, allow the operators to write progression marks, to record timing and parameters information, to place bookmarks, to browse ahead and back, to open several procedures at the same time and compare, and so on. The operators exploit the physical characteristic of the procedures to facilitate pace keeping, aiding memory, and improving anticipation strategies (e.g. reading ahead, simulating alternative transitions to other procedures). When procedures were implemented in computerized systems without preserving these affordances the result was that important functionalities were lost and operators’ procedure following strategies were impaired (Ockerman & Pritchett, 2000).

5. An Information Flow Map for Emergency Operation

Information flow maps are graphical ways to represent the (generalized, not detailed) decision strategies that operators (can) use when performing work tasks (Rasmussen, 1986). They include the data (information observed and expected from the system state), models (mental representations of the anatomical or functional structure of the system) and the tactical rules that control the actual performance of a task (god/bad judgements, comparing data, yes/no choices, references to memorized patterns, mental models modifications, etc.).

In real time performance, the operators shift strategies when difficulties in the current strategies occur or new information is acted upon. Shifts are frequent and impulsive, as they are determined by person and situation dependent aspects (Rasmussen, 1983, p.38).

CSE describes several “idealized” strategies (Rasmussen et al., 1994), but only few have been represented as information flow maps: the topographic diagnostic search strategy, and the three symptomatic diagnostic search strategies of pattern recognition, decision table, and hypothesis and test (Rasmussen, 1986; Vicente, 1999).

The information flow map for decision making in nuclear control centres (Fig. 1) is the application-specific version of the hypothesis and test diagnostic search strategy, which is the CSE strategy for dealing with unfamiliar and complex faults (Vicente, 1999, p. 232). It slightly modifies and simplifies the original and adds domain-specific aspects, including the sources for the hypotheses and the verification activities that allow the comparison of the situation to the operators' understanding (model) of the situation.

Rather than as a diagnostic search strategy, emergency operation is here seen as a continuous diagnostic tests of the match between the procedural guidance and the abnormal, emergency situation.

The strategy starts with a test of the operators' hypothesis, which can be the hypothesis on the situation built in the procedure or procedure's step in effect, or can be derived from one of the procedure interpretation tactics, if a mismatch between the situation and the expected response was ascertained at an earlier pass of the strategy, or from other strategies (e.g., pattern recognition).

The strategy requires a functional model of the plant and systems, including flows and levels in the mass/energy flows structures and balances, in order to make the necessary adaptations / modifications to the procedures ("adjust procedure") and obtain the pattern of expected data. However, models of the normal and current functioning of the system are not represented explicitly in the map for space and parsimony.

Expected data are deduced, if the test is conceptual, or produced, if the test is an "experiment in practice" (Schön, 1983) thereby the operators act on the system to produce an intended change. When the expected response matches the data pattern representing the situation the operators return to the procedure/step in effect ("accept procedure interpretation"). They then assume the "procedure hypothesis" (the procedure/step built-in hypothesis) which is interpreted in light of the operators' "situation interpretation tactics". In this way, they assume the procedure hypothesis by "understanding and implementing" the procedure letter and verifying the relative responses (which in some EOPs are in fact referred to as 'expected response obtained/not obtained').

The model makes explicit a set of tactical rules that impact on the situation/expected-response match evaluation ("Situation/expected response match?" box). These are tactics operators may employ to verify the adequacy of the current hypothesis/situation match. The least operators employ these strategies the likely they will not detect a mismatch, and the likely they will continue following the procedures literally.

In the next section the verification, situation interpretation, and procedure interpretation tactics are described in more detail, explaining how procedures are understood, implemented, and adjusted.

6. Verification and interpretation tactics

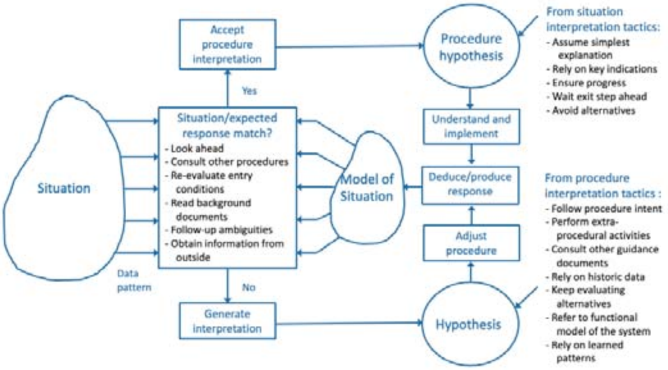

Fig. 1.The information flow map for operation with emergency procedures. It is an application-specific version of Rasmussen's (1986) hypothesis and test strategy.

Nuclear power plant control room operators continuously compare the procedures to the situation. Therefore they construe their model of the situation based on their interpretation of both situation and procedures. As the situation is dynamic this requires a continuous verification of the match between the mental model and the situation. The operators do this against a background of uncertainty that characterises disturbance and emergency operation, as well as within a procedure compliance regime that requires both adherence and expeditious progress. In other words, the operators have to solve a good deal of uncertainty with limited time.

6.1. Situation Interpretation Tactics

The procedures contain an interpretation of the situation. The operators' interpretation of the situation is highly influenced by the procedure in effect. As long as the operators' and procedure's interpretations are consistent the procedure is implemented without delay and difficulty. In ambiguous situations (e.g., presence of unreliable cues) or when procedures do not seem highly effective, the operators will start re-interpreting the procedure situation match. However, the procedure interpretation is maintained as long as: (a) at least some reliable indications ensure procedure match (to a reasonable degree), and/or (b) the procedure is ensuring progress (even if effective alternatives are known); (c) the operators expect an exit/re-evaluation step ahead; (d) evaluation of formal (allowed) alternatives is expensive (e.g., too long time to evaluate if an alternative mentioned in the procedure background is more appropriate).

A tactic that is often observed is that the operators assume the simplest, familiar hypothesis about the situation as long as it tenable. Operators rely on the most salient available indications for situation identification. If there are conflicting or unreliable cues, a single but salient, unambiguous cue can be enough to support the initial hypothesis. For instance, the operators tend to explain multiple successive leaks as a single increasing leak. Distinguishing information is not sought after as long as the overall situation is compatible to the single leak hypothesis (Massaiu & Holmgren, 2014).

Indications available in the control room and obtained from outside as per procedure steps (e.g., the procedure directs to obtain local radiation measurements) are considered more salient than other cues and are given priority. Alternatives are considered when the hypothesis is no longer compatible with accumulated/emerging evidence or when time/resources are available for consideration/production of alternatives.

6.2. Verification tactics

Implementing a procedure implies an evaluation of its effectiveness, at the very least that the step is correctly executed. Proficient operators continuously evaluate whether the procedures is achieving its goals and is consistent with the evolving situation. Expert operators look ahead of steps and procedures, read different procedures, re-evaluate entry conditions, read background documents, consult plant information diagrams, and may abandon the original situation understanding at procedure entry for an updated one. Operators may follow-up ambiguities by obtaining information that is not directly called by the procedure or displayed in the control room. For instance, by dispatching staff to inspect or perform measurements locally.

6.3. Procedure interpretation tactics

The operators are familiar with the emergency procedures, their purposes and overall strategies. However they might not always question why a procedure is entered (rather than another), where it is going, and/or if it is still beneficial after entry conditions have changed.

The intention of the procedure step is not always considered: understanding how to implement the step and following literally ensures progress and helps reducing uncertainty. The operators then comply with the procedure without performing extra checks, actions, or evaluating alternatives. Contributing factors for this strategy are concerns about possible delays, own errors, or sanctions.

Literal step following is also preferred when the operators are uncertain: a) about conditions of applicability of procedures (e.g., in multiple events/failure conditions), b) whether conditions for entry are no longer in effect, c) about steps that are repeating already performed actions in previous procedures (action will be performed again), d) whether it is beneficial/allowed to anticipate important steps.

On the other hand, operators align the procedures to their understanding of the situation. Operators make adjustments when they identify a divergence between the procedure/step letter and the procedure/step intention. The operators recognize that the procedures may need historical information for correct interpretation (is a parameter stable or increasing?). Therefore they note down or memorize information that they expect to be relevant later. Conditions no longer present when the relevant procedures steps are reached may be followed-up and re-considered.

The operators can refer to other instructions (appendices, backgrounds of steps in effect) to support their understanding instead of following the procedure step letter.

Another available tactic is to follow the procedure (or wait before entering a procedure), and to perform extra procedural activities. These might include entering other procedures (parts) without a specific transition.

When the operators/procedure hypothesis discrepancy is not immediately resolved the operators comply with the procedure in effect but keep evaluating the progression against alternatives. The operators might then adapt/leave the procedure when the alternative is found, or at least, resolve the discrepancy when this is exited/complete.

7. Conclusion

In many complex sociotechnical systems the operators interact dynamically with their environment. Task analysis methods produce descriptions of this interaction in terms of sequences of actions from which operating and emergency procedure can be derived. This approach is not completely adequate for tasks that involve flexible cognitive processes and for which the applied strategies (and consequent actions) depend on subjective and situational factors.

These strategies can be identified through cognitive and formative task analyses tailored to specific applications and domains. Knowing the strategies allows to design technologies, training and work processes that: (1) support the operators using strategies they may use anyway, (2) facilitate strategy use by automating burdensome aspects, and (3) support workers' flexibility to swich between strategies. A second use of the strategies is in risk analysis. Knowing what decision strategies the operators adopt when following the emergency procedures allows to realistically represent deviation scenarios, an important requisite in advanced human reliability analysis (Barriere et al., 2000).

This paper has proposed an information flow map for emergency operation in nuclear control room centres. Information flow maps are best used in the context of performing a strategy analysis in Cognitive System Engineering's "activity analysis" (Rasmussen, 1994) (which also includes "activity analysis in work domain terms" and in "decision making terms", i.e. using the decision ladder) or Cognitive Work Analysis (Vicente, 1999; Austin et. al., 2022; Hilliard & Jamieson, 2017). The paper supports cognitive task analysis also outside CSE/CWA by providing a version of the "hypothesis and test" information flow map that specifically accounts for the presence of written procedures, that is, a model of decision making with procedures (or a model of procedure following during emergencies). Compared to the original "hypothesis and test" information flow map it further makes explicit and discusses the tactics operators use for generating interpretative hypotheses about the situation and the procedures, and for verifying the match between the situation data pattern and the operators' model of the situation (the expected response). This should facilitate formative task analyses for nuclear power plant control centres and other process control and operational settings that address safety through emergency operating procedures.

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