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Naturalistic decision making in process control: The guidance-expertise model and the model of resilience in situation

S. Massaiu
Institute for Energy Technology, Halden, Norway

ABSTRACT: The defining elements of naturalistic decision-making, such as proficient decision makers, ill-defined goals, uncertainty, high stakes, tools, and teamwork, are clearly present in process control. However, the domain is still heavily anchored in normative approaches for design, analysis and evaluation of human-technology systems that make unrealistic assumptions about the operators. The paper presents two naturalistic decision making models for process control developed in the nuclear power production sector and based on extensive observations of control room emergency operation in high-fidelity, human-in-the-loop simulators: the Guidance-Expertise Model (GEM) and the Model of Resilience in Situation (MRS). Unlike better-known naturalistic decision-making models, the GEM and MRS models recognize the central role that operating procedures and other organizational prescriptions play in process control decision making, elaborating on aspects that so far have received little attention in the naturalistic decision making community.

1 INTRODUCTION

1.1 *Process control and naturalistic decision making*

Control centers operators in process industries supervise systems that are extensively automated and intervene in case of malfunctions. Control centers are technological environments in which the operators' interactions with the system are mediated by human-machine interfaces and supported by decision aids ranging from pen and paper to intelligent expert-systems. The single most important decision support aid used by control centers operators is represented by the operating procedures. In the nuclear energy sector, for instance, when an emergency arises the control room operators respond by immediately opening the emergency operating procedures and implementing these until the reactor is brought to a safe state. In this environment understanding decision-making requires understanding how the operators interact with the procedures. The second distinguishing aspect of decision-making in process control industries is the collective nature of the decisions. Most of the times the decisions are made by groups, often called operating crews. Even when single operators are the decision makers, the high level of proceduralization of their work implies some sort of deferred relation with other actors like procedure designers, trainers, or management, who sets expectations on the decisions and behavior of the front-line operators. The most critical decisions in process control centers occur during incidents and accents. In such conditions the decision landscape typically include elements of time pressure, stress, ill-defined or conflicting goals, uncertainty about conditions, and high stakes. In other words, process control is a good illustration of all defining elements of naturalistic decision-making (Lipshitz, Klein, Orasanu, & Salas, 2001). At the same time the central role of operating procedures (and other organizational prescriptions) for process control is an aspect that sets it apart from other, more studied, naturalistic settings and makes widely-known naturalistic decision making models less readily applicable to the sector.

1.2 *The prevalence of normative approaches in process control*

Although process control decision-making is clearly a naturalistic setting, normative approaches still dominate system analysis, evaluation and design in the sector. This is likely a legacy from when these industries viewed their technical core areas as sufficient for designing productive and safe systems. The nuclear industry, for example, did not pay attention to human and organizational factors before the Three Mile Island and Chernobyl accidents, assuming that reactor physics, thermodynamics and other technical factors were solely responsible for designing safe plants (Moray & Huey, 1988). In normative approaches the operators are assigned the role of executors of procedures. As the procedures incorporate the rational benchmark for how to behave in different situations, they define what the operators are required to do in terms of actions, and even cognitive processes, in order to achieve the system's goals. The situations for which the procedures are made are seen as predictable conditions in which there are limited ways of performing the tasks correctly. Although these assumptions may have been appropriate for workers of the first industrial revolution, they are inadequate for automated and computerized production processes (Vicente, 1999). These are characterized by external disturbances (unanticipated faults, automation failures) and other forms of uncertainty (degraded indicators) for which the procedures do not apply and in which the operators are required to adapt to moment-by-moment changes in conditions by generating appropriate responses based on their conceptual understanding of the work domain. In such cases there are no standards of correct performance and no pre-defined correct decisions, if not after the fact. Research from anthropology, activity theory and naturalistic decision making has show that "workers' actions frequently do not—and indeed, should not—always follow these normative prescriptions" (id., p. 62). From the point of view of this paper the main problem of relying on normative approaches to decision making in process control is that the assumptions they make on the operators are not realistic and therefore of limited use for the design, analysis and evaluation of systems in which human and organizational factors play a critical role.

2 NATURALISTIC MODELS OF PROCESS CONTROL DECISION-MAKING

This section describes two naturalistic decision making models for process control work. They are both based on extensive observations of nuclear power plant control room emergency operation in high-fidelity, human-in-the-loop simulators. This section provides a description of the models' theoretical foils, concepts, purposes and applications. Their limitations will be discussed also taking into account their level of maturity and intended use.

2.1 *The guidance-expertise model of procedure following*

The Guidance-Expertise Model of Procedure Following (GEM) is a methodology to describe and predict nuclear power plant operating crews' behavior in emergency operation (Massaiu, Hildebrandt, & Bone, 2011; Massaiu & Bones, 2011). The model, based on the framework of cognitive system engineering (Rasmussen, Pejtersen-Mark, & Goodstein, 1994) assumes

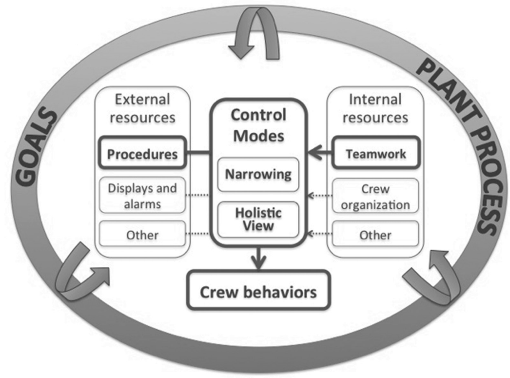

Figure 1. Conceptual diagram for the Guidance-Expertise Model of procedure following (GEM).

that macrocognitive processes, or control modes, determine decisions in proceduralized operational environments (Figure 1). In cognitive system engineering control is defined as the way the next action at any given point in time is chosen. Cognitive control refers to the organization of cognitive functions (e.g. monitoring, evaluating) and processes (e.g. heuristics, externalization of memory storage) in a situation (Hollnagel, 1998). Control modes in the language of activity theory are different orientations towards the object of activity that result in different ways of acting (Kaptelinin & Nardi, 2006). Basically, the control modes are different ways of thinking in a situation that determine behavior.

The GEM model borrows the language of 'situated course-of-action' theory (Theureau, Jeffroy, & Vermersch, 2000) and defines three control modes: Narrowing, Holistic View and Persisting Narrowing. During narrowing the operator's horizon is limited by what is referenced by the procedures. When the operators read the procedure in this mode their attention is focused, the situations are classified by their structural-mechanistic features, and are mapped into pre-planned methods of action. During narrowing, information is not actively searched for except for what is required by the procedure. The pre-planned methods for actions are incorporated in the emergency procedures as well as previously trained. Narrowing in a broader sense is the cognitive control mode in which the operators let the procedures guide them and do not try to figure out ad-hoc plans for dealing with the situation.

Holistic view occurs when the operators interpret the procedure steps relative to the situation dynamics, which include the activities of automated systems and of other people. As such it is analogous to the concepts of situation awareness and sense-making. In holistic view information is actively searched for in the control panels and through communication with other crewmembers to create an interpretation of the situation in a functional way, by considering the process as an integral whole. Holistic view takes into account larger time windows: the present is explained as the effect of previous events (diagnosis), the future evolution is represented to evaluate if the planned course of action is appropriate (Lipshitz et al., 2001). Holistic view includes metacognition (thinking about thinking) which will manifest itself in activities such as reconsidering the course of actions, determining whether to act outside the procedure while following them, redirecting procedure paths, detecting strains in teamwork and making adjustments.

Switching from one control mode to the other can be challenging in several ways, as the two modes require different cognitive effort and different configurations of cognitive functions, including how much is memorized and consciously represented. Changing from holistic view to narrowing implies difficulties in establishing the necessary local focus and attention as well as the right procedures progression pace. It can also challenge the capacity to re-construct an uncompleted course of action from the exact point it was left. Low-level errors, like slips and lapses, might occur as a result. Yet, most performance difficulties occur when the required control mode is holistic view but the crew struggle in establishing it, thereby continuing in narrowing mode. A typical example is when the crew starts engaging in problem solving behavior (e.g., discussion of transfer points, evaluation of novel events) but ends up reverting to literal procedural adherence. In such cases sustained periods of narrowing impede the achievement of a holistic view (i.e., a level of situation awareness adequate to develop an autonomous plan of action). This state is termed '*persistent narrowing*' and is considered a third control mode. The longer the narrowing continues, the higher the risk of losing global situation understanding. For self-paced processes, like emergency operation in nuclear power plants, the more the crew lags behind the process the more it will be pushed into a reactive mode and the more difficult it will be to achieve holistic view. Persistent narrowing ends when the crew is able to constructively generate a solution strategy, even if this is not an effective one.

In order to make predictions regarding crew behavior in emergency situations, the GEM model relates the control modes to aspects of the situation on one side and to aspects of crew expertise on the other. Regularities among situations, control modes and expertise for specific operational settings are derived from empirical human-in-the-loop simulations. The model outcome behaviors are task-independent behaviors that nuclear power plant operating crews exhibit in emergencies (Table 1).

Table 1. The 16 outcome behaviors included in the GEM model are task-independent behaviors that nuclear power plant operating crews exhibit in emergencies.

#	Outcome behaviour
1	Slow progression by meticulous procedure following
2	Slow reaction to *recently discovered* information
3	No reaction to *important* information received
4	No/slow action to unexpected event
5	Literal step following rather than purpose
6	Incorrect procedural transition
7	Cue explained away
8	Notes/warning/foldout pages ignored
9	No priority between concurrent goals
10	Priority given to minor goal/most recent deviation
11	Autonomous decision avoided
12	Successful step execution
13	Incomplete step execution
14	Inference to previous condition not made
15	Sub-step skipped
16	Stuck in procedure step

According to the model, two formal features of the emergency procedures are the most important environmental aspects to consider. Procedural features are identified as being either 'loose' or 'detailed', with the understanding that there is variance of the degree. Broadly speaking, when the procedures provide meticulous step-by-step direction they are pronounced to be "detailed", otherwise as "loose" (e.g., evaluation of trends, adjustment and control actions, navigational decisions).

Empirically observed regularities between procedural features and control modes should help predicting the crews' procedure progression in accidental conditions. According to the model the procedures-behavior pairings are in fact determined by the control modes, which in turn are determined by the crew expertise. In GEM expertise is measured by teamwork indicators through a classification scheme based on both generic and nuclear-specific process control teamwork literature (Braarud & Johansson, 2010; Klein, 1999; Norros, 2004; Salas et al., 2005; O'Connor et al., 2008). The model considers 8 teamwork dimensions: monitoring progress, communicating intents, communicating interpretations, looking for same cues, reconciling viewpoints, adapting, backing-up, team monitoring & flexibility.

The GEM model has thus three elements: (1) structural features of the procedures, (2) control modes, and (3) the crew expertise.

2.1.1 *Application of the GEM model*

The GEM methodology was tested by Massaiu and Bones (2011) in a retrospective analysis of

74 critical decisions by four Nuclear Power Plant (NPP) operating crews' in simulated Steam Generator Tube Rupture (SGTR) events (Massaiu & Bones, 2011). The four crews that exhibited most operational difficulties (the models' outcome behaviors) were selected to test whether the model could describe the observed performances and help estimating the likelihood of the outcome behaviors given observable aspects of the context of action (i.e., the procedural features) and the crew cognitive control modes.

The analysis showed different patterns of outcome behaviors, control modes and procedural conditions as well as different patterns between the crew expertise (as measured by indicators of teamwork proficiency) and observed control modes. For instance, almost all the times a crew transitioned to a wrong procedure (outcome behavior 6 in Table 1) it was with 'loose' procedural guidance and in 'persistent narrowing' control mode. Different teamwork characteristics were associated with the three control modes. The preliminary results showed that nearly all instances of positive teamwork were observed under the 'holistic view' control mode, and that all negative teamwork dimensions were observed when the crews exhibited 'persistent narrowing'. No positive teamwork indictors and some negative indicators were observed when the crews were in 'narrowing' mode (and to a lesser degree than when in 'persistent narrowing').

2.1.2 *Evaluation of the GEM methodology*

The GEM model can be used as classification system for analysis of observed team decision-making and behavior. Its main benefit is the possibility of evaluating the likelihood of outcome behaviors given observable features of the environment and to measured team expertise. The intended use of the methodology is for cognitive simulation and predictive task analysis. However the methodology has been tested on a small data set only and a number of challenges remain to be solved. These are the main ones:

1. The set of outcome behavior is not a complete and not-overlapping set.
2. Further aspects of the guidance system should be included (e.g., the crew operating policies and training).
3. The model is currently limited to two environmental features: the procedural features and the crew expertise (which determines the control mode). Although these are recognized as the most important factors for crew performance in emergency, the inclusion of other structural features of task and environment in the model is likely necessary for improving its predictive accuracy.

2.1.3 *The model of resilience in situation*

The Model of Resilience in Situation underlies the human reliability method MERMOS (Pierre Le Bot, Cara, & Bieder, 1999). Its primary application has been in the context of predictive risk analysis, but it has proved a valid tool for retrospective accident analysis in the nuclear (Le Bot, 2004) and medical (Le Bot, 2008) fields. Recently it has been proposed as a way to analyze human and organizational factors in a High Reliability Organizations perspective for supporting design of risk-critical systems (Le Bot & Pesme, 2014).

The MRS explains how operating teams in emergency organizations make decisions during the course of an accident. The model is based on Jean-Daniel Reynaud's theory of social regulation (Reynaud, 1989), a sociological theory that understands social relations (particularly in the working environment) as social regulations, that is, the social production of formal and informal rules governing the behavior of groups.

In the MRS the object of analysis is the Emergency Operating System (EOS), the ensemble of control room operating crew, the human-machine interface, and the operating procedures. The MRS is about team decision-making mediated by technology and procedures and thus consistent with Edward Hutchins' distributed cognition paradigm (Hutchins, 1995; Hutchins & Klausen, 1998) in assuming that cognitive resources are not only in the operators' heads but also in the procedures and the interface.

The MRS can be seen as constituted by three interrelated building blocks: (1) a description of the dynamics of emergency operation (Figure 2); (2) the functions that the EOS fulfills during emergency (Figure 3), and (3) the stable characteristics, or features, of the emergency operating system (see Table 3 for an example) (Massaiu & Braarud, 2013).

The dynamics of emergency operation are described by cycles of stability, ruptures, and new stability phases (Figure 2). During a stable

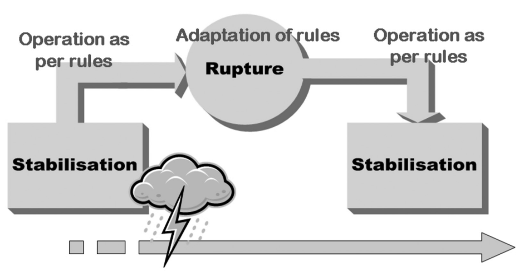

Figure 2. The dynamics of emergency operation according to the model of resilience in situation.

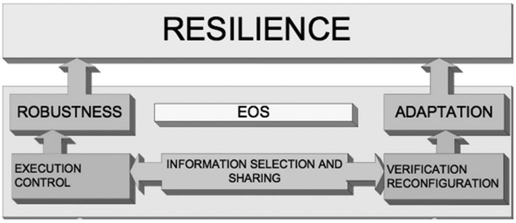

Figure 3. The Model of Resilience in Situation (MRS) identifies five functions of the Emergency Operating System (EOS): 'Execution' and 'Control' ensure the system's robustness, 'Verification' and 'Reconfiguration' the system's adaptation, while 'Information selection and sharing' is a cross-cutting function enabling the other functions.

Table 2. The MRS model specifies 'sub-functions' and 'details' for the main functions of the model depicted in Figure 3. Here are the sub-functions and details for 'Control' (of rule execution).

Sub-function	Detail
Understand goals and priorities	Understand timing of tasks (when to do, when to get info, time lags, urgency)
Allocate resources (cognitive, material, human)	Distribute tasks/Position operators in CR
	Understand task allocation
Continuous monitoring of expected plant responses	
Small deviations detections and adjustments	Keep focus on task and process
Recovery (of individual errors)	Team monitoring, communicate significant actions
	Consult and peer check before performing significant actions (feed forward control to avoid need for recovery)
Concentrate on current plan	Avoid distractions: Do not respond to all incoming information/requests
	Attention on procedure following, read notes, read foldout, referenced parameters
Resist external demands (for resources)	Keep focus on priorities
Reach plan goals	Ensure goals achieved
	Completing pending procedures/steps
Manage dynamics (e.g. Concurrent goals)	Manage multiple/parallel tasks (procedures)
	Manage interruptions and deferred tasks (including continuous EOPs' steps and conditions)

Table 3. The emergency operating system 'Features' are the structural elements that determine the systems' capacity to perform its functions (Figure 3). Here the EOS sub-features and indicators for the category 'Procedures'.

Sub-feature	Indicators
Monitoring/re-evaluation loops	Re-evaluate procedure appropriateness
	Re-evaluate procedure optimality
	Continuously/periodically re-evaluate priorities
Writable/bookmarks	To aid memory
Redundant information sources	Look for extra information to validate itself
	Look for extra information to assess reliability of cues
Overview/status trees	Counter fixation on current plan
	Takes into account simultaneous influences
	Easy to look ahead/browse

operating phase, called the stabilization phase, the system follows the effective rules that it has set itself, typically the operating procedures, allowing the attainment of its objectives and avoiding the continual demands made by the dense flow of information (for instance, several hundred alarms in a nuclear power plant control room). However, this organizational inertia, protecting the actors from unexpected demands, must be counterbalanced by permanent redundant verification (or monitoring), i.e., constantly checking that the rules applied are appropriate to the situation (for example, that the procedure in effect is adequate). A rupture occurs when the active rules become inappropriate and the operating system has to be reconfigured so that it has new effective rules. This can happen for two reasons: (1) the objectives may have been reached in compliance with the applied rules; or (2) the rules are not longer adequate due to (2a) errors in rule implementation necessitating a reconfiguration (re-planning) that is more than mere error recovery, or (2b) when the team recognizes that conditions existed or have newly arisen for which the rules in effect are not adequate. In these cases, the verification of the of rule's inadequacy should trigger a "rupture" of the operation so that the system reconfigures itself with new effective rules. (Figure 2).

It should be noted that during emergencies at nuclear power plants the rupture phases may last minutes while the stability phases may last hours.

The second building block of the MRS model is the description of the functions of the operating system (Figure 3).

There are two main functions that define the resilience of the EOS: "Robustness" and

"Adaptation". Adaptation is accomplished by the functions described above of verification (i.e., verifying that the plans are good for the situation) and reconfiguration (the capacity to timely produce plans that fit changed conditions). Robustness is defined by Execution and Control. Execution is defined as "acting on the process given the effective operating rules". It includes object discrimination (selecting the right control out of similar ones and the right mode in multi-mode displays) and situation discrimination (acting differently in different plant operating modes). "Control" consists in a permanent monitoring of the consistency of actions and effective operating rules (are the rules well applied?). Control is about the execution of the rule in effect, is the function that ensures that the rule is being implemented as intended. Effective control requires continuous monitoring of process and staff, detection of deviations, rapid adjustments, and management of concurrent demands and interruptions.

In order to perform these functions the system has also to select and share information from the environment. Information Selection is then defined as a "common function" needed by Control, Verification and Reconfiguration. Teamwork is treated as a set of processes (e.g., cooperation, team situation understanding) used in performing EOS functions. Therefore, teamwork functions are not represented as independent functions but are 'built-in' in the other functions.

The third building block of the MRS model is constituted by the "emergency operating system features", i.e., stable characteristics of the system that allow it to perform its functions. Features are identified for the personnel (e.g., staffing, training, safety culture), the human-system interface (e.g., displays, alarm logs) and the procedures (e.g., symptom based) elements of the system. The EOS features determine the systems' capacity to perform its functions. Different configurations of personnel, HSI, and procedures will produce different capabilities with regard to the various EOS functions. For instance, an operating crew with authoritarian line of command will likely facilitate execution and control functions, but might counter effective reconfiguration. The MRS model organizes the features under the following categories: Team, Prescriptions, Formal communications, Human-Machine Interface (HMI), Training, and Procedures (see for instance the features for Procedures in Table 3 below). These six categories include sub-features, that is, specific indicators that evaluate their contribution to the fulfillment of the EOS functions. For example, the HMI feature includes the "Control Room Layout" sub-feature to evaluate whether the HMI provides "visibility of other operators" and "visibility of others' actions" (i.e. "does the control room layout allow the operators to see each other and their actions?"). Another example is the Team feature's sub-feature "Supervisory function", that evaluates among others the system capability of "Monitoring others actions" and "Searching redundant information" (i.e. "does the supervisor monitor operators actions and search for redundant information?").

The MRS model specifies the influences of the EOS features on the EOS functions. The result is a complete matrix of influences from the features' indicators to the sub-functions' details.

2.1.4 *Evaluation of the MRS methodology*

The Model of Resilience in Situation is the theoretical backbone of the human reliability method MERMOS, and in this form it has been applied in the French nuclear industry for more than a decade. The decision-making model presented in this paper has received a more limited application and testing, but it nonetheless has proved capable of capturing the essentials aspects of the decision-making processes followed by nuclear control room crews responding to simulated accidents in full scope simulators. These were detailed, minute-by-minute analyses of teams of professional operators performing in realistic conditions. Compared to other naturalistic decision-making models the MRS model treats decision processes that span over relatively long time windows and include several decision points, as it is necessary for dealing with emergency operation in nuclear power plants. A second innovative aspect, also strongly dependent on the model's domain of origin, is the importance reserved to the technology and the organizational environment in which the decision makers operate. These are furthermore teams rather than individuals so that teamwork aspects become central. Finally, the model lends itself to predictive applications (trough the MERMOS human reliability method), retrospective accident analysis, for verification and validation purposes (by providing an overall framework that can be used as basis for performance-based evaluation of human-machine systems), and as an observation protocol for on-line recording and classification.

The main limitation of the MRS model is that, beside the applications for human reliability which is at an industrial stage, the methodology needs further refinement and testing (Massaiu & Braarud, 2012).

3 CONCLUSION

Normative approaches are still the preferred option for analysis, design and evaluation of human-technology systems in process control industries.

This is partly due to the field strong technical tradition, one that assumes that the core technical disciplines are sufficient for achieving safe and productive systems, but also to field specificities (like the prominence of operating procedures) that make well-known naturalistic decision making approaches less readily applicable.

This paper has presented two decision-making models specifically developed in process control settings. The models are informed by extensive empirical observations and have been tested and implemented at varying degrees for different applications. The two models contribute to the naturalistic decision making discipline at large by tackling the not so well-studied aspect of team decision making *with* operating procedures.

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