Resilience in Everyday Operations: A Framework for Analyzing Adaptations in High-Risk Work

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Managing complexity and uncertainty in high-risk sociotechnical systems requires people to continuously adapt. Designing resilient systems that support adaptive behavior requires a deepened understanding of the context in which adaptations take place, of conditions and enablers to implement these adaptations, and of their effects on the overall system. Also, it requires a focus on how people actually perform, not how they are presumed to perform according to textbook situations. In this paper, a framework to analyze adaptive behavior in everyday situations in which systems are working near the margins of safety is presented. Further, the variety space diagram has been developed as a means to illustrate how system variability, disturbances, and constraints affect work performance. The examples that underlie the framework and the diagram are derived from nine focus groups with representatives working with safety-related issues in different work domains, including health care, nuclear power, transportation, and emergency services.

Keywords: resilience engineering, topics, adaptation, analysis methods

INTRODUCTION

Work processes in complex systems are associated with fluctuations, unexpected events, and disturbances and require people to change their behavior to meet variations, in both the long and the short term (Hoffman & Woods, 2011; Rasmussen, 1986; Woods, Dekker, Cook, Johannesen, & Sarter, 2010). The everyday adaptations give rise to performance variability, affected by each person's individual adaptations as well as those made by others around them. Although human performance variability in some cases may lead to unsafe situations, the vast majority of adaptations made by humans are successful (Hollnagel, 2009a, 2009b). However, as performance variability is often acknowledged only when leading to an unsafe situation, the traditional view has been that performance variability is hazardous to system safety. Therefore, there is limited knowledge about factors contributing to successful adaptations that lead to successful outcomes and that thereby avoid undesirable outcomes. Analyzing situations in the aftermath of an unwanted outcome (as done in incident and accident investigations today) provides a retroactive interpretation of what has gone wrong and often fails to provide information about factors contributing to when it goes right (Dekker, 2004; Woods et al., 2010). A shift in focus from human inability to human ability is central for proactive safety management. In the emerging field of resilience engineering, this issue is being emphasized, and performance variability is seen as essential to ensure a system's resilience (Hollnagel, Paries, Woods & Wreathall, 2011; Hollnagel, Woods, & Leveson, 2006; Nemeth, Hollnagel, & Dekker, 2009). Resilience is defined as the ability to sustain required operations in both expected and unexpected conditions (Hollnagel, 2012b).

The framework proposed in this article has been developed as a tool for researchers and practitioners to analyze adaptations in everyday work situations. A main objective is to contribute with a proactive safety management model to complement a traditional safety perspective. By recognizing how practitioners cope with daily risks and variations that fall outside of the organization's formal instructions or procedures,

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Journal of Cognitive Engineering and Decision Making
Volume 8, Number 1, March 2014, pp. 78–97
DOI: 10.1177/1555343413498753

we aim to gain a deepened understanding for the complexities of the work situation, the system strengths, and the system vulnerabilities. In organizations today, critical details of how practitioners cope through everyday adaptations are often not recognized, documented, or acknowledged and are known only as implicit knowledge by individuals and teams. If not acknowledged, important functions might be "designed away" (Rasmussen, 1986), thus reducing the organization's resilient abilities (Furniss, Back, Blandford, Hildebrandt, & Broberg, 2011). By exploring how practitioners anticipate, monitor, and respond to "gaps" in the system and making this knowledge more readily available, work environments can be better designed and organizations better prepared to support the successes of human variability.

In this study, we aim to address some of the limitations of traditional incident investigation and safety management by providing a complementary model with guidance on how to structure and analyze adaptations in everyday work situations. The study is a continuation of a research project investigating the underlying theoretical models used in accident investigations in high-risk organizations in Sweden (see Lundberg, Rollenhagen, & Hollnagel, 2009; Lundberg, Rollenhagen, Hollnagel, & Rankin, 2012; Rankin, Lundberg, & Woltjer, 2011). In the study, examples of how organizations managed variations kept emerging, prompting more directed studies on this topic. For the purpose of this study, multiple organizations are included to identify commonalities between organizations' adaptive abilities and to investigate the potential for general models of resilience.

The first section includes a brief overview of limitations of traditional perspectives on safety management and an introduction to the resilience engineering perspective. In the second section, we present the method used for gathering data. In the third section, we introduce the developed framework for analyzing adaptations in high-risk work and the variety space diagram, a tool to illustrate the relationships between the categories of the framework. In the fourth section, we demonstrate the framework's use and potential by providing examples that have been analyzed using the framework and plotted in the variety space diagram. The last section offers reflections on the contribution of the framework and considerations for further development.

THE PERSPECTIVE OF HUMANS AS A HAZARD TO SYSTEM SAFETY

Traditionally, safety research and industrial safety management have largely focused on unwanted events and outcomes, through risk and incident/accident analysis, known as the Safety-I perspective (Hollnagel, 2012b). This perspective has provided nuanced ways of describing and talking about system failures using in-depth analyses (e.g., Harms-Ringdahl, 2001; Rollenhagen, 2011; Sklet, 2004), usually uncovering deviation and violation of operational processes and prescribed rules (Dekker, Cilliers & Hofmeyr, 2011). Although learning from accidents and incidents is a critical part of safety management, it is also important to be aware of the limitations when making interpretations of the outcome in hindsight. A main concern is that *hindsight bias* may distort the analysis (Dekker, 2002; Fischoff, 1975; Woods et al., 2010). Interpreting people's actions in the light of what "should have happened" and what they "could have done" to avoid the incident allows a convenient explanation of the situation, but it does not necessarily provide a deeper understanding of underlying factors contributing to the outcome, such as context, pressures from the organization, and conflicting goals (Dekker, 2004; Lundberg et al., 2009; Woods et al., 2010). A focus on failure gives the impression that human performance variability is a major hazard and does little to uncover the details of successes and opportunities created by human adaptations.

The perspective of humans as a hazard to system safety is, however, gradually shifting along with a growing understanding that all contingencies cannot be fully accounted for in operating procedures (Dekker, 2011; Guldenmund, 2000; Hollnagel, 2004, 2009b; Perrow, 1984). In the growing field of *resilience engineering*, a more proactive approach to safety management is pursued. Things that go right and things that go wrong—success and failure—are seen as outcomes of the same underlying behavior. Thus, to understand failure, one must also understand success (Hollnagel, 2009b; Hollnagel et al., 2006). Variability, fluctuation, and unexpected events are viewed as natural parts of system operation and should be expected. A system's resilience is determined by its abilities to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operation in both expected and unexpected conditions (Hollnagel et al., 2011).

Adaptive Systems

People and technology working together in a complex environment toward a common goal can be described as a sociotechnical system. In this work, we focus on high-risk systems whereby unsuccessful adaptations may have major consequences, such as in health care, transportation, emergency services, or process industry. In this section, we describe different concepts used to portray adaptations, the complex nature of high-risk systems, and the role of people working in them.

Human factors literature is replete with examples of sharp-end personnel adapting or "filling in the gaps" in order to complete tasks in an efficient and safe way. Finding alternative solutions to the intended use of technology has previously been named "tailoring," "work-arounds," or "kludges" and includes, for example, extending or evading current functionality or identifying new ways of working to compensate for design flaws or component failures (Cook, Render, & Woods, 2000; Cook & Woods, 1996; Koopman & Hoffman, 2003; Nemeth et al., 2007; Woods & Dekker, 2000). A main factor contributing to the need for the these sharp-end adaptations is the rapid evolution of system technology to increase efficiency, production, and safety, which produces side effects, such as unintended complexities and increased practitioner workload and performance pressure (Cook et al., 2000; Cook & Woods, 1996; Woods, 1993; Woods & Branlat, 2010; Woods & Dekker, 2000). As noted by Cook and Woods (1996), the constant compensation for system design flaws comes at a cost of increased vulnerability, as outcomes are hard to predict and patterns of change are difficult to identify.

Another way to describe adaptations is through the principle of approximate adjustments (Hollnagel, 2012a). As conditions of work never completely match what has been specified or prescribed, adjustments (minor changes) are constantly made by individuals and organizations to meet the demands of the situation at hand. As resources are finite, adjustments are always approximate rather than exact (Hollnagel, 2012a).

In cybernetic terms, adaptations can be described as *variety*. Complexity is characterized by a large number of interactions between variables, leading to high system variety, that is, a large number of possible future system states. To meet the demands of process variety (e.g., fluctuations, changes, disturbances) caused by the system, agents controlling the process must have at least the same amount of variety (i.e., adaptive ability; Ashby, 1956). High variety makes outcomes difficult to predict, as different paths may lead to the same goal and the same actions do not always lead to the same outcome (Brehmer, 1992; Hollnagel, 1986; Nemeth et al., 2007).

Other studies of practitioners coping with complexity in high-risk environments describe adaptations as representing *strategies* used by individuals to detect, interpret, or respond to variation (Furniss, Back, & Blandford, 2011; Furniss, Back, Blandford, et al., 2011; Kontogiannis, 1999; Mumaw, Roth, Vicente, & Burns, 2000; Mumaw, Sarter, & Wickens, 2001; Patterson, Roth, Woods, Chow, & Gomes, 2004). Strategies may include informal solutions to minimize loss of information during handoffs or to facilitate process monitoring to compensate limitations in existing human–machine interfaces (Mumaw et al., 2000; Patterson et al., 2004). In this study, the notion of strategies has been used to represent the adaptations identified in the analyzed examples.

System Boundaries and Trade-Offs

The terms *sharp end* and *blunt end* are often used to describe different functions of a system and how they relate to each other (Reason, 1997; Woods et al., 2010). The sharp end includes the people who operate and interact in the production processes, for instance, doctors, nurses, pilots, air traffic controllers, and control room operators. The blunt end includes people who manage the functions at the sharp end, such as managers, regulators, policy makers, and government. However, sharp-end/blunt-end relations should be described and analyzed in relative rather than absolute terms in order to understand an organization's performance, since every blunt "end" can be viewed as a sharp "end" in relation to its managerial superior function(s) (see, e.g., Hollnagel, 2004, 2009a).

Human and organizational—and blunt-end and sharp-end—adaptive performance can be understood in terms of trade-offs, such as optimality–brittleness, efficiency–thoroughness, and acute–chronic (Hoffman & Woods, 2011; Hollnagel, 2009a). Given a number of overarching values and goals set by the blunt end concerning effectiveness, efficiency, economy, and safety, the sharp end adapts its work accordingly. Hence, modifications of performance are continuously made at the sharp end, even in highly controlled task situations (Furniss, Back, Blandford, et al., 2011; Mumaw et al., 2000; Rasmussen, 1986). It is important to note that balancing these issues is "locally rational," that is, based on limited knowledge, time, and resources available in specific situations (Simon, 1969; Woods et al., 2010).

Although it may be hard to detect, over time, many small adaptations may have a substantial effect on the organization as a whole (Cook & Rasmussen, 2005; Hollnagel, 2004, 2012b; Kontogiannis, 2009). Although each individual decision to adapt may be locally rational, the overall effect on the system may differ from what anyone intended or could have predicted. Rasmussen (1986) describes this migrating effect in terms of forces, such as cost and effectiveness, which systematically push work performance toward the boundaries of what is acceptable to ensure safety. This pattern of adaptations is also illustrated in the law of stretched systems (Woods, 2002; Woods & Hollnagel, 2006), which suggests that every system is stretched to operate at its capacity; if there is an improvement, it will be exploited to achieve a new intensity and tempo of activity. This theory has been further developed in the analogy of the stress-strain model, illustrating how sources of resilience are used as a system is stretched in a nonuniform way (Woods & Wreathall, 2008).

The Resilience Perspective

The aforementioned studies show that operators of complex systems take an active part in the design of their working environment to bridge gaps created by poor design, facilitate complicated processes, and manage conflicting goals. The resilience engineering perspective broadens the scope of studying adaptations compared to traditional human factors literature. In human factors, there is a focus on the design of technology. Adaptations or work-arounds are pointers to identify a poor fit between technology and procedures and the actual conditions of work (Koopman & Hoffman, 2003). From a resilience perspective, the focus is on the system's ability to cope with increasing demands and compensate for the increased demand by adapting its performance. Hence, adaptations are viewed not only as sharp-end work-arounds to cover for design flaws in technology but as a vital part of system functioning to cope with multiple goals, organizational pressures, and complexity.

To be resilient, a system needs to be able to *anticipate* what may happen, *monitor* what is going on, *respond* effectively when something happens, and *learn* from past experiences (Hollnagel, 2009b). Resilience engineering is about understanding and anticipating what sustains and what erodes adaptive capacity (Patterson, Woods, Cook, & Render, 2006). To be resilient, a system must monitor forces and conditions affecting the system to ensure that the system is not operating too close to its safety boundaries. We argue that observing sharp-end adaptations aimed at avoiding performance breakdowns in everyday operations is critical to identify system brittleness and resilience.

Learning From Adaptations

We have argued that system performance varies in everyday work because of a number of internal and external conditions and that people adapt their performance to meet these uncertainties. Unfortunately, knowledge about performance variability is not commonly recognized as an asset, and informal solutions to systemic problems often go unnoticed by organizations. In contrast to analyses of undesired events, models and methods for systematically gathering knowledge regarding necessary adaptation are rarely seen in organizations today. An increased awareness of the adaptive strategies used and their effect on system performance is necessary to ensure that the strategies are supported by the system design and to strengthen the organization's abilities to anticipate and monitor change. In this study, we recognize previous limitations by providing a complementary model with guidance on how to analyze adaptations in everyday work situations.

METHOD

The examples reported in this article stems from nine focus groups with a total of 32 participants. The participants all work with safety-related issues and accident investigation. The following organizations (and number of participants) were represented: health care (13), nuclear power (8), occupational safety (3), air traffic control (2), maritime transportation (2), emergency services (2), rail transportation (1), and road transportation (1). Although no attempt was made to include the same number of representatives from each organization, the intention was to get experts from different organizations to describe and contrast safety in their work environments. Each focus group therefore included representatives from two or more organizations. A main objective of the discussions was to get practitioners involved in discussions on learning from "what goes right" and how this could be incorporated into their safety work. The focus group methodology was based on approaches described in literature (Boddy, 2005; Jungk & Mullert, 1987; Morgan, 1997; Wibeck, 2000).

The focus groups were carried out on two separate days and were full-day events. The morning session included an introduction to resilience engineering and safety culture. In the afternoon, 3-hour focus group sessions were carried out, with 3 to 4 participants and one focus group leader in each group. Results from the first four focus groups provided many examples of everyday work situations that require local adaptations to cope with hazardous situations. The topic of the five remaining focus groups was consequently narrowed down to "working near the safety margin," focusing on everyday situations in which adaptations were made to cope with fluctuating demands.

All focus group sessions were recorded and the audio files transcribed. The transcriptions were coded by one analyst using iterative bottom-up and top-down approaches. The transcriptions were first divided into categories based on the main topics of the focus group discussions. The bottom-up analysis was then performed, allowing new categories and subcategories to emerge from the data (Miles & Huberman, 1994). ATLAS.it, a qualitative analysis software tool, helped identify links between quotes, codes, comments, and memos tagged in the transcription.

A total of 73 examples of working near the safety margin were extracted from the data. The bottom-up analysis highlighted the connections between the situations both within and between organizations. In 17 of the 73 examples, sharp-end strategies outside of the system's performance envelope were identified. All examples used for further analysis were reviewed by two other analysts. Out of the 17 strategies, 10 were recurring adaptations in everyday situations, 4 were used during irregular events, and 3 were unique adaptations used in a single situation. A subset of the examples is described in detail in the next section.

The examples including sharp-end strategies were subsequently analyzed top down by applying three theoretical frameworks (Furniss, Back, Blandford, et al., 2011; Hollnagel, 2009b; Hollnagel, Pedersen, & Rasmussen, 1981). Two of the frameworks are previously used methods for analyzing system resilience abilities (Furniss, Back, Blandford, et al., 2011; Hollnagel, 2009b). The framework developed by Furniss, Back, Blandford, et al. (2011) aims to identify common features of resilience manifestations across domains. Hollnagel's (2009b) "four cornerstones" framework describes the four main system capabilities critical for achieving resilience. The framework by Hollnagel et al. (1981) was used to analyze the examples on different levels of abstraction, from raw data analysis to a formal and subsequently a more conceptual level of description.

Each example was analyzed in its contextual setting using the resilience marker framework (Furniss, Back, Blandford, et al., 2011) and the four cornerstones (Hollnagel, 2009b). As the resilience markers framework by Furniss, Back, Blandford, et al. (2011) did not capture all findings in the bottom-up analysis of the examples,

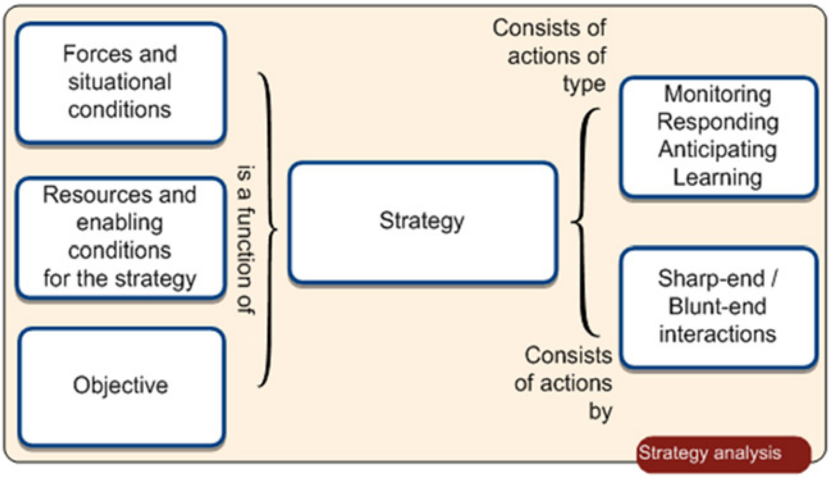

Figure 1. Strategies framework.

some categories were taken out and others revised (see Results section for more detail on included and revised categories).

The result of the analyses was the development of the strategies framework. Further, the variety space diagram was developed to visualize relations between the framework categories.

RESULTS

This section presents the strategies framework and the variety space diagram.

The Strategies Framework for Analyzing Adaptations

The framework is a tool to structure and analyze strategies in everyday work situations in complex systems (see Figure 1). The categories in the framework target three main areas: (a) a contextual analysis, (b) enablers for successful implementation of the strategy, and (c) reverberations of the strategy on the overall system. The following categories are included:

- *Strategies* describes the coping mechanisms (adaptations) used to interpret or respond to variation in the dynamic environment. The strategies may be developed and implemented locally (sharp end) or as part of an instruction or procedure enforced by the organization (blunt end) or both. Furniss, Back, Blandford, et al. (2011) similarly describe strategies as countermeasures taken on the basis of the anticipation of or in response to an outcome.
- *Objective* is the outcome that the strategy is aimed at achieving (similar to Patterson et al., 2004). There may be one or several objectives for the strategy. This category was originally named *vulnerabilities and opportunities* in the markers framework (Furniss, Back, Blandford, et al., 2011). However, the description in the narratives did not allow such a classification and was therefore renamed *objectives*. The *objective* category helps the analyst to identify the intentions of the person implementing the strategy and should be analyzed in combination with the forces and situational conditions. The objective is related to identifying demands, pressures, and conflicting goals.
- *Forces and situational conditions* describes the context in which strategy is carried out. This category was not part of the resilience markers framework (Furniss, Back, Blandford, et al., 2011) but was added to describe the contextual setting and what shapes it. Situational conditions are factors that are believed to influence the system's need to adapt. The conditions occur due to forces, which may be external (e.g., the weather) or internal (e.g., profit) to the system adopting the strategy. Together, the analysis of the forces and the current situation provides information on the manifestation of organizational pressures in a particular context and their effect on trade-offs made by operating personnel.

- *Resources and enabling conditions* describes necessary conditions for successful implementation of the strategy, as described by Furniss, Back, Blandford, et al. (2011). Conditions may be “hard” (e.g., availability of a tool) and “soft” (e.g., availability of knowledge). This category extends the analysis of situational conditions in that it focuses on what allows (or hinders) the strategy from being carried out, revealing information on the systems flexibility.
- *Resilience abilities* refers to the four cornerstones; anticipating, monitoring, responding, and learning, as described by Hollnagel (2009b). A strategy may pertain to one or several of these abilities. When used in analysis of multiple examples, patterns of system abilities (and system inabilities) can be identified in relation to the type of disturbances faced.
- *Sharp-end and blunt-end interactions* has been added to identify how the strategy affects different parts of the distributed system. A sharp-end strategy is created and carried out locally, and a blunt-end strategy is designed and enforced at the blunt end and may affect the sharp-end work in various ways, including what resources, procedures, and training are provided to cope with system variety. A learning system will demonstrate well-functioning sharp-end/blunt-end interactions. High rates of adaptations outside normal work routine may indicate system brittleness. For example, a change in situational conditions may lead to unfitting procedures. To identify how organizational changes affect work performance, the interactions of the different system parts must be monitored.

Variety Space

Variety can be described as the number of states a system can have (Ashby, 1956). This notion has previously been used to demonstrate how operators control complex systems on the basis of continuous feedback and adjustments (Ashby, 1956; Hollnagel & Woods, 2005; Weick, 1995). According to the *law of requisite variety*, the controller of a system has to match the variety of the process to be controlled, and continuous reciprocal adjustments of the interacting systems components are required (Ashby, 1956). As disturbances or unforeseen events occur, an increased amount of variety may be necessary to handle a situation.

The notion of *variety space* is introduced as part of this study and includes all available actions in a particular system state, given system and situational constraints and the ability to make sense of the situation. This means that a system’s ability to deal with disturbances cannot be fully defined but is a function of the social, technical, and environmental constraints at a particular moment in time. The notion of variety space is, hence, used to demonstrate shifts and extensions of the available actions. For the purpose of illustrating adaptations using variety space, three types of variety are introduced: control variety, sensemaking variety, and disturbance variety (Figure 2). *Control variety* covers all the available actions, given environmental constraints. *Sensemaking* is a term used to describe how people structure and organize input from the environment and is the process of seeking information, ascribing meaning, and anticipating events (Klein, Moon, & Hoffman, 2006; Weick, Sutcliffe, & Obstfeld, 2005). *Sensemaking variety* therefore includes the ability to process information and revise it as the world changes, given contextual constraints and the experience and knowledge of the individuals involved. *Disturbance variety* is the range of events that a system may or may not be able to control. A disturbance is that “which displaces, which moves a system from one place to another” (Ashby, 1956, p. 77). A disturbance in the context of this framework is defined in relation to the situational conditions and forces. To manage the disturbance variety, appropriate sensemaking abilities and control actions are required.

The variety space diagram. The variety space diagram (Figure 3) has been developed to illustrate the interactions between a system’s variety and the categories in the strategies framework. The three main points shown in the diagram are (a) how frequent the disturbance is (regular, irregular, or exceptional), (b) the availability of responses to cope with the disturbance (basic, shifted, or extended variety space), and (c) how well the strategy is recognized and supported (or unsupported) by other parts of the organization (sharp- and blunt-end interactions). These three main parts, and the relations between them, illustrate important knowledge

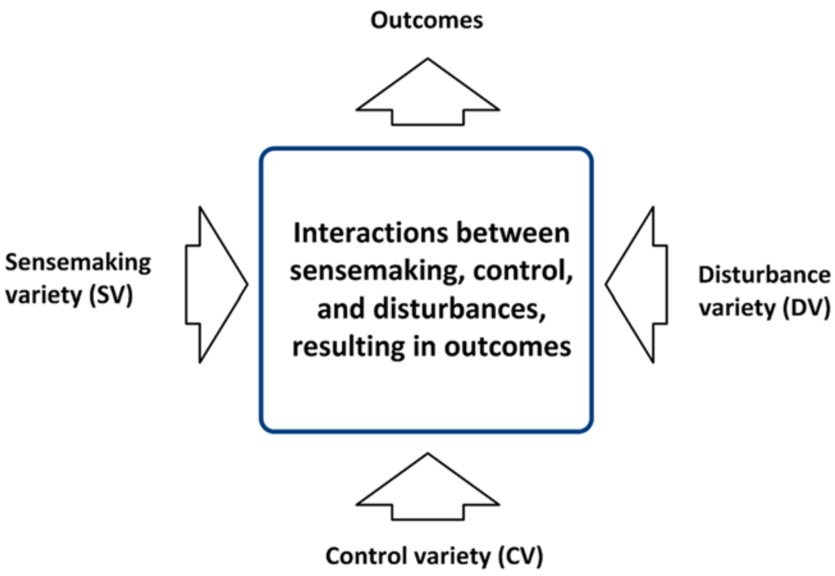

Figure 2. Variety interactions.

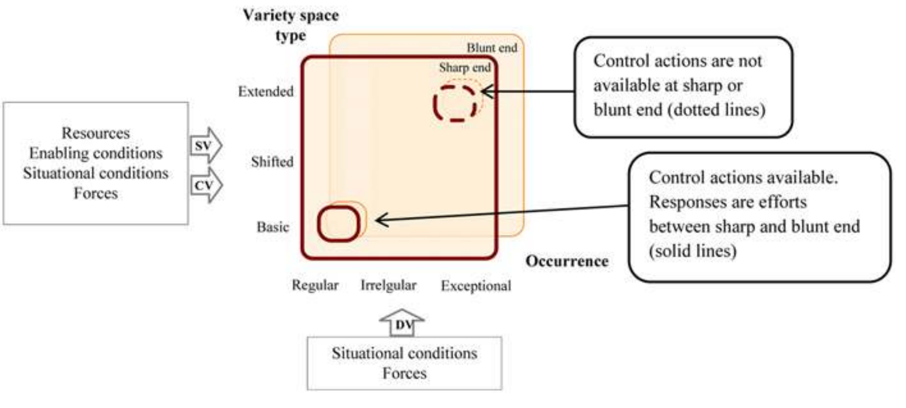

Figure 3. The strategies framework categories illustrated in the variety space diagram.

on the organization's ability to extend its adaptive capacity. A more detailed description of the components of the variety space diagram is presented next.

The variety space types (*y*-axis) allow a distinction between three different types of control actions: basic, shifted, and extended. The availability of control actions is based on sensemaking and control variety, which are combined in this axis, reflecting the dynamical systems perspective focusing on higher-order properties of the perception-action-dynamic in systems where the flow between system and environment is crucial (Jagacinski & Flach, 2002, chap. 1). *Basic variety space* includes familiar and commonly used actions, either described in procedures or checklists or embedded in the system design or as part of the informal work carried out. *Shifted variety space* describes actions available to the system as it goes from one mode to another. The mode of operation refers to the way the system organizes itself (as described by Furniss, Back, Blandford, et al., 2011), and a shift may allow a different set of available actions, such as when a hospital staff reorganizes during an emergency. Note that a shifted mode may involve a reduction of available responses. For example, the time constraint during an emergency may limit the control actions available. *Extended variety space* describes actions that fall outside of the system's current variety space, that is, actions that are not part of formal procedure and the informal work strategies commonly used by the sharp end. The variety space available depends on the controller's sensemaking and control variety, which is affected by forces, situational conditions, resources, and enabling conditions (Figure 3).

The notion of variety space is used to describe "work-as-done" rather than "work-as-imagined" (Hollnagel, 2012b). System variety, affected by, for example, environmental conditions, organizational pressure, and variety created by individuals working in the system, is the underlying force that changes the system demands as well as its ability to cope. As a system evolves, the variety space will shift. For example, novel actions, or the "extended variety space," used by the sharp end to cope with the dynamic environment will become part of the regular work routine, or the "basic variety space," a process described by Rasmussen (1986) as the sharp end "finishing the design."

Basic and extended variety space can be described using the terms *exploitation* and *exploration* as described by Wears (2011). The added value of the variety space concept is the inclusion of what enables (or what may disable) a control action, that is, the controller's ability to make sense of the situation and the resources needed to respond to it. Shifted variety space has been added as mode shifts often have a significant effect on available responses. Shifted variety space helps illustrate the importance of being able to shift modes at the right time to sustain required operation and prevent situations from "going sour," that is, exhausting the system's adaptive capacity (Woods & Sarter, 2000). Further, plotting the situations in the variety space diagram shows how patterns of small adaptations over time become more permanent adaptations, changing the system in potentially unexpected and unintended ways.

The occurrence frequency (x-axis) provides information on the regularity of the particular system state being analyzed: regular, irregular or exceptional. *Regular occurrences* refers to situations that happen regularly enough that there is a standard response to cope with it (note that the regularity does not imply that responses can be performed at all times). *Irregular occurrences* are situations that are known to happen but are not as common and for which responses may not be as well rehearsed as in regular occurrences. *Exceptional occurrences* include situations that are rare enough not to have a ready response and require the system to adapt outside its performance envelope. The categories can be compared to Westrum's (2006) typology of situations, although *unexampled* has been modified to *exceptional*. As "unexampled" situations are extremely rare, *exceptional* was seen as a more appropriate term to describe situations that are rare enough to not have a predefined or ready response but not necessarily situations that fundamentally change the understanding of the system, that is, unexampled.

The occurrence frequency axis demonstrates how often a particular situation occurs, and the variety axis describes the actions available to deal with the occurrence. An occurrence can therefore be exceptional but still be dealt with using basic variety space. The system state is affected by the disturbance variety, which in turn is shaped by situational conditions and system forces. The relationship between the two axes allows a representation of a system's ability to cope with disturbances (at all frequency levels) on the basis of familiar responses and in what type of situation novel action is commonly invented. Over time, as multiple data points are collected and analyzed, this representation may allow the emergence of patterns of a system's adaptive capacities and brittle parts.

The sharp- and blunt-end interactions are illustrated as a three-dimensional box in the diagram (Figure 3). The front represents the sharp end, and the back represents the blunt end. A solid line indicates that the action is available, and a dotted line represents a lack of available action or lack of support for an action.

Analysis

In this section, examples from the focus group discussions demonstrate the use of the framework and the variety space diagram.

TABLE 1: Summary of Strategies Framework Analysis, Examples 1 and 2

Framework	Example 1	Example 2
Strategy	Short planning based on previous training, copilot watches over captain according to procedure	—
Forces and situational conditions	Weather conditions, busy ports, limited room	Leaking chemical substance, incorrect information, checklist not available, resources unavailable
Resources and enabling conditions	Staff, trained procedures, copilot	—
Sharp/blunt end	Blunt end procedure implemented at sharp end	Blunt end procedure is not implemented at sharp end
Objective	Avoid collision	Mode shift
System ability	Anticipating/monitoring/ responding	—

Examples include situations when the system has sufficient variety available to manage the disturbance (Example 1), when there is insufficient variety to manage the disturbance (Example 2), and when the basic and shifted variety is insufficient but the system successfully manages to adapt by extending its variety (Examples 3 through 6). All examples are presented as follows: (a) summary of analysis with the strategies framework (Tables 1 and 2), (b) summary and analysis of each event, and (c) an illustration of the example in the variety space diagram (Figures 4 through 9). (Summaries are based on the narrative provided by the focus group participants and have been modified by the analyst and first author for the purpose of clarity and readability in this article.) Examples are also described in terms of the four fundamental resilience abilities: anticipating, monitoring, responding, and learning.

Sufficient Control Actions

Example 1 demonstrates a situation in which the system is able cope with changes in the environment.

Example 1: Busy ports (maritime transportation). Operating a ship during peak traffic time in a busy port is inevitably full of situations in which minor failures to adapt may have large consequences. Practitioners report working with small margins of safety and taking evasive maneuvers to avoid collision (regular occurrence, basic variety space). External factors, such as bad weather conditions, other vessels, and limited room, add to the complexity. Strategies used by the crew include having a copilot watch over the captain. As a situation deteriorates, such as in extreme weather conditions, there are a number of "short-term strategies" (part of standard operating procedures) that are implemented (shift variety space). The strategies allow a set of coordinated maneuvers to monitor and respond to changes in the environment. As illustrated in Figure 4, the successful outcome of applying short-term strategies comes from the interplay between the blunt and the sharp end; the standard operating procedures are enforced at the blunt end and realized at the sharp end.

A systematic analysis of the use of strategies that provide sufficient control actions in response to difficult situations aims to provide a more comprehensive overview of the forces and conditions faced by the system, the most important strategies used, and what enables them. Capturing formal and informal strategies can shed light on system reserve capacity and system brittleness. This information can lay the basis for a more predictive analysis, such as the effect of introducing new situational conditions (e.g., a staff decrease) and how this affects enablers of common strategies.

TABLE 2: Summary of Strategies Framework Analysis, Examples 3 to 6

Framework	Example 3	Example 4	Example 5	Example 6
Strategy	Slow down, push and pull people on and off train, close doors 30 seconds prior to departure	Get expert knowledge from neighboring plant	Organize medication, order from different suppliers	Prioritize strategy, create new "high-workload" procedure
Forces and situational conditions	Train doors unlocked due to EU regulation, late passengers try to get on train, train aims to leave on schedule due to system dependencies and economic gain	Loss of power in important parts of the plant, in-house knowledge and instructions unavailable, maintenance of plant is largely outsourced	Medicine packets of varying potency look similar; barriers are sometimes bypassed in emergencies, increasing the risk of giving wrong medications	Inadequate resources due to many births, patient sent from emergency room because overloaded
Resources and enabling conditions	Detect dangerous act, staff availability, ability to go slowly	Availability of expert	Knowledge of local adaptation, time to implement strategy	System structure supporting reorganization
Sharp/blunt end	Sharp- and blunt-end strategies available	Sharp end	Sharp end	Sharp-end strategy turns into blunt-end procedure
Objective	Avoid passengers' getting hurt	Regain power at plant	Give patients the right medication	Manage workload with current resources
System ability	Monitoring/ responding	Responding	Anticipating/ learning	Responding/ learning

Insufficient Control Actions

Example 2 demonstrates a situation in which there are insufficient control actions to cope with changes in the environment.

Example 2: Preparing for the wrong situation (emergency services). A firefighter team receives an alarm regarding a leaking chemical substance at a petrol station (irregular occurrence; Figure 5). The team leaves the fire station and prepares the operational work by going through procedures for the reported chemical (basic variety space). However, upon arrival, it becomes clear that the wrong chemical has been reported. The fire chief has to reevaluate the situation, and the team that is sent out is not able to manage the situation. The team attempts to shift modes to deal with the chemical, which causes a delay in response, and important steps in the response procedure are left out (unsuccessful shift variety space).

Actions to cope with the different chemicals are part of the system's repertoire of control actions, supported by the blunt end. However, preparing for the wrong occurrence forces the system to shift mode in order to respond to the situation. The system lacks resources to deal with the situation and has no strategy to aid the shift of modes, and the system has to "restart." The lack of strategies at the sharp end is illustrated

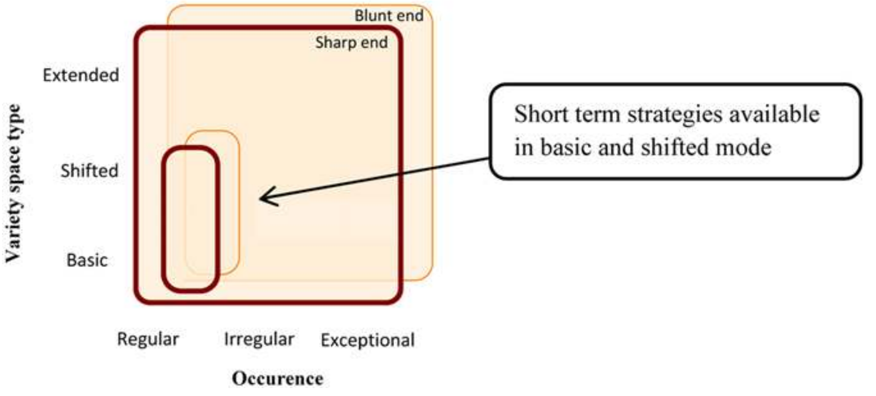

Figure 4. Example 1 (busy ports) illustrated in the variety space diagram.

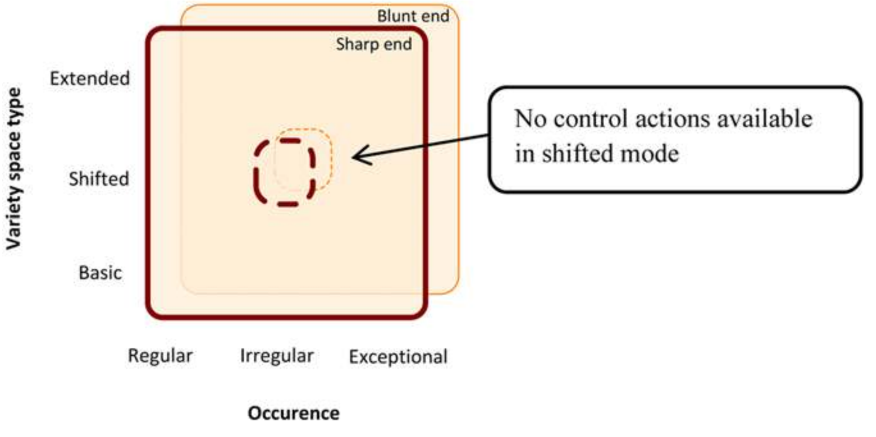

Figure 5. Example 2 (preparing for the wrong situation) illustrated in the variety space diagram.

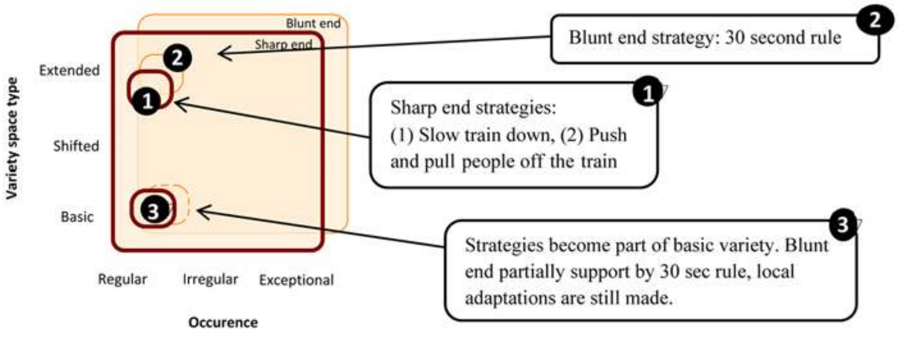

Figure 6. Example 3 (late passenger) illustrated in the variety space diagram.

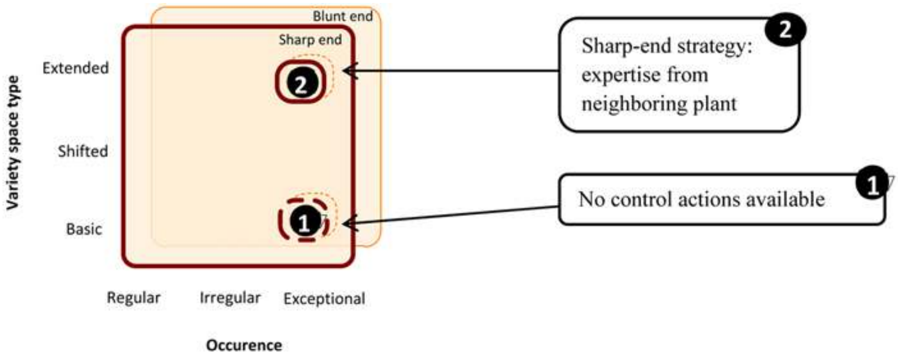

Figure 7. Example 4 (the open valve) illustrated in the variety space diagram.

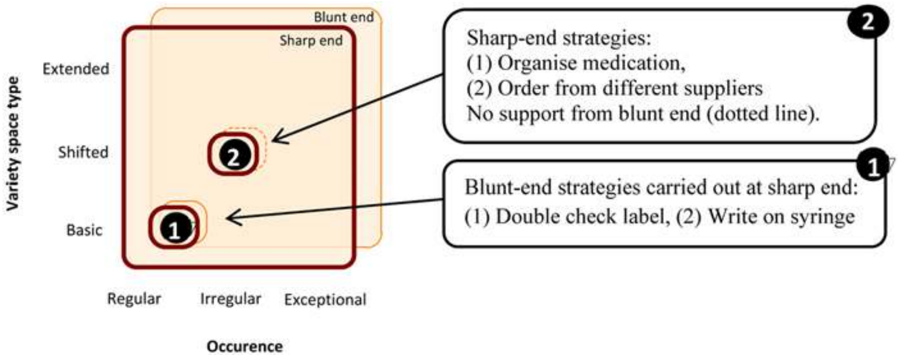

Figure 8. Example 5 (medication packaging) illustrated in the variety space diagram.

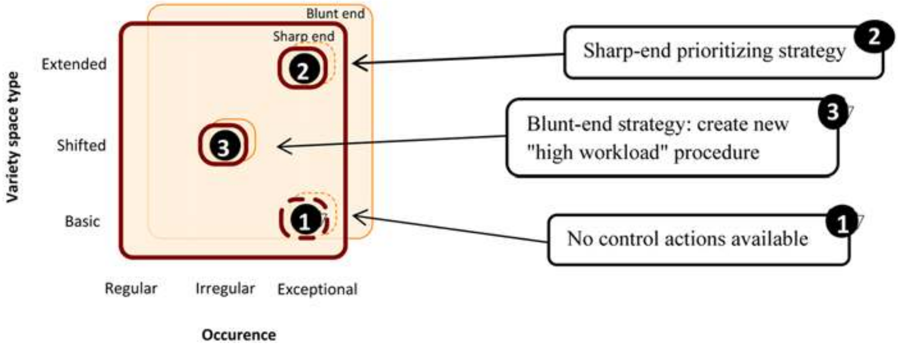

Figure 9. Example 6 (too many births) illustrated in the variety space diagram.

by a dotted line in the variety space diagram. The blunt end also remains dotted, as there is no support for the sharp end to rapidly get the right recourses in place (Figure 5).

Novel Control Actions (Extending the Variety Space)

One way to handle a situation when there is no predefined response is to create a novel response, that is, increase the amount of control actions and extend the system's variety space, as is shown in Examples 3 and 6. Resilient acts do not only include an increase in the control and sensemaking variety but can also be strategies to minimize the disturbance by lessening the effect they have on the system, as is shown in Examples 4 and 5.

Example 3: Late passengers (rail transportation). On some types of intercity trains, late passengers open the doors and get on when the train is already in motion. This activity happens on a daily basis (regular occurrence). Although it is against the law, it is rarely reported as an incident as it is considered "normal." Several severe accidents have occurred, some with fatal outcomes. An external force affecting the situation is a law within the EU stating that train doors cannot be locked if there is a step and handle on the outside. The step and handle cannot be removed as the shunting personnel need them to perform their work. Incidents and accidents are often avoided thanks to staff intervention. Strategies identified include the following: (a) The train driver slows down if he or she detects a passenger trying to get on, and (b) conductors (or other staff members) push or pull passengers on or off the train. The strategies require staff availability to monitor and respond and enough lag time to drive slowly. In circumstances such as shortage of staff or when the train is behind schedule, there is limited ability to detect and respond to the dangerous behavior. In an attempt to improve the situation, the rail operator has recently enforced a new rule stating that the train doors should close 30 seconds prior to departure. This is, however, not enough to eliminate the problem, and local adaptations are still made.

As there is no available control action to manage the hazardous situation, the train staff adapts by extending its repertoire of actions (Figure 6, No. 1). The blunt end provides support by enforcing the 30-second rule (Figure 6, No. 2). Although the blunt-end procedure improves the situation, it is not sufficient to deal with the occurrences, as illustrated by the semi-dotted line, and local strategies still have to be implemented (Figure 6, No. 3). As the sharp- and blunt-end strategies are proven fruitful, they become part of the staff's normal operational routine, that is, their basic variety space. This example demonstrates how adjustments at the sharp end to meet situational demands may turn into a strategy used as part of the normal work routine. Over time, such adaptations may create a gap between work-as-imagined (blunt-end view) and work-as-performed (sharp-end reality). An increasing gap can create vulnerabilities farther down the line as organizational changes are made without the ability to foresee its effect on the sharp-end work. The strategies in the example demonstrate system potential to increase its ability to monitor and respond to recurring disturbances.

Example 4: The open valve (nuclear power). One afternoon, for seemingly unknown reasons, power was lost in critical parts of a nuclear plant. For almost all disturbances, there are instructions available to identify and solve problems. However, in this exceptional case, there was no suitable instruction and the operators found themselves without in-house knowledge and ideas of how to search for, and solve, the problem (Figure 7, No. 1). Following several "trials and errors," the operators were finally able to get an expert from a neighboring plant to come over and resolve the mystery (extended variety space; Figure 7, No. 2). The reason for the power loss was a closed service valve. The valve had been closed during maintenance and its reopening overlooked. As maintenance work is largely outsourced (to keep costs down), knowledge about the valves was also outsourced. Hence, the issue was solved by extending the variety space through allocating and relocating resources. This source of input is, however, not a stable one; had the occurrence happened at a different time or on a different day, it may not have been available. Learning from this incident by making sure expert knowledge is available in case of an emergency (as suggested by the respondent) would have exemplified a learning system. However, as illustrated in Figure 7 (and in comparison to Example 5), actions at the blunt end to extend the variety space were not taken, and the line in the variety space diagram has therefore been dotted. Although the system did demonstrate the ability to successfully respond to the disturbance, given the current resources and enabling conditions, the analysis highlights that the success was partly due to enabling conditions that were uncontrolled. These remain uncontrolled and may therefore be available sometimes but not at other times.

Example 5: Medication packaging (health care). Medicine packets from pharmaceutical companies in Sweden sometimes look very similar. Highly potent medicine can therefore be placed next to similar-looking, commonly used, less potent medication. For instance, an ampule containing 10,000 units can look exactly the same as an ampule containing 100,000 units, apart from an extra 0, even though the medication containing 100,000 units is much more potent. Usually, before giving medication (regular occurrence), a nurse will put a label on the syringe and enter information regarding type and dosage of the medication, double-checking the label on the original package (basic variety space). The strategies are enforced at the blunt end and carried out at the sharp end, as illustrated in Figure 8, No. 1. However, in a state of emergency (irregular occurrence), time is critical, leading to a decrease in possible actions (shift variety space), and these barriers are often bypassed. Two different hospitals report using local, sharp-end adaptations to create a more robust situation (Figure 8, No. 2). At one hospital, the sharp-end staff organizes the medicine room, the emergency carriage, and the operating room to provide a spatial barrier between medicine packets with a similar appearance. At another hospital, sharp-end personnel order different potencies from different pharmaceutical companies, resulting in different-colored ampules and thus creating a color barrier (Figure 8, No. 2).

The blunt-end-supported procedures are insufficient when time is most critical, and local sharp-end strategies are implemented as a result (Figure 8). To cope with the situational demands, sharp-end personnel create additional barriers, which become part of normal routine operations (basic variety space). The sharp-end personnel thus demonstrate the ability to learn from previous incidents and anticipate potentially hazardous situations. However, the blunt end remains dotted, as there are no reports that the risk of similar medicine packages has been acknowledged, or if staff members know, they have not taken any actions to improve the situation (e.g., enforce strategies as procedures, change pharmaceutical company). As is described in the section Sharp-End and Blunt-End Interactions, this situation has had negative consequences as changes are made in other parts of the system. The importance of the strategies is greatest during an emergency, when some control actions are unavailable due to time constraints (i.e., in shifted variety space).

Example 6: Too many births (health care). A remarkably large number of births one evening led to chaos at a maternity ward (exceptional occurrence). The ward was understaffed and no beds were available for more patients arriving. Further, patients from the emergency room with gynecological needs were being directed to the maternity ward. To cope with the situation, one of the doctors made the decision to free resources by sending all fathers of the newborn babies home (extended variety space). Although not a popular decision among the patients, this reorganization freed up beds, allowing the staff to increase capacity and successfully manage all the patients and births. After this incident, an analysis was performed that resulted in a new procedure for "extreme load at maternity hospital" (irregular occurrence, shift variety space).

Figure 9 illustrates the changes in variety space. First, the system performance exceeds its boundaries, as current resources are insufficient to manage all patients in need of care (Figure 9, No. 1). Second, a prioritizing strategy is implemented that brings the number of patients to a level at which the basic control actions are sufficient to cope (Figure 9, No. 2). Third, the system actively takes steps to learn from the occurrence and extends its variety space by adding a new procedure to the repertoire of actions available (a variety space shift) should a situation like it happen again (Figure 9, No. 3). The occurrence is now irregular rather than exceptional, as a prepared response is now in place

(Figure 9, No. 3). The system has adapted and demonstrates several important abilities contributing to system resilience by using its adaptive capacity to respond to the event and further learn from it.

Sharp-End and Blunt-End Interactions

Adaptive performance for increasing resilience can manifest on all levels of an organization and affect all other parts of the system. As illustrated in the variety space diagram, the strategies are the result of decisions made at both the blunt and the sharp end. Further, the examples show that strategies can start out as local adaptations (sharp end) but over time be implemented as a procedure (blunt end), signifying that the system has the ability not only to respond by adapting to harmful situations but also to learn from them (e.g., Example 6), something also demonstrated in previous studies (e.g., Cook & Woods, 1996). This example can be compared to Example 4, in which a mobilization of resources resolved the immediate problem but no effort was made at the blunt end to acknowledge the exposed system brittleness and learn from the incident. Also demonstrated in the examples is the power of complementary strategies, that is, strategies from several levels of the organization working toward the same goal (e.g., Example 3). As the blunt-end-induced strategy (closing the door 30 seconds prior to departure) reduced the disturbance, this strategy enabled the sharp-end staff to free more resources and better manage the unsafe situations.

However, if local adaptations are not communicated and acknowledged upward and downward in an organization, it could potentially harm the system. For example, the color-coding strategy used by medical staff in Example 5 is implemented only locally. One time the pharmacy (external actor) placed the order with a different supplier (the supplier was temporarily out of the required medication), and the local color codes were therefore no longer correct. As this change was not communicated to the nurses, the system is now at a much higher risk than had the strategies never been implemented in the first place. Potential harmful side effects show the importance of monitoring local adaptations. System variability constantly requires new ways to handle situations, and over time, the consequences of unmonitored (unknown) adaptations has on the system are hard to predict.

Resilience and Brittleness

Strategies that have a positive effect in one system part may affect a different part of the system negatively. As the examples show, the allocation and reallocation of resources serve an important role in realizing the strategies. Adapting a system to current conditions often entails a shift in resources by, for example, moving them from one part of the system to another (e.g., Example 6). Such a reorganization has previously been identified as a critical marker for resilience (Stephens, Woods, Branlat, & Wears, 2011) and can be very effective as it allows an increase in resources where it is necessary. In other situations, a strategy may not rely on reorganization of resources but instead contribute to increased strain on existing resources. For example, in Example 3, the sharp-end adaptation of pushing and pulling people off the train absorbs resources designed for other areas of operation. The blunt-end adaptation of enforcing a new procedure does not solve the problem but allows a certain amount of pressure to be released from staff. If adaptive acts lead to reduced (in some parts) or overall diluted resources, it may lead to problems in other parts of the system. As resilience is increased in one area, it may lead to brittleness in another.

To identify indicators of system resilience and its relation to system safety boundaries, the four system-abilities classification is used (anticipating, monitoring, responding, and learning). Although some element of uncertainty will be continuously present, proactive adaptations often have the advantage that they “buy time” (Examples 1 and 5) compared to reactive responses (Examples 3, 4, and 6) when little or no time for feedback can more readily result in an unwanted outcome (Example 2). The resilience indicators help in identifying cognitive pressure points (Woods & Dekker, 2000) and areas for further investigation. An understanding of system capabilities in relation to system boundaries requires systematic data gathering of adaptive performance to see how they change over time.

DISCUSSION

The strategies framework and the variety space diagram are tools developed to facilitate the analysis of how systems adapt in everyday operations to cope with variability and compensate for system limitations. The framework should be viewed as a complementary perspective to established incident investigations and risk analysis by highlighting not only system weaknesses but also system strengths. By charting and analyzing enablers of successful adaptations and how adaptations affect other parts of the system, information is gained that may not surface in traditional safety analysis methods. Highlighting sociotechnical systems' adaptive abilities provides direction on how to improve the design of systems, including the introduction of new technology, training, and procedures.

Framework Contribution and Application

The strategies framework extends previous studies of adaptation in several areas. First, it describes the adaptation-enabling factors, and second, it supports both retrospective and prospective safety management activities. Third, the development of the variety space diagram allows an illustration of the framework analysis.

Resilience engineering focuses not only on creating resilient systems but also on maintaining and managing system resilience (Hollnagel, 2011). This process requires monitoring patterns of adaptive responses to detect system brittleness, system resilience, and how close a system is operating to its safety boundaries. The strategies framework is a tool to report findings, structure cases, and make sense of them. A main contribution is its emphasis on describing adaptation-enabling factors and their relation to organizational forces shaping the work environment. Systematic gathering of information regarding adaptation enablers is important for understanding the conditions creating and limiting adaptive opportunities in the environment.

The strategies framework aims to describe everyday work practices, information that can be used to analyze past events and future scenarios. The framework is therefore intended to support both retrospective and prospective safety management activities. Retrospective analysis is demonstrated in the examples provided in this article. Prospective analysis is supported by the framework analysis of adaptation enablers, objectives, and situational conditions. This information supports making predictions on how changes (e.g., increased production pressure or the introduction of new technology) may affect the system. In this sense, it fits together with risk assessment and related predictive safety management activities, rather than being a predictive model in itself.

The variety space diagram is a tool to illustrate how abilities in a situation continuously change depending on current situational conditions and constraints and how this change affects the use of strategies. It allows for a differentiation between actions supported by the blunt end (procedures, instructions, system design) and actions created by the sharp end to cope with system variability in the work environment. It also helps distinguish between strategies created outside of the design base (extended variety space) and strategies that have been developed over time and are part of individual's, team's, or an organization's regular work performance (basic and shifted variety space). Identifying how systems manage disturbances of different occurrence frequencies opens up a forum for discussion of system design and training programs. For some disturbances, it might be valuable to support people in being innovative and creative (extended variety space), and for other disturbances, support through guiding procedures should be available if needed (shift variety space).

Besides being a tool for analysts, a potential application area for the framework is as a discussion guide for practitioners and managers. In the focus group discussions, it was emphasized several times that there is a lack of understanding for the work carried out at the sharp end and that little attention is paid to the "things that go right." The strategies framework can be used as a guide to discuss work practices and work patterns not explicitly available through procedures and other documentation. How practitioners and their management recognize, communicate, and perceive work practice is critical for managing and maintaining system resilience. Directed attention to informal knowledge exchange in or between workgroups allows insights into individual and team abilities to cope with the dynamics of their complex work environment.

Limitations and Further Research

The framework is an initial step. Further studies are encouraged to evaluate and develop the framework as a means for researchers and practitioners to systematically analyze adaptive strategies and as a practical methodology to integrate with established safety management. Results from systematically applying the strategies framework are intended to provide information that can be used to make predictions on system changes and how they may affect the overall system. The framework is thus a starting point for both researchers and practitioners to identify critical enablers and for the systematic analysis of adaptations that may not surface through traditional safety reporting mechanisms. Next steps include analyzing strategies on a more abstracted level (Rankin et al., 2011), which will provide indications, on a more general level, of the system's adaptive abilities, what enables them, and what affects the situations in which adaptations are necessary.

CONCLUSIONS

This study suggests, in concurrence with many previous studies, that people hold great capabilities to adapt to unfolding events in a complex and uncertain environment. To increase system resilience potential, the system design should support and enable people to be adaptive. This, however, does not suggest that people should be expected to cover for all limitations of system design. On the contrary, systems should be designed on the basis of knowledge of how people perform, the organizational forces, and conditions of situations. The trade-off between prepared-for responses (basic and extended variety space) and the need to adapt (extended variety space), while also considering the occurrence frequency (regular, irregular, exceptional), should be emphasized. Further, processes of sharp-end and blunt-end interactions must be considered to uncover how sharp-end adaptations may be strengthened, how they strengthen the system as a whole, or how they become weakened or are turned into vulnerabilities through interactions with the blunt end.

Understanding how organizations cope as they work close to their safety margin in everyday work situations helps identify system brittleness and resilience. Systematic identification and analysis of strategies will help unravel important elements of adaptations that can guide organizations and prepare for disturbances and unforeseen events.

The main contributions of this work are (a) the strategies framework for practitioners and researchers to report findings, structure cases, and make sense of sharp-end adaptations in complex work settings; (b) a description of adaptation-enabling factors and their relation to organizations' forces shaping the working environment; (c) support for retrospective and prospective safety management activities; (d) the variety space diagram to illustrate how system variety can describe strategies and blunt-end/sharp-end interactions; (e) a demonstration of how local adaptations are created outside the system design base and then turn into system adaptations to cope with risks identified in the system; and (f) analysis of examples from different work settings demonstrating the possibility of using the same analysis framework in different complex, sociotechnical systems.

There is a great deal to learn from systematic gathering and analysis of sharp-end responses to disturbances and unforeseen events. Shifting attention from past negative experiences to methods that enable organizations to anticipate future changes is necessary to further increase successful performance (and avoid future failures). This requires that we further increase our knowledge on everyday sharp-end adaptations and factors affecting them.

ACKNOWLEDGMENTS

This study was sponsored by the Swedish Civil Contingency Agency. We are also indebted to the accident investigation professionals who participated in our focus groups. We are grateful for the comments of reviewers and audience of the 4th Resilience Engineering Symposium, where an initial version of this research was presented (Rankin et al., 2011), and for all the insightful comments by the anonymous reviewers of this article.

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