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Conceptualizing Multiagency Emergency Management System as Joint Cognitive System

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Emergency management system (EMS) provides a crucial barrier for the protection of socio-ecological infrastructure from man-made disasters and natural threats. To meet diverse demands from hazardous events, resilience engineering is considered as an effective approach to enhance the performance of EMS. While conceptual and qualitative descriptions of resilience are abundant, ideas of operationalizing resilience are scarce. In this regard, the present work redefines resilience in the EMS and proposes a framework of measuring resilience by abstracting the EMS as a joint cognitive system.

INTRODUCTION

Several major catastrophic incidents that occurred in the past few decades reassure the inherent limitations of controlling risks in complex systems. Such examples include Fukushima Daiichi nuclear meltdown (2012), Macondo well blowout (2010) and Hurricane Katrina (2005). While preventing such disasters is of utmost primacy, accidents in complex systems are often unavoidable. To minimize, once they take place, the extent of detrimental impact on the human lives, and social and environmental infrastructure, efforts for effectively managing emergency play the most pivotal defensive role (Kanno & Furuta, 2006).

Like other complex systems in which humans interact with various advanced technologies, emergency management system (EMS) not only takes benefits from technologies amplifying human capabilities but, at the same time, these systems may be vulnerable to loss of control. This vulnerability becomes more critical in the face of large-scale events that require longer-term efforts and multijurisdictional collaborations.

Managing unexpected, unforeseen disruptions necessitates a different approach that aids the system to maintain its control against perturbations that escalate and facilitates the adaptation to emerging changes. More often than not, this becomes com-mon undertakings in joint cognitive systems in which human-machine ensemble has to cope with complexity in the use of various technological artifacts in order to remain in control (Hollnagel & Woods, 2005). Among other approaches, resilience engineering offers proactive approach for maintaining control by understanding what is happening (monitor), forecasting what may occur (anticipate), knowing what to do (respond) and updating a priori knowledge from both failure and success (learn) (Hollnagel, Woods, & Leveson, 2006)

WEALTH AND DEARTH IN RESILIENCE

A plethora of theoretical and anecdotal discourses about resilience has hitherto been accumulated. In particular, there are vigorous attempts to conceptualize resilience and narrate resilient patterns from real-life examples in hindsight (see Hollnagel, 2013; Hollnagel et al., 2006). As a result, evidences justifying the need of a new safety paradigm are amassing and definitions of resilience are converging to a consensus despite the nuanced differences in the context from which it is approached.

What is most obviously lacking to date is quantitative measures of resilience that then render a condition for supportive system designs and decision-making processes in cognitive systems. A dearth of operational definitions for resilience and differentiation from other system properties has been pointed out by a multitude of authors (Francis & Bekera, 2014; Hoffman & Hancock, 2016; Madni & Jackson, 2009; Righi, Saurin, & Wachs, 2015).

Since resilience is a tacit systems attribute, it manifests itself as resilient performance, which is generated from the interaction of distributed cognition, goal-means relations, and sudden demands (Cook & Nemeth, 2006). In such regard, emergency-handling situations themselves provide excellent opportunities to examine how human cognition actually functions near and over the boundaries of experience and capability (Mendonça & Hu, 2007). This also agrees to the necessity to examine 'cognition in wild' for better understanding how works are actually done by cognitive systems (Hollnagel & Woods, 2005; Hutchins, 1995). In healthcare systems, emergency departments (EDs) serve as the most suitable laboratory for observing resilient performance (Stephens, Woods, Branlat, & Wears, 2011). Analogous to EDs, it is assumed that EMS working against man-made and natural disasters can act as an excellent studio that displays resilience of the organization.

EMS AS A JOINT COGNITIVE SYSTEM

Cognitive Characteristics of EMS

Cognitive engineering refers to the study of design principles that enhance human performance of problem-solving in complex systems (Woods & Roth, 1988). Incessant development of technology and thus increasing system complexity calls for more focus on cognitive functions between human and machine rather than physical and physiological interaction because such system largely relies on the use of knowledge about itself as well as about the environment (Hollnagel & Woods, 1983). More recently, Hollnagel and Woods (2005) define a cognitive system as "*a system that can modify its behavior on the basis of experience so as to achieve specific anti-entropic ends."* According to their definition, some if not all machines and technological artifacts can be regarded as cognitive systems forming a Joint Cognitive System (JCS) along with humans.

It is easier to say than to prove that an emergency management system (EMS) is a joint cognitive system (JCS). To understand complex interactions between humans and other components of EMS, tenets of Cognitive Systems Engineering are employed. CSE shows promise in taking an ecological approach that assesses how humans solve problems by interacting with technical artifacts in the multifaceted, dynamic and open world (Woods & Roth, 1988).

In order to understand the cognitive characteristics of the EMS, the several standpoints are discussed:

Coping with complexity. The EMS is operated and supported by a host of technological artifacts. These artifacts are highly coupled and jointly work. Hence, failure of one system may bring the whole system to a collapse. Moreover, operators and practitioners in EMS are confronted with excessive amount of data coming from both internal and external sources.

Ecological approach. It would be remarkably difficult to observe how humans solve problems in EMS in a controlled setting such as a research laboratory. Hence, studying EMS is likely best achieved when it is situated in a real or realistic environment as presented in **Error! Reference source not found.**. This argument naturally relates to the next standpoint about semantics of the domain.

Domain-specific knowledge. This is concerned with how operators and practitioners in the EMS perform by satisfying cognitive requirements that the emergency they're facing imposes. Hence, this approach is problem-driven in that the cognitive engineering practices such as representational aids, decision support and supervisory tool, vary upon the problem-solving context.

Figure 1. A Simulated Incident Management Training (Source: Texas A&M Engineering Extension Service)

The performance of the EMS is goal-oriented (e.g., control of hazards and saving lives) and therefore it strives to improve the performance by planning and changing its actions predicated on the understanding about itself and the environment. This is why a cognitive system becomes an adaptive system (Hollnagel & Woods, 1983).

Even though there are numerous occasions of human-machine interaction in the EMS, the ultimate goal of CSE in this domain is not limited to improving individual interface between human and machine, but it is mostly focused on how the entire EMS performs as a multilayered JCS.

Figure 2 represents the multiple layers of JCS identified in the structure of EMS. To simply put, one team is comprised of multiple sections such as Planning Section and Operations Section. Next, a section has a certain number of functional units, for example, Situation Unit and Documentation Unit in the Planning Section. Functions assigned for each unit are accomplished by single or multiple operators (Department of Homeland Security, 2008). On the other side, these entities interact with tools at different levels such as personal computer (operator level), telecommunication device (operator level), white board (unit/section level) and large displays (team level). Thus, the performance of the EMS is a system's emergent behavior that results from the interaction across different layers. Tenets of CSE provide how to couple human cognitive functions and technological tools, how to improve the holistic performance of a human-machine ensemble or coagent and how to maintain control of what it does (Hollnagel & Woods, 2005; Woods & Roth, 1988).

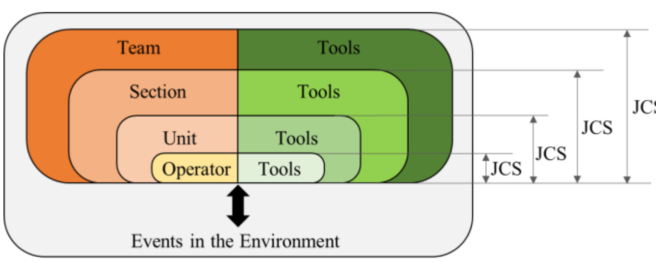

Figure 2. Multilayered JCS in the EMS

Maintaining Control in EMS

The primary goal of the EMS is to recover from unwanted consequences, for example, rescuing the injured from the scene and putting out a fire in a refinery. If these measures do not work, the condition deteriorates over times, then EMS is bound to lose control as a result. Resilience is "a form of control" and resilience engineering concerns about designing a system in a way that it is able to maintain control in the face of changes (Leveson et al., 2006). Especially, the EMS like any other JCS is susceptible to limited time, limited knowledge, lack of competence and limited resources (Hollnagel & Woods, 2005). With that said, the following proposal for redefining and operationalizing resilience in emergency management would help identify cognitive processes within the system and provide analytical approach to address the deficits mentioned above.

CONCEPTUALIZATION FRAMEWORK

Direct measurement of implicit system qualities such as resilience is not simple and may not be possible. Accordingly, the current study takes a hierarchical approach similar to (Hoffman & Hancock, 2016) that consists of three steps: 1) redefining resilience in EMS, 2) characterizing components and features that suit such a definition, and 3) developing operational specifications of those components.

Redefining Resilience in EMS

Due to the relentless efforts to make resilience a useful and usable construct, definitions of resilience are affluent across different disciplines but scant is the definition of resilience in the domain of emergency management (Hosseini, Barker, & Ramirez-Marquez, 2016; Righi et al., 2015). Among those, Cook & Nemeth offer the definition of resilience as "*a feature of some systems that allows them to respond to sudden, unanticipated demands for performance and then to return to their normal operating condition quickly and with a minimum decrement in their performance* (Cook & Nemeth, 2006)." In EMS, the system copes with various events which not only occur suddenly or but also slowly escalate or even that are planned ahead. Moreover, the performance of EMS is fundamentally constrained (or facilitated) by the deployment of resources. Hence, this study by giving these additional features proposes the following definition of resilience: *a system's capability to respond to different kinds of disrupting events and to bring the system back to a desired state in a timely manner with efficient use of resources, and with minimum loss of performance capacity*.

In order to make this definition operational in EMS, conceptual framework of cognitive process is proposed as shown in **Error! Reference source not found.**. The fundamental underlying assumption for this model is that the information processing system of a joint cognitive system *must* resemble that of a human operator, an original cognitive system. In the EMS, the largest JCS comprises three critical cognitive functions: Command, Planning and Operations. National Incident Management System (NIMS) specifies two additional functions: Logistics and Finance & Administration (F&A) (Department of Homeland Security, 2008). Logistics feeds required and requested resources such as workforce, equipment and material for the system operations and F&A does the accounting of resources as those resources are actually used to execute its given missions.

External stimuli to this JCS are events that occur outside of its boundary such as uncontrolled events, or simply accidents. When these events do happen, they are typically perceived by the 'boots-on-the-ground' in the Operations function. The perceived data are reported and transported to the Planning function in which such data are transformed into useful and meaningful information. This information provides knowledge base for establishing a set of decisions. Subsequently, Command function selects some of those decisions and authorizes them with adequate resources so that Operations actually take actions to the uncontrolled events. This compensation process continues until the JCS achieves its systematic goal which is controlling the event.

As a virtual processor among these functions, collective working memory (CWM) and collective long-term memory (CLTM) are suggested. CWM can be manifested in the form of shared displays, document or whiteboards used by teams. Similarly, CLTM can take forms of past accident reports, procedures and guidelines.

Characterizing Components of Resilience

Resilience is a multifaceted construct which can be approached by multiple components or features. Some of these features include adaptability, robustness, flexibility, improvisation to mention only a few. Sheer comparison among these features may not be possible *yet* but continual efforts to discriminate resilience from other system properties are necessary. In this work, the following components are proposed as resilient performance factors (RPF) which characterize how resilient an organization is:

- Adaptive response
- Rapidity of recovery
- Resource utilization
- Performance stability
- Team Situation Awareness (TSA)

Adaptive response. One of the most evident patterns of resilient performance is that the responses are adaptive to the changing environment or stimuli from such environment (Leveson et al., 2006; Rankin, Lundberg, Woltjer, Rollenhagen, & Hollnagel, 2013). The adaptive capability is not only confined to reactive compensation for its performance but also it requires to adapt to the evolving conditions by forecasting what may occur (Woods, 2015).

Rapid recovery. Another factor that typifies resilience of a system is how quickly it bounces back from perturbations (Hosseini et al., 2016). To be resilient, a system must be quick in resolving disruptions and restoring its control. However, there exists an efficiency-thoroughness trade-off or ETTO by which a system cannot attain any outcome that is both thorough and efficient (Hollnagel, 2009). Often true is that the restored level of control may not be equal to what it was but it should come within a state that enables to sustain its performance.

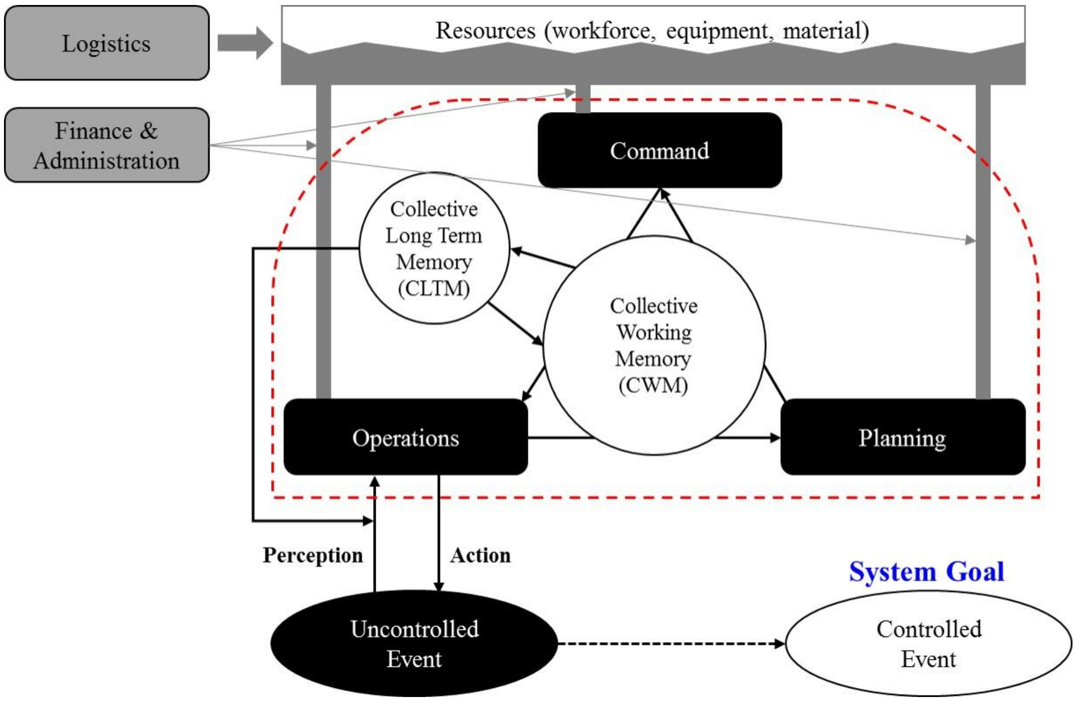

Figure 3. Cognitive Process of EMS as a JCS

Resource utilization. In most systems, resources are constrained. When resources such as workforce, equipment and material required to correspond to varying demands are deficient, the external event runs out of control (Hollnagel & Woods, 2005). In addition, common resources are shared – functionally, mostly not physically – among different functions of the system as illustrated in **Error! Reference source not found.**.

Performance stability. Once a function is loaded with inputs resulting in demand for establishing plans, the performance level of the function tends to diminish. This performance level not only depends on the quantity supplied from the resource pool but also relies on how such resources are actually effectuated. This process is not serial in EMS and resilient performance means accepting many things in parallel. If achieving a higher goal is threatened by a sudden exorbitant demand, then the system needs to sacrifice lower-level ends to maintain the performance stability (Cook & Nemeth, 2006).

Team situational awareness. EMS is expected to possess the ability to perceive what is currently taking place, to comprehend what such occurrence actually means, and to anticipate what may happen and decide what to do about it. When this occurs within a team, it is often referred to as Team Situation Awareness (TSA) (Endsley, 1995; McManus, Seville, Brunsdon, & Vargo, 2007).

Operationalizing Resilience

Measuring is a precondition for improvement in the system design and performance. In order to operationalize the RPF, the following measurement methods are devised.

Adaptive response. Adaptation in cybernetics presupposes variety (Ashby, 1956). Hence, sustaining a system's operation requires that agents who control the system have at minimum the same number of response variety as that of external demands (Hollnagel & Woods, 2005). When there is mismatch between these two types of variety, the system becomes vulnerable to such unmatched threat and may lose control (Rankin et al., 2013). **Error! Reference source not found.** illustrates two different mappings between disturbance variety (DV) and response variety (RV). In one-to-one mapping, a failure (marked as hollow red cloud) occurs when there is no designated response strategy (R3) against a particular type of disturbance (D3). On the other hand, many-to-many mapping presumes that each disturbance has a finite set of requirements to be met. Likewise, each response possesses different strategies to satisfy some, if not all, of those requirements. As shown in the red box, a failure is encountered when RVs (R1, R3, R4 and R5) do not satisfy some requirements of a DV (D3). In the EMS, DVs mean different types of uncontrolled events such as fire, chemical release, mass casualty incident (MCI), or hurricane. RVs for these can be various kinds of operations services such as law enforcement, firefighting, emergency medical service (EMS), or public works and hazardous material (HazMat).

However, it must be noted that RVs are not only restricted to predetermined procedures or a set of rules. Rather, they include tactics that they create impromptu or improvise to avoid the disruptions (e.g., using hotel rooms for accommodating patients in a mass casualty incident).

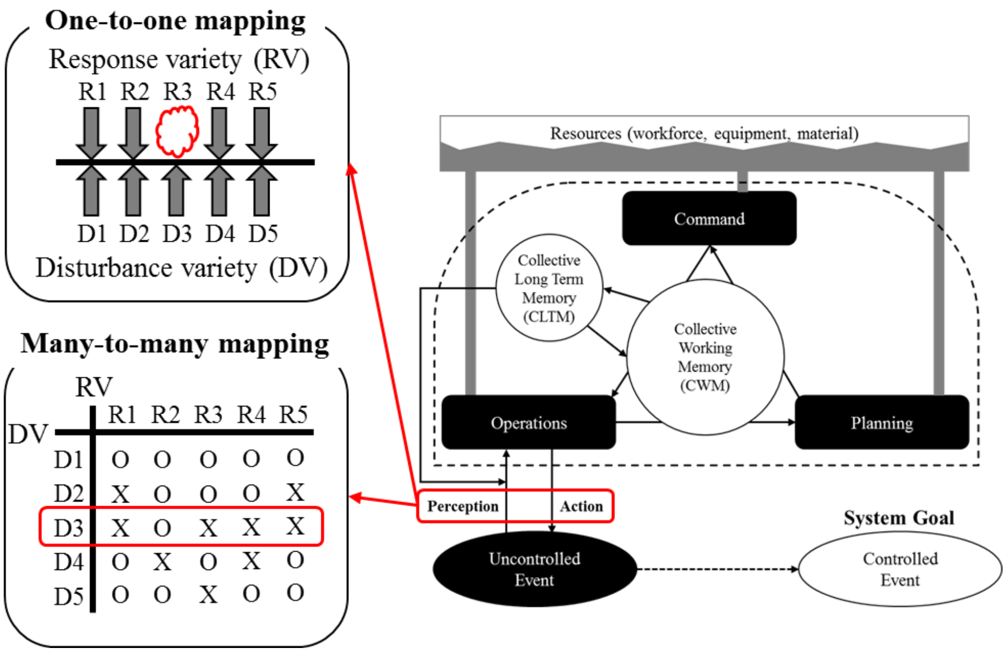

Figure 4. Variety Mapping between Disturbance and Response

Rapidity of recovery. Figure 5 depicts four types of time to be measured in this macrocognitive process: time to detect (T_D), time to decide (T_E), time to act (T_A) and time to recover (T_R). T_D means time between the onset of an uncontrolled event or meaningful change in such event and the earliest perception by operations crews. T_E indicates time taken from the point of perception through establishing decisions to the selection of a portion of those decisions. Following this, T_A means time lapsed from the choice of decisions until the action is practiced to the disturbance. Finally, T_R represents the time taken to make changes in the event that the system copes with after the action is taken. In some cases, this iterative process persists until such changes finally settle the situation in control.

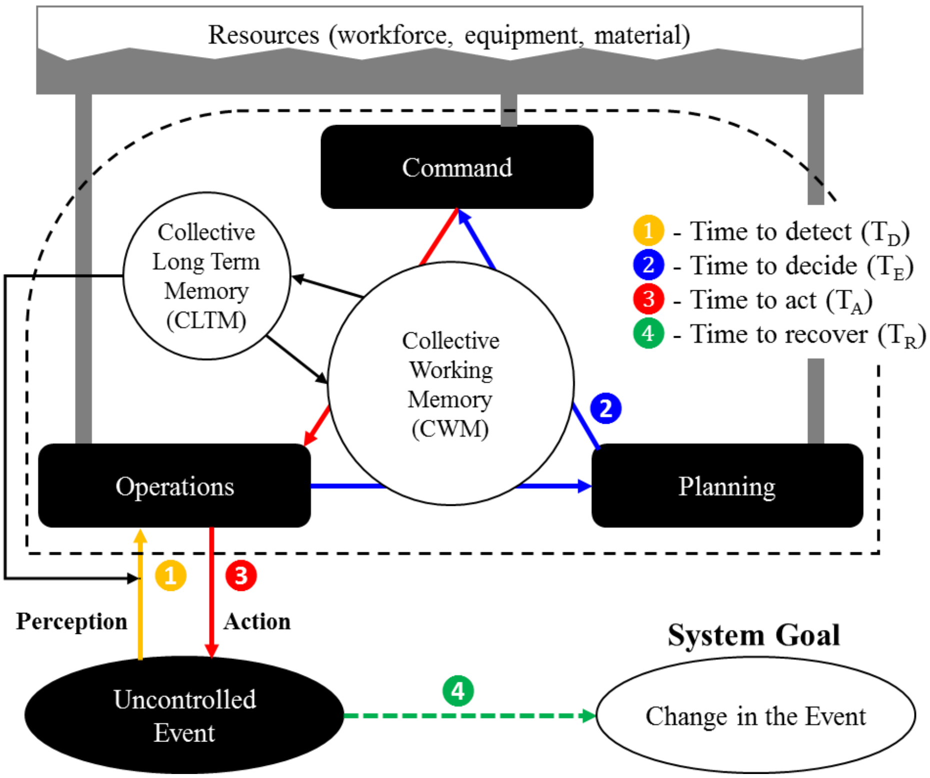

Figure 5. Types of Time to Measure

Resource utilization. This framework assumes that there is a common resource pool that each function draws upon. In actual emergency operations, these resources are constrained by budgeting. That is to say, different sorts of resources such as workforce, equipment and material, can be translated into equivalent monetary value. F&A and Logistics do accounting for its utilization: how much, how fast and for whom.

Performance stability. As seen in multilayered JCS diagram (Figure 2), each function – Operations, Planning and Command – and each unit within such function is a JCS, respectively. Therefore, the performance of those inner JCSs can be measured by observing how inputs and outputs are processed, for instance, performance throughput (number of tasks per unit time) and number of threads processed in parallel.

Team SA. A host of SA measurement tools have been developed and validated. In the study of team environment such as C4i (command, control, communication, computers and intelligence), most of existing SA measurement techniques disclose innegligible flaws (Salmon, Stanton, Walker, & Green, 2006). However, as they suggest, a combination of observer rating, a post-trial inquiry, a freeze probe and analysis of video/audio transcription may provide a near-term solution.

DISCUSSION

Despite the pioneering efforts to define and measure resilience of a joint cognitive system, this model is built upon many assumptions that have yet justified. In reality, cognitive and information processing of a JCS does not occur in a linear fashion. Rather, it is reciprocal and nonlinear among various actors across different levels. In addition, increasing construct validity is crucial to the overall acceptance of the approach discussed in this study and testing such validity still requires further efforts.

Studying actual emergency operations is deemed impossible because it is quite challenging to observe, obtain data from, and control such activities. Work is in progress in validating this measurement methodology by taking advantage of a high-fidelity emergency management training program developed and managed by Texas A&M Engineering Extension Service (TEEX).

CONCLUSION

Responses to emergency situations have long been regarded as one of the most critical barriers to protect the socio-ecological infrastructure from various threats. Due to intrinsic nature of emergency management systems that cope with varied disturbance, the imperative of resilience engineering is stressed in this paper. Concepts of resilience and precepts of resilience engineering have widely been accepted in many disciplines. EMS, nonetheless, appear to trail behind this transition due to the limitations in operationalizing such tacit construct. This work sheds some light on the characteristics of EMS as a joint cognitive system. Based on this foundation, a working definition and metrics for resilience in the EMS are proposed. Work is in progress to test and validate this theoretical proposition.

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