Applied Ergonomics 87 (2020) 103114

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: http://www.elsevier.com/locate/apergo

Investigating resilience in emergency management: An integrative review of literature

Changwon Son [a], Farzan Sasangohar [a,c,*], Timothy Neville [b,1], S. Camille Peres [b], Jukrin Moon [a]

[a] Industrial and Systems Engineering, Texas A&M University, 101 Bizzel St., Colleg Station, Texas, 77843, USA
[b] Environmental and Occupational Heaelth, Texas A&M University, 212 Adriance Lab Road College Station, TX, 77843, USA
[c] Center for Outcomes Research, Houston Methodist Hospital, 6565 Fannin St, Houston, TX, 77030, USA

ARTICLE INFO

Keywords:
Resilience engineering
Emergency response
Systematic review
System safety

ABSTRACT

There is a growing need for resilience in dealing with unexpected events during disasters. The purpose of this review was to summarize and synthesize the literature that examined resilience in the context of emergency management (EM). Four groups of findings were synthesized: definitions, key dimensions, technical tools, and research settings employed in the research. First, definitions of resilience, improvisation, and adaptation were summarized and critically evaluated. Second, four key dimensions of EM resilience were identified: collective sensemaking, team decision making, harmonizing work-as-imagined and work-as-done, and interaction and coordination. Third, this review identified five prevalent technical tools used to enhance resilience in EM: mapmaking, event history logging, mobile communication applications, integrated information management system, and decision support tools. Fourth, two major design features of emergency simulations, incident scenarios and participant roles, are evaluated. For each finding, directions for future research efforts to improve resilience in EM are proposed.

1. Introduction

Recent disasters such as catastrophic hurricanes and wildfires have consistently demonstrated the need for emergency management (EM) systems to adapt their performance to both expected and unexpected disruptions – a property often referred to as *resilience* (Boin et al., 2010; Shakou et al., 2019). Disasters pose severe challenges to affected communities and individuals in preparing for, making sense of, and responding to adverse events: disasters are unpredictable, usually propagate severe consequences, entail risks and time pressure, and deplete available resources, all of which render established emergency plans ineffective (Perry, 2007). The 9/11 World Trade Center attack was an archetypal event for which the need for resilience in managing unanticipated events was clearly recognized. For example, exploitation of civilian airplanes for mass destruction was neither expected nor prepared for (Comfort and Kapucu, 2006); emergency operation plans did not work as intended, and responses among emergency operation teams were not communicated or coordinated as planned (Kendra and Wachtendorf, 2003). A similar call for resilience during disasters has been identified even in expected events. Hurricane Katrina, though anticipated through advanced forecasting, showed how emergency personnel and organizations could fail to adjust, improvise, and innovate their decisions and actions to situations that cascade into a catastrophic event (Boin and McConnell, 2007; Waugh and Streib, 2006).

Recognizing such apparent needs, researchers have studied resilience in EM from multidisciplinary viewpoints. For instance, crisis and disaster studies have examined why resilience is needed and have critically examined emergency management policy and administration (Boin et al., 2010). These studies were primarily concerned with understanding the etiology of incidents and influencing policy makers and public administrators towards more resilient approaches (Boin and McConnell, 2007; Wise, 2006). One of the primary efforts in this area was to highlight factors that hinder or promote resilience of incident management protocols such as the Incident Command System (ICS) and the National Incident Management System (NIMS) (Bigley and Roberts, 2001; Buck et al., 2006). However, such an approach has lacked efforts to aid in evaluating system's resilience or engineering resilience in the EM domain (Boin et al., 2010).

To address this gap, a discipline called resilience engineering (RE) has emerged to enhance knowledge regarding resilience of socio-

* Corresponding author. 3131 TAMU, College Station, TX, 77843, USA.
E-mail address: sasangohar@tamu.edu (F. Sasangohar).
[1] Moved to Australian Football League.

https://doi.org/10.1016/j.apergo.2020.103114
Received 15 March 2019; Received in revised form 16 February 2020; Accepted 3 April 2020
Available online 24 April 2020
0003-6870/

technical systems in which human operators and technical tools jointly adapt to and cope with complexity of unanticipated events (Hollnagel and Woods, 2005; Hollnagel et al., 2006). Various definitions of resilience have been proposed in the RE literature. Woods (2006) defined resilience as a system's capability to handle disruptions that fall outside a designed performance envelope, emphasizing adaptations to unanticipated situations (2006, p. 21). Later, Hollnagel (2011b) proposed a refined definition of resilience as the system's inherent ability to adjust its functioning before, during, and after changes and disturbances (2011b, p. xxxvi). Several characterizations of resilience have focused on identifying factors that contribute to resilient performance. For example, Hollnagel (2011a) suggested four main capabilities of resilience (i.e., ability to anticipate, monitor, respond, and learn) and these factors were used to assess resilience of socio-technical systems such as healthcare organizations (Chuang et al., 2020; Patriarca et al., 2018b). Woods (2006) described underpinning properties of resilience such as buffering capacity, flexibility, margin, tolerance, and cross-scale interactions. These attributes were evaluated to assess resilience of other complex systems such as chemical processing plants (Shirali et al., 2016), emergency departments (Son et al., 2019b), and disaster response organizations (Mendonça, 2008). Finally, research efforts have focused on engineering resilience into systems, in other words, making a system more resilient. For example, scenario-based training was designed and implemented to nurture resilience skills needed to build a shared understanding of situations-at-hand and to plan response strategies ahead (Saurin et al., 2014). Another study proposed a novel design of healthcare information technology (e.g., infusion pump) that monitors current dosage and anticipates future states, which are essential pre-conditions for adaptive response to unpredicted adversaries (Nemeth and Cook, 2007).

While RE has hitherto contributed to addressing emerging challenges and identifying new capabilities in complex socio-technical systems (Woods, 2017), commensurate efforts to examine resilience in EM, compared to other domains, are still limited. Several existing literature reviews aimed at providing an extensive overview of resilience literature (Bergström et al., 2015; Righi et al., 2015), a summary of definitions (Hosseini et al., 2016), and a focused evaluation of healthcare resilience (Patriarca et al., 2017). However, none of these reviews explored resilience in the EM domain, which requires greater attention due to increasing catastrophic disasters. In addition, Hosseini et al. (2016) concluded that there is lack of a universal definition across application domains. While previous reviews were largely based on RE literature since its initial advent (e.g., Hollnagel et al., 2006), resilience, in conjunction with other notions such as adaptation and improvisation which are crucial concepts in emergency and disaster management research (Alexander, 2013; Kendra and Wachtendorf, 2003) has not been explored. Moreover, existing reviews focused mostly on summarizing various definitions ('what is resilience?') and application areas ('how is resilience used?') with limited attention to documenting constituent dimensions of resilience ('what makes a system resilient?'). Finally, none of the previous reviews investigated technical tools used to support individuals and organizations in achieving resilient performance. Such tools enable interactions between social (e.g., individual responders and organizations) and technical factors and contribute to system resilience (Salmon et al., 2014). To address these gaps, the current research, by reviewing a broad range of resilience literature in EM, aims to examine definitions of resilience and other related constructs, contributors to resilient performance in EM, and technical tools to achieve resilient performance in EM. Based on our synthesis, we propose directions for future research efforts.

2. Method

2.1. Search protocol

A systematic review librarian was consulted for the development of literature search and review strategies and techniques, including search database selection. Two coders applied a systematic review protocol to search documents published between January 1990 and December 2019. The five databases were chosen to cover relevant literature in various fields of study: Compendex for engineering literature, PsycINFO for psychology literature, JSTOR for social science literature, and MEDLINE and CINAHL for healthcare literature. Non-indexed sources such as proceedings of Resilience Engineering Association symposia and chapters of RE-related books (Resilience Engineering: Concepts and Precepts, Resilience Engineering Perspective Vol. 1 and 2, Resilience Engineering in Practice Vol. 1 and 2, Resilient Health Care Vol. 1, 2, and 3, and Delivering Resilient Health Care) were searched using the established search and selection protocol.

In order to retrieve relevant publication archives, two search strategies similar to Jenuwine and Floyd (2004) were employed. In the subject search strategy, a list of controlled terms was developed (Table 1) for each database and literature search was carried out to locate documents concerning subjects of interest. Subjects such as cognitive system, human-machine system, and decision making were considered to be significant in this search since these concepts are major topics in resilience engineering (Woods and Hollnagel, 2006). In addition, disaster- and emergency-related idioms were also deemed as necessary subjects to be searched. Due to the differences in subject vocabulary between the databases, a respective set of controlled terms for each database was developed and applied to the literature search. A second strategy then applied non-indexed or free-text terms to extract the target literature. Three keywords were used in this strategy: *emergency*, *management*, *resilience* and their relata (Table 2). Two additional terms, *adaptation* and *improvisation*, were included as free-text terms as they are often used interchangeably (Grøtan et al., 2008; Righi et al., 2015).

2.2. Inclusion and exclusion criteria

The initial search was limited to documents published between 1990 and 2019 in order to embrace early literature on resilience and improvisation in emergency response such as Weick (1993) and Mendonça

Table 1
Controlled search terms used for different databases.

Database	Controlled terms	Database	Controlled terms
CINAHL	Decision making Decision support systems Decision support techniques Disaster planning Disasters Emergency service Information systems Natural disasters	PsycINFO	Decision making Decision support systems Disaster Emergency preparedness Emergency Management Human machine systems design Human machine system Group decision making Natural Disaster
JSTOR	Cognitive systems Decision making Decision support systems Human machine systems	MEDLINE (Ovid)	Cognitive science Decision making Decision support systems Decision support technique Emergencies
Compendex	Cognitive systems Command and control systems Decision making Decision support systems Disaster Emergency services		

Table 2
Free-text search terms.

Keyword	Emergency	Management	Resilience
Relata	$emergency $disaster $incident $crisis	$manage $control $respond $operate	resilien* adapt* improvis* improviz*

Note: $ for auto-stemming and * for truncation.

et al. (2001) while the major attention to RE was raised around 2006, following Hollnagel et al. (2006)'s seminal work. The initial search results were then screened using Rayyan (Ouzzani et al., 2016). Documents were excluded if (a) the abstract covered domains other than emergency and disaster management, (b) the type of the publication was review article, dissertation, technical report, or white paper, or (c) the document was not written in English. Duplicate records were eliminated using a duplicate-handling feature of Rayyan. Two authors (CS and JM) independently coded approximately 12% (n = 480) of the initial search results by screening the abstracts. The intercoder reliability with Cohen's kappa (κ=.76) was interpreted as substantial (McHugh, 2012). A full-text screening was then conducted to exclude documents that (a) discuss less relevant constructs such as environmental, psychological, architectural, or financial resilience or (b) do not treat resilience as a core subject. The same authors (CS and JM) individually screened the full documents for eligibility. The intercoder reliability for the full-text screening was also shown substantial (κ=.79). Discrepancies that occurred at each round of screening were resolved through clarification on inclusion criteria and consensus-building.

2.3. Data extraction and analysis

First, relevant information such as bibliographic data (e.g., authors, published year, journal/conference proceeding) and major findings (e.g., research focus, study design and methods, type of events considered, technical tools examined, study location) were extracted from the selected literature and entered into a spreadsheet. Next, in line with Alias and Suradi (2008) and Rowley and Slack (2004)'s recommendation, a concept mapping tool called CmapTools (Institute for Human & Machine Cognition, 2017; cf. also Cañas et al., 2004) was used for thematic analysis (Braun and Clarke, 2006). Concept maps are deemed suitable to elicit various concepts (nodes) and relationships between them (arcs) using visualization features (Braun and Clarke, 2006; Wheeldon and Faubert, 2009). In CmapTools, individual documents were represented as a high-level (parent) node and specific findings from each document as low-level (child) nodes. As the review progressed, the nodes were continuously regrouped and the arcs between the nodes were iteratively adjusted to code main themes. Fig. 1 presents an example of the concept map developed to elicit themes and sub-themes regarding the harmonization of work-as-imagined (WAI) and work-as-done (WAD).

2.4. Search and screening results

The initial search yielded 4,158 documents from which 55 were finally selected for review after abstract and full-text screening based on the inclusion and exclusion criteria. Fig. 2 shows the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) diagram (Moher et al., 2009) of the current review, depicting the literature search and selection process in more details.

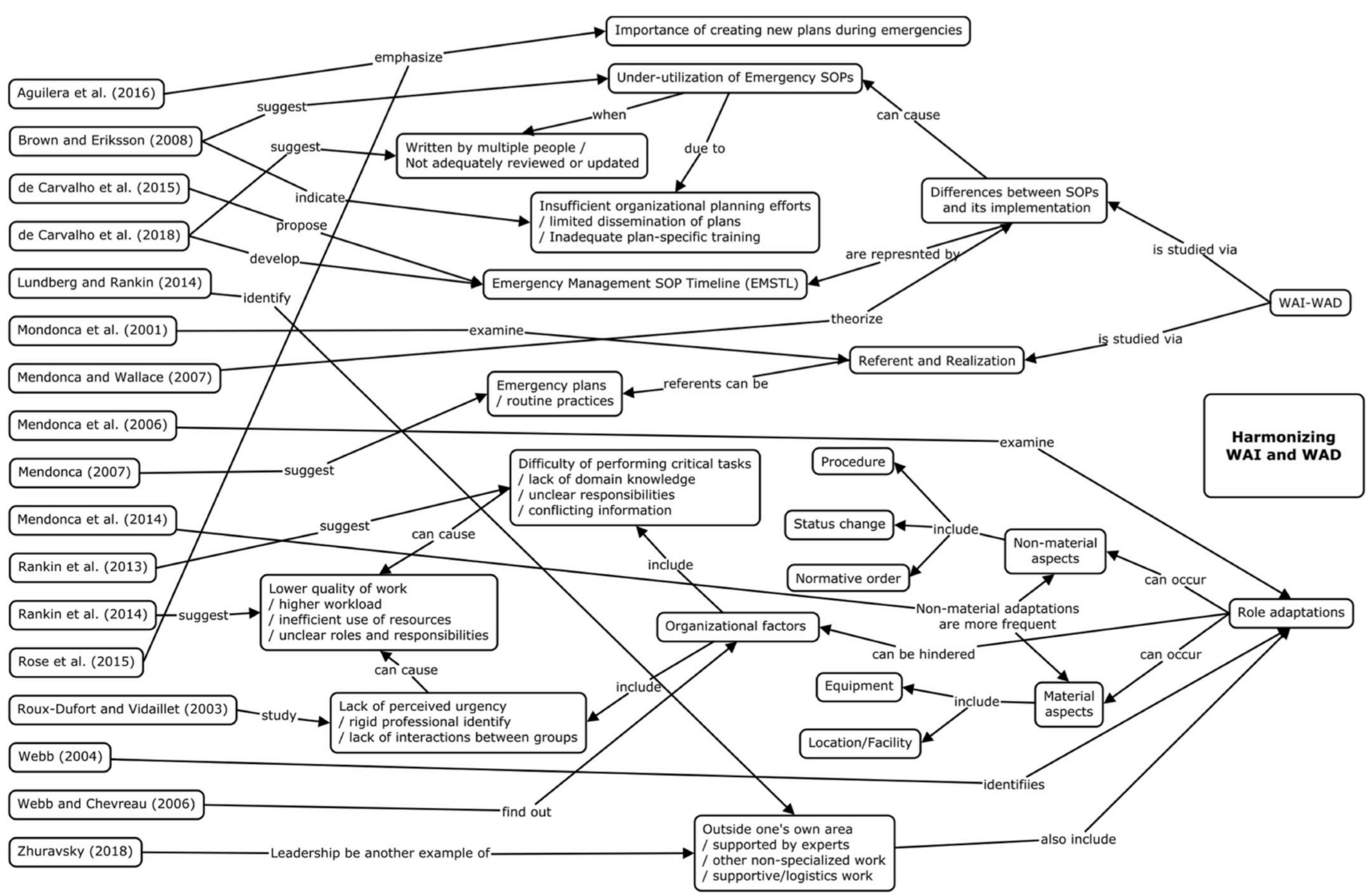

Fig. 1. An example of the concept map developed to code findings from the literature.

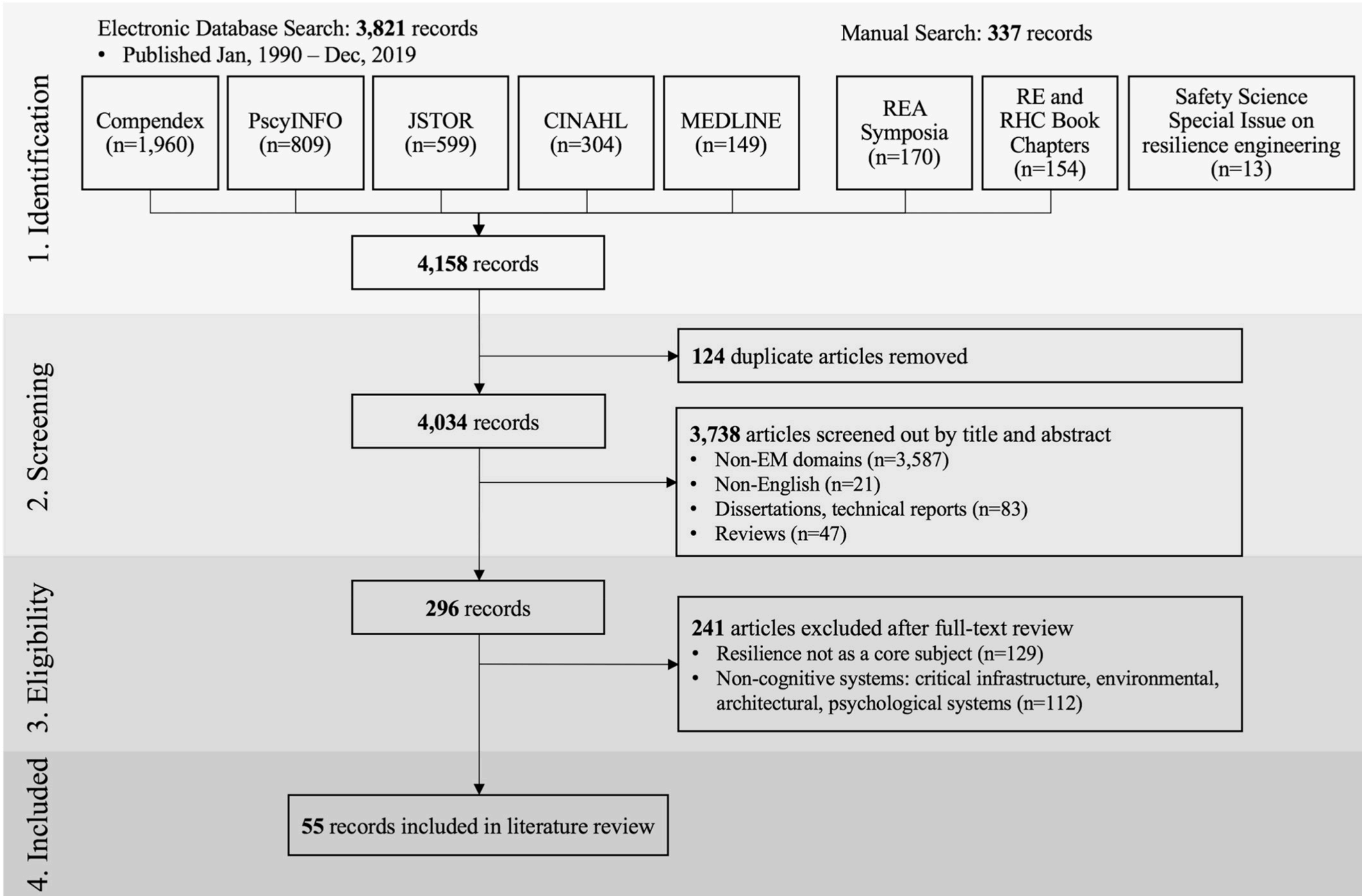

Fig. 2. PRISMA flow chart of literature search and inclusion/exclusion process.

3. Results

3.1. Overview of research characteristics

Findings from the current review indicate that there is variability in research efforts for resilience in EM (see Appendix A for details). With respect to publication types, over half (n = 32) were journal articles, 15 conference papers, and eight book chapters. For study designs, a majority of the research (n = 46) employed empirical techniques rather than theoretical approaches. Of those 46 documents, a large portion (n

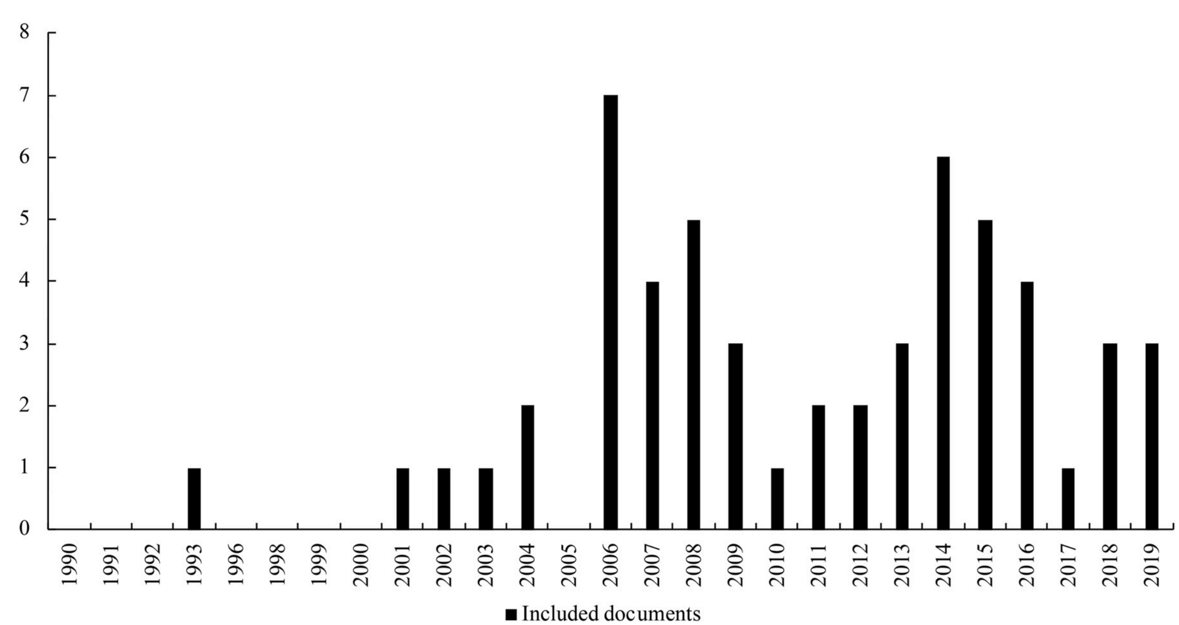

Fig. 3. Annual number of included documents in the present review.

= 37) were based on qualitative methods such as observation, interview, group discussion, or audio-video recording. While many studies adopted mixed methods, observation (n = 19) and interview (n = 19) were two primary ways to collect research data. Only eight documents reported quantitative results by adopting controlled experimentation, document analysis, or survey analysis. Various types of emergency events were examined in the literature. From 43 documents that specified incident types, 17 covered natural disasters (e.g., wildfire, storm, earthquake, landslide), 16 addressed technical incidents (e.g., chemical spill, maritime incident, hazardous material), and 10 examined civil events (e.g., terrorism, riot, sports events). Regarding the geographical location of research, 20 were conducted in North America, 17 in Europe, five in South America, and three in Oceania. The annual trend of included documents was also assessed as illustrated in Fig. 3. The graph shows a continued interest in studying resilience in EM during the past three decades.

3.2. *Definitions of resilience in EM*

The findings from this review show large variability in how resilience, adaptation, and improvisation in EM have been defined in the literature (Table 3). In line with Righi et al. (2015), the current review confirms a high degree of cross-reference between thethree terms in the EM context. For instance, resilience is generally defined as a system's adaptive capacity or adaptation to variable conditions in and around the system (Lundberg et al., 2012; Woods and Branlat, 2011). Similarly, definitions of improvisation include adaptation to changing situations where new responses need to be planned and executed in a timely manner (Mendonça and Wallace, 2002; Trnka et al., 2016).

In general, three distinct aspects have emerged from the definitions: a temporal aspect, expectancy of disruption, and means for achieving resilience, adaptation and improvisation. The first aspect identified from the definitions is an EM system's temporal behavior along different phases of emergency management (i.e., prevention, preparation, response, and recovery). Some definitions use a *reactive* framing to highlight the capacity to respond to and recover from a disruption *after* its occurrence (Abbasi et al., 2010; Caldwell, 2014; Hollnagel and Sundström, 2006). Other definitions stress a *proactive* behavior such as prevention and preparation *before* an adverse event in addition to response and recovery (Longstaff and Yang, 2008; Righi et al., 2016; Westrum, 2006; Woltjer et al., 2006).

The second emerging aspect in the definitions is the expectancy of disruption. In particular, the ability to deal with *unexpected* events is highlighted as an essential attribute of resilience (Aguilera et al., 2016; Gomes et al., 2014; Righi et al., 2016). However, others (e.g., Comfort, 2002; Hollnagel and Sundström, 2006) posit that any changes, either expected or unexpected, in the system require the capacity for resilience, adaptation, or improvisation. In addition to expectancy, resource limitation (Lundberg et al., 2012) and time pressure (Mendonça and Wallace, 2002; Wybo et al., 2006) are addressed as other challenging traits of the disruption to EM systems.

The third aspect is the means for achieving resilience, adaptation and improvisation. In the field of EM, commonly employed means to cope with varying demands of an emergency include allocating roles and resources (Abbasi et al., 2010; Comfort, 2002; Voshell et al., 2008), handling incident information (Bharosa and Janssen, 2009) or adjusting emergency procedures (Franco et al., 2009).

While resilience, adaptation, and improvisation have common attributes, nuanced differences also exist. First, *adaptation* is defined in a more generic manner that highlights changes in the EM system's performance of allocating roles and resources (Abbasi et al., 2010; Caldwell, 2014), not addressing the temporal nature of the response (proactive vs. reactive), nor the severity of the demands that is common in the definitions of resilience and improvisation. Second, definitions of *improvisation* tend to stress the capability of creating and implementing novel or non-routine actions shortly or immediately after recognizing

Table 3
Definitions of resilience, adaptation, and improvisation.

Author(s)	Definition
Abbasi et al. (2010, p. 821)	"[Being **adaptive** means being] able to recover quickly and effectively reallocate roles as the situation changes … in a variety of situations, in time and in space."
Aguilera et al. (2016, p. 20)	"[**Resilience** is] the adaptive capacity, or the ability of the system to identify and to adapt to handle unanticipated perturbations in order to keep the system under control."
Bharosa and Janssen (2009, p. 1)	"**Adaptivity** refers to collective system property different from concepts such as agility and flexibility, which indicate the possibilities for adapting from the one state to the other. More specifically, we define adaptivity as the degree to which a decision-making unit has a variety of dynamic capabilities and the speed at which they can be activated, to match information demand and supply."
Caldwell (2014, p. 320)	"[**Resilience** considers] how quickly and completely can one recover after the event prevents reasonable operations."
Comfort (2002, p. 34)	"[**Adaptation** is] the ability to reallocate resources and action to meet changing demands from the environment."
Franco et al. (2009, p. 2)	"[T]he context of **improvisation** … would describe the balance of procedural versus management tasks anchored, for example, by first responders adjusting procedures to fit a given situation at one end, and the organizational flexibility of an Emergency Operations Center at the other."
Gomes et al. (2014, p. 782)	"**Resilience** can be very widely defined as the capacity of the system/organization to successfully handle disturbances, including the surprising ones."
Hollnagel and Sundström (2006, p. 339)	"A **resilient** system, or organization is able to withstand the effect of stress and strain and to recover from adverse conditions over long time periods."
Longstaff and Yang (2008, p. 1)	"[**Resilience** is defined as] capacity of a system to absorb disturbance, undergo change, and still retain essentially the same function, structure, identity, and feedbacks. In other words, the system has the ability to bounce back after a surprise."
Lundberg et al. (2012, p. 101)	"[R]**esilience** … [is] adaptation to the changes in the situation, for instance an unusually high demand for limited resources, often together with breakdown of communications technology and other technical systems."
Mendonça and Wallace (2002, p. 1)	"To **improvise** is to rework knowledge to produce a novel action in time to meet the requirements of a given situation."
Righi et al. (2016, p. 119)	"[**Resilience**] can be defined as the ability of a system to adjust its operation, before, during or after disruption in order to maintain the necessary operations under both expected and unexpected conditions."
Trnka et al. (2016, p. 253)	"**Improvisation** … [is] an intentional process of thinking and doing through which individuals and team (organizations) continuously adapt to changing needs and conditions in order to generate novel responses."
Voshell et al. (2008, p. 423)	"A **resilient** organization must have the adaptive capacity and resource management capability to cope with complexity and surprise."
Webb and Chevreau (2006, p. 67)	"[I]**mprovisation** refers to social activities that are carried out in non-routine, atypical, or unexpected ways."
Westrum (2006, p. 59)	"**Resilience** is the ability to prevent something bad from happening, [o]r the ability to prevent something bad from becoming worse, [o]r the ability to recover from something bad once it has happened."
Woltjer et al. (2006, p. 72)	"**Resilience** is … defined as the ability to anticipate, prevent, detect, and recover from harmful events."
Woods and Branlat (2011, p. 129)	"**Resilience**, as a form of adaptive capacity, is a system's potential for adaptive action in the future when information varies, conditions change, or when new kinds of events occur …"
Wybo et al. (2006, p. 2)	"[R]**esilience** is the ability of the organization (at any level) to remain under control when faced to hazardous situations, uncertainty, time pressure and threats, from outside and inside."

the need to depart from established plans or procedures (Franco et al., 2009; Mendonça and Wallace, 2002; Trnka et al., 2016; Webb and Chevreau, 2006). Hence, improvisation can be seen as quick, creative adaptation and one of the possible behavioral markers of EM resilience in the response phase.

Unlike the other two constructs, definitions of *resilience* point to an overarching systems concept that encompasses all the EM phases (Righi et al., 2016; Westrum, 2006). Also, resilience is concerned with coping with both expected and unexpected disruptions in order to maintain EM system functions (Aguilera et al., 2016). Indeed, this inclusive framing incorporates both adaptation and improvisation into the conception of resilience (Lundberg et al., 2012; Trnka et al., 2016; Woods and Branlat, 2011).

3.3. Key dimensions of resilience in EM

Utilizing a thematic analysis approach, this review has identified the following four key dimensions of EM resilience: (a) collective sensemaking, (b) team decision making, (c) harmonizing work-as-imagined (WAI) and work-as-done (WAD), and (d) interaction and coordination. Table 4 presents a list of the literature that addresses any of the four dimensions. While findings regarding each dimension are presented in subsequent subsections respectively, these dimensions are largely interrelated and complementary, serving as constituent attributes of resilience in EM.

3.3.1. Collective sensemaking

Comfort (2007) posits that the 'cognition' of emerging and evolving risks is a crucial element of emergency response. In RE theory, monitoring what happens in a system, which is an essential element of resilience, depends on the system's cognitive processing of information (Hollnagel, 2011b). In EM practice, this cognitive process is described as creating a 'common operating picture (COP)' which serves as collective awareness of incident status shared among emergency responders (Wolbers and Boersma, 2013). This review has identified several factors associated with collective sensemaking during an emergency. For example, in Weick (1993)'s study, the death of a firefighting crew was ascribed to the crew's failure to quickly and accurately establish common understanding of evolving bushfire conditions. Then, four sources of resilience that foster collective sensemaking were suggested: improvisation or bricolage (i.e., creative reconfiguration of existing resources at hand), virtual role systems (i.e., imagining what others would do even when they are lost), attitude of wisdom (i.e., avoiding overconfidence and overcautiousness), and respectful interaction (i.e., honestly reporting to others and respecting others' report). Later in the Sumatra tsunami, the failure of a foreign government to make initial sense of the disaster was ascribed to a delayed deployment of overseas rescue operations for its citizens (Hollnagel and Sundström, 2006). Researchers further examined the relationship between collective sensemaking and resilience in EM. For instance, Lundberg et al. (2012) found that an EM team's collective sensemaking is associated with essential factors of resilience such as buffering capacity, flexibility/stiffness, tolerance, margin, and cross-scale interactions (Woods, 2006). Particularly, Hunte (2017) indicated that similar experience in the past helps increase the buffering capacity (e.g., human and physical resources) in the face of a large civil disorder that occurred after a major ice hockey play-off. Aguilera et al. (2016) emphasized collective sensemaking efforts across multiple response organizations to keep chemical spill assessment up to date.

While collective sensemaking is a key to EM resilience, its maintenance during emergency situations may come at the cost of cognitive overload due to excess influx of incident data (Gomes et al., 2014). To relieve such overload, emergency personnel take advantage of standard operating procedures (SOPs) as they prescribe what actions need to be implemented and they promote routine behaviors (Righi et al., 2016). SOPs, nonetheless, may increase the cognitive load when a situation

Table 4
Four key themes identified from the literature.

Reference	Collective sensemaking (n = 14)	Team decision making (n = 15)	Harmonizing WAI and WAD (n = 18)	Interaction & coordination (n = 15)
Abbasi et al. (2010)				✓
Aguilera et al. (2016)	✓		✓	
Bergström et al. (2008)		✓		
Bharosa and Janssen (2009)	✓			
Brown and Eriksson (2008)			✓	
Caldwell (2014)		✓		
Comfort (2002)		✓		
Comfort (2007)	✓	✓		
Comfort et al. (2004a)	✓	✓		
de Carvalho et al. (2015)			✓	
de Carvalho et al. (2018)			✓	
Domeneghetti et al. (2018)	✓	✓		
Franco et al. (2009)				✓
Frye and Wearing (2016)	✓			
Gomes et al. (2014)	✓			✓
Harrald (2006)				✓
Hollnagel and Sundström (2006)	✓			
Hunte (2017)	✓			
Klimek et al. (2019)	✓			✓
Longstaff and Yang (2008)				✓
Lundberg and Rankin (2014)			✓	
Lundberg et al. (2012)	✓			
Mendonça (2007)		✓	✓	✓
Mendonça et al. (2006)		✓	✓	
Mendonça et al. (2001)			✓	
Mendonça and Hu (2007)		✓		
Mendonça and Wallace (2007)			✓	
Mendonça et al. (2014)		✓	✓	
Pramanik et al. (2015)				✓
Rankin et al. (2013a)	✓		✓	
Rankin et al. (2014)			✓	
Reuter et al. (2014)		✓		
Righi et al. (2016)	✓		✓	
Rose et al. (2015)		✓	✓	
			✓	

(*continued on next page*)

Table 4 (*continued*)

Reference	Collective sensemaking (n = 14)	Team decision making (n = 15)	Harmonizing WAI and WAD (n = 18)	Interaction & coordination (n = 15)
Roux-Dufort and Vidaillet (2003)				
Stachowski et al. (2009)				✓
Son et al. (2018)		✓		✓
Trnka et al. (2016)				✓
Voshell et al. (2008)				✓
Webb (2004)			✓	
Webb and Chevreau (2006)			✓	
Weick (1993)	✓	✓		✓
Westrum (2006)				✓
Woods and Branlat (2011)				✓
Zhuravsky (2018)		✓	✓	

unfolds in unplanned ways. As an alternative approach to SOPs, Frye and Wearing (2016) emphasize two metacognitive skills of emergency responders: self-awareness (i.e., an ability to maintain situation awareness by reconciling a 'big picture' and 'ground truth') and self-regulating (i.e., a skill to prioritize one decision over another and to regulate decision making tempo).

In addition to cognitive skills of individuals working in the EM area, collective sensemaking requires clear organizational processes for information management. For example, Comfort et al. (2004a) emphasize the importance of designing an adaptive information communication process in inter-organizational incident management. The study found that failure of inter-organizational adaptation had largely resulted from ineffective search, processing and integration of information. As a way to facilitate collective sensemaking during an emergency, Bharosa and Janssen (2009) proposed four types of capabilities: preemptive (i.e., extending organizational boundaries), protective (i.e., loosening coupling of and diversifying information resources), exploitative (i.e., forecasting information needs), and corrective (i.e., accommodating new pieces of information when they arrive). On the other hand, Rankin et al. (2013a) investigated information and communication flow of a crisis response team and identified three factors that contribute to reduced adaptive performance: i) lack of linguistic skills, ii) lack of domain-specific knowledge, and iii) inadequate organizational structure for disseminating, updating and validating information. With respect to the communication pattern, Klimek et al. (2019) found out that horizontal communication was prevalent when facing unanticipated situations while vertical communication took place more frequently for expected events. Domeneghetti et al. (2018) observed more frequent information communication (e.g., face-to-face) to expediate collective situation awareness in EM organizations.

3.3.2. Team decision making

The second key dimension of resilience in EM is team decision making in order to adapt to challenging and changing conditions. Decision making during an extreme event has typical traits such as rarity, uncertainty and high consequences of the event, complexity among infrastructure systems, time pressure, and multiple decision makers (Mendonça, 2007; Mendonça and Hu, 2007). Under these constraints, common decisions for the EM team to make during an emergency include how to allocate limited resources, how to circulate information within EM teams as well as to the affected population, and how to keep responders from hazards (Mendonça et al., 2006; Rose et al., 2015). In order to cope with rare, unpredictable, and high-stake situations, EM teams generally adopt an analytical and coordinated decision making protocol such as the Incident Command System (ICS) (Mendonça et al., 2014; Son et al., 2018). Also, training on generic decision making protocols, thus not specific to a certain scenario, was helpful in promoting proactive decision making (Bergström et al., 2008).

Decision making of EM teams goes hand in hand with collective sensemaking following a cyclic process of information search, information exchange, comprehending emergency situations, establishing action plans, implementing or adapting the plans, and organizational learning (Comfort, 2007). The negative effect of lack of collective sensemaking on team decision making was actually noticed in previous incidents such as terrorist attack (Comfort, 2002) and wildfire (Weick, 1993). More recently, Domeneghetti et al. (2018) observed that decision makers at a local command center relied on pre-established decisions (e.g., evacuation perimeter and shelter-in-place), and leveraged information being fed into the center to determine if the original plan requires adaptation. In this regard, Caldwell (2014) theorizes *boundary resilience framing* to explain decision makers' approach towards situations that exceed the boundary of designed capabilities. Domeneghetti et al. (2018) also found that delayed information feed made it more difficult for decision makers to adapt their decisions, and that expertise on subject matter (e.g., nuclear radiation) was crucial to deal with specific hazardous scenarios.

There are also temporal and spatial differences between organizational decision makers and implementers of such decisions, which make coordination between EM personnel difficult (Reuter et al., 2014). Hence, researchers claim that EM teams should accommodate distributed and coordinated decision making as well as centralized processes in order to more readily adapt to unexpected events and to reduce pressure on central decision makers (Bergström et al., 2008; Zhuravsky, 2018). To support the distributed decision making, system-wide information sharing is needed as it facilitates mutual adaptation among multiple decision makers and prevents locally, as opposed to globally, adaptive decisions (Comfort et al., 2004a).

3.3.3. Harmonizing WAI and WAD

Another key dimension of EM resilience identified in this review is the relationship between WAI and WAD. WAI stipulates how work should be done and WAD refers to how such work is actually done under varying circumstances (Wreathall, 2006). Researchers viewed SOPs for emergency response as an instance of WAI and examined which steps of the SOPs were actually implemented or omitted for WAD (de Carvalho et al., 2015; Righi et al., 2016). Further, de Carvalho et al. (2018) found that only about one third of steps of emergency SOPs were carried out as prescribed. To compare and contrast between WAI and WAD in emergency operations, event timeline analysis methods such as 'Emergency Management SOP TimeLine (EMSTL)' (de Carvalho et al., 2018) were developed and applied.

Possible reasons for the gaps between WAI and WAD can be found in the way the SOPs were developed. SOPs may be written by those with different ranks and expertise or not adequately reviewed and updated. It may be due to lack of alignment between specific circumstances of situations at hand and the abstraction level of the SOPs (de Carvalho et al., 2018). Brown and Eriksson (2008) suggest that misapplication or under-utilization of emergency SOPs may occur due to insufficient organizational planning processes, limited dissemination of plans, inadequate plan-specific training, inaccurate hazard and vulnerability assessment, and issues with design and usability of the plans. Therefore, the ability of the EM organizations to adapt plans and to create new solutions is considered essential to mitigate the limitations of emergency plans and procedures (Aguilera et al., 2016; Rose et al., 2015).

From improvisation theory, implementation of WAI into WAD can occur in two stages. The first stage is to recognize either that no appropriate plan is available or that an appropriate plan cannot be implemented due to lack of resources needed. The second stage is to create and execute a new plan spontaneously (Mendonça and Wallace, 2007). The dichotomy between WAI and WAD is similarly found between a *referent* and its *realization*. A referent is an abstract direction that guides one's cognition or behavior and is then realized into a specific course of action given situational constraints (Mendonça et al., 2001). One such realization is generating an alternative resource when a standard resource cannot be mobilized, for example, using a gravel truck to block a road in lieu of a police vehicle (Mendonça et al., 2006). Other referents in emergency response may include routines formed from past experience (Mendonça, 2007), pre-defined roles and responsibilities, and highly-skilled individuals (Rankin et al., 2013a).

WAD has been studied in the context of emergency personnel's role changing behavior. For example, Rankin et al. (2013a) highlighted that behavioral changes occur within the same role or by taking a different role. Webb (2004) identified five types of role changes of emergency personnel: i) procedure change (i.e., altering ways of performing a role), ii) status change (i.e., assuming additional or broader scope of the role), iii) normative order change (i.e., laying unusual restrictions on public access, acquiring private assets without consent), iv) equipment change, and v) location/facility change. Such role adaptation in practice was similarly assessed in the 1995 Oklahoma City bombing and the 9/11 attack (Mendonça et al., 2014). These studies found that changes in the intangible norms (e.g., procedural, status) were more frequent than changes related to tangible materials (e.g., equipment, facility). With respect to role change, Lundberg and Rankin (2014) identified four categories: i) performing specialized work outside one's own expertise, ii) conducting the same specialized work supported by a highly skilled expert, iii) practicing non-specialized work, and iv) performing works otherwise handled at an organizational level (e.g., logistics). Moreover, Zhuravsky (2018) observed that even the leadership was shared among multiple members of the organization in response to a catastrophic earthquake incident.

While WAD represents a common practice of adaptation in the emergency context, there are some organizational traits that hinder WAD from being laid out: over-reliance on documented rules and standard procedures, excessive specialization of tasks, focusing on a 'plan' instead of 'planning,' failure to learn from near-misses, strong dependence on centralized command and control, and an attitude to replace emergency personnel with technology (Webb and Chevreau, 2006). In a similar vein, Roux-Dufort and Vidaillet (2003) postulated conditions in which EM personnel's adaptive behaviors may not occur, such as an absence of shared perception of urgency, an extreme level of urgency and surprise, rigid professional identity, and a lack of interaction across different response groups. In addition, adaptations realized in WAD may accompany some negative impacts such as lower quality of work, higher workload, inefficient use of resources, and unclear roles and responsibilities of EM personnel (Lundberg and Rankin, 2014; Rankin et al., 2014). To mitigate such shortcomings, the following recommendations are given: providing training on non-routine roles, defining roles and responsibilities for tasks more formally, sharing updated information to relevant roles in a timely fashion, and allowing personnel to observe various emergency cases (Lundberg and Rankin, 2014; Rankin et al., 2013a).

3.3.4. Interaction and coordination

The fourth dimension that emerged from the literature is that interaction and coordination among individuals facilitate EM resilience by promoting exchange and synthesis of knowledge for problem-solving and mutual adaptation to emerging risks (Weick, 1993). For example, an EM team coordinator's effort to brief and debrief on incident information is instrumental for a common understanding across different organizations (Domeneghetti et al., 2018; Gomes et al., 2014). Moreover, coordination is required among distributed multiple decision makers to adapt to changing or unexpected conditions (Harrald, 2006). In reality, standard EM protocols such as the ICS tend to place incident commanders in the center of organizational decision making, and thus the protocol may not work between different organizations (Mendonça, 2007). Issues associated with the lack of coordination and collaboration between multiple disciplines and jurisdictions were clearly identified in the 9/11 attack (Westrum, 2006). Also, interaction and coordination is necessary to reconcile WAI and WAD. Gomes et al. (2014) also found that ad hoc sub-teams were formulated to deal with specific incident scenarios. Thus, the study proposes that diversity of team members would be a source of resilience in coordination and problem-solving. Along with this claim, Franco et al. (2009)'s experimental work suggests that team heterogeneity (i.e., a degree to which team members were not trained together) would enhance the adaptive performance of ad hoc EM teams. As another example of adaptation through coordinating team members, Trnka et al. (2016) observed that EM teams coordinated different expertise and skills as responders arrived at the scene and resolved the mismatch between initial plans and actual needs. Stachowski et al. (2009) indicated that effective EM teams tend to circumvent routine interaction patterns to adapt to non-routine events.

Coordination across multiple EM operators and organizations, however, is subject to at least five challenges. First, inter-linked EM functions need to be assigned to the same role to facilitate coordination between such functions. Second, a change in one organization's tempo that is faster or slower than that of others along evolving situations may cause coordination loop asynchrony. Third, disparity in levels of support between one's own team and other organizations may result in support asymmetry (Voshell et al., 2008; Woods and Branlat, 2011). Fourth, the lack of familiarity and expectancy of using external resources may hinder the actual resource utilization. Indeed, Pramanik et al. (2015) found that when familiarity with other organizations' capabilities and expectation of future collaboration was increased, the EM personnel were more likely to work with other units and utilize their resources. Finally, lack of trust among members is found to increase the need to consult with additional members, stifling coordination among them (Longstaff and Yang, 2008).

Methods such as social network analysis have been used to understand social interaction and coordination among members of EM systems. Gomes et al. (2014) performed a brief analysis on number and direction of interactions, proposing further efforts to identify critical roles in communication and decision making and to understand routine or non-routine patterns of interaction. Abbasi et al. (2010) conducted a survey with fire and emergency service personnel and identified that social network measures such as individual and team tie strength (e.g., perceived amount of time spent together, emotional connectivity and intimacy) were positively associated with team coordination. Results of a recent quantitative study (Klimek et al., 2019) indicate that when encountering unexpected situations, vulnerability and redundancy of EM organization network increased and efficiency of the network decreased due to the addition of new responders and bottlenecks. To represent the interactions in a temporal dimension, Son et al. (2018) developed the 'interaction episode analysis' method and examined how a large-scale team handles incident information through interactions between EM personnel and technical tools.

3.4. Technical tools that support human operators for resilience in EM systems

Our review has identified five common technical tools used to support tasks and processes of individual operators and EM organizations for improved EM resilience: (a) geospatial mapping, (b) event history logs, (c) mobile communication applications, (d) integrated information management systems, and (e) decision support tools.

(a) Mapping or map-making tools are widely employed in emergency operations. For example, Petersen (2015) viewed map-making as collective generation of risk knowledge through collaborations among multiple operators. The study compared two mapping approaches: centralized vs. distributed map-making. While the centralized mapping was suitable for maintaining authority and security, the ad hoc mapping strategy that enabled distributed public engagement was more capable of providing up-to-date information and helping make sense of changing conditions. Bharosa and Janssen (2009) investigated roles of a plotter or a mapper in assisting decision making units. Such roles were responsible for visualizing and integrating incident information into figures and maps, and sharing them with information managers of decision-making units. Also, it was suggested that integrating other data such as weather and potentially hazardous areas would enrich the 'common operating picture (COP)' (Bharosa and Janssen, 2009; Reuter et al., 2014).

(b) Event history log is another common tool used in the EM field that provides a chronological repository of situations reported and actions taken during an emergency (Comfort et al., 2004). The event history log is also an important artifact that facilitates coordination and information sharing by serving as a common source of updated incident information (Rankin et al., 2013a; Tveiten et al., 2012). However, the updates in the log are often not communicated well with other emergency personnel, so it may also cultivate incorrect information (Rankin et al., 2013a). Tveiten et al. (2012) supported this finding and stressed the need to protect event history log managers from receiving an excess amount of information and requests for information.

(c) Due to advanced mobile information technology, *mobile communication applications* have become a common tool in EM (Robinson et al., 2015). Although standardized communication systems are required to ensure technical interoperability among different organizations, emergency operators frequently utilize off-the-shelf consumer applications such as social media and cloud workspace for informal and improvised communication. Usage of instant messaging mobile applications has been documented for inter-agency communication in real-world emergencies such as civil disorders (de Carvalho et al., 2015). To facilitate the informal and ad hoc communication, Reuter et al. (2014) demonstrated a mobile application called 'Mobile Collaboration (MoCo)'. This application was conceived to allow for improvised, multilateral communication across both designated and unplanned participants while addressing the limitation of one-to-one cellphone communication. The study claims that participating agencies and stakeholders in the emergency response would receive benefits from the informal yet informative mobile communication systems for better sensemaking of changing situations and coordination among different response efforts.

(d) An integrated information management system is also found to be necessary for adaptive inter-organizational decision making during an emergency. For instance, Comfort et al. (2004) designed and implemented a prototype of 'Interactive, Intelligent, Spatial Information System (IISIS)' to improve collaboration among multiple organizations across different jurisdictions. To support the EM organizations in adapting to emerging and evolving hazardous conditions, IISIS features real-time communication between different organizations, real-time access to a distributed database (e.g., geographic information) and rapid risk assessment. Neville, Doyle, Sugrue, and Muller (2013) provided an overview of commercial incident information management systems including functional requirements such as multi-agency collaboration mandated by the NIMS.

(e) For adaptive decision making in EM systems, decision support tools have been developed. Mendonça et al. (2001) and Mendonça et al. (2006) created a group decision support system (GDSS) named 'emergency management improviser (EMPROV)' and conducted an experiment to examine whether the GDSS influences planning and execution of team decisions regarding resource allocation during an emergency. To generate alternative resources when a standard resource becomes unavailable, EMPROV incorporated cognitive processes for improvisation: determining whether an event can be handled by existing resources, searching for a pertinent referent for such resources, and generating alternatives. The results of the experiment showed that supported groups spent relatively less time on planning for the allocation of alternative resources and reported a lower level of perceived improvisation than unsupported groups.

3.5. Use of simulation to investigate resilience in EM

The current review found out that emergency simulation exercise is predominantly used as a study setting. Due to the inherent risks involved in observation and collection of data from real emergencies, of 39 studies that involved data collection, 22 (56%) were conducted in simulated exercises. Among these, a few studies discussed design factors including exercise scenarios, roles, and techniques for increasing the realism of the simulation as well as for cultivating resilience skills. For example, Trnka et al. (2016) proposed six design variables for stimulating adaptive behaviors in emergency response: i) risk (i.e., likelihood and consequence of an adverse event in the simulation), ii) dynamism (i.e., magnitude of a situation change), iii) tempo (i.e., how rapidly or slowly such change occurs), iv) stress (i.e., a gap between work demands and available resources in the response operations), v) information structure (i.e., distribution of information across multiple participants), and vi) feedback (i.e., provision of the state of the simulated occurrences to the participants). In addition, Trnka et al. (2016) suggest that providing information inputs or 'injects' to the participants in real-time further increases the realism of the exercise. Furthermore, Field, Rankin, van der Pal, Eriksson, and Wong (2011) suggested three ways to manipulate the realism of the simulated emergency: i) number of events (increasing or decreasing may affect the risk and tempo of the design variables above), ii) randomness of events (degree of expectation of a situation occurring), and iii) situational complexity (configuration of contextual factors of an incident scenario).

While the scenario design is concerned with creating a *stage* for emergency response, the design of roles is an important step for assigning tasks to *actors* on that stage. Indeed, a role-play exercise is considered an effective approach to understand how actors in the exercise perform in a fluid and complex conditions (Woltjer et al., 2006). Indeed, Trnka et al. (2016) observed how the roles of participants in emergency exercises were adapted over time. Such adaptation occurred when the team was initially charged with an emergency situation and when new tasks were identified along the course of the exercise. In both instances of adaptation, similar functions were merged into one role (e.g., information management and media relations) and a team member assumed another role outside of that member's specialized area. The role-play exercise can be devised with a different level of fidelity. Hermelin et al. (2019) indicate that the exercise may take place from a simple table-top setting to a full-scale facility. Regardless of the fidelity, however, after-action review of the exercise is recommended as an effective way to self-reflect about which adaptations were successful and to mitigate similar issues in the future (Hermelin et al., 2019; Woltjer et al., 2006).

4. Discussion

By recognizing escalating threats from recent disasters as well as lack of focused attention on resilience in the context of emergency management, we conducted a systematic literature review and provided a summary and synthesis of resilience in EM research. While a majority of the research efforts have taken an empirical approach and thus provided actual evidence for EM resilience, the predominant use of qualitative methods may reduce the generalization of findings and make comparison between the findings difficult (Gelo et al., 2008). Given sufficient contextual knowledge of resilience in EM, future studies are recommended to employ quantitative approaches (e.g., controlled experiments and hypothesis testing) to infer generalizable knowledge and predict resilient performance of an EM system. In what follows, we discuss the defining elements of resilience in EM, key factors and technical tools to achieve resilience in EM, and the value of simulation studies in future research to further enlighten knowledge of resilience in EM.

4.1. Three aspects of definitions of resilience in EM

Unlike previous reviews (Hosseini et al., 2016; Righi et al., 2015) that were mostly focused on resilience, the current review evaluated definitions across three cognate concepts in EM—resilience, adaptation and improvisation—and provided distinctions between these constructs along three aspects (i.e., temporality, expectancy of adverse events, and means for achieving resilience). Specifically, in line with Patriarca et al. (2018a), our evaluation of the definitions further supports that improvisation is an essential phenomenon for resilience in EM where quick actions are required under time pressure. By highlighting each of the three aspects, future work should focus on i) investigating what the EM system does to prepare for and respond to an adverse event, ii) measuring the effects of unexpectedness of an emergency situation on the EM system's performance adjustment, and iii) developing and testing means (e.g., training programs, work processes, and technical tools) that support adaptation under changing and challenging conditions.

4.2. Four key factors to achieve resilience in EM

The current review elicited four key dimensions that contribute to resilience in EM: i) collective sensemaking, ii) team decision making, iii) harmonizing WAI and WAD, and iv) interaction and coordination. While some of these factors were partially claimed in the previous RE literature (Hollnagel, 2011b; Woods, 2006), our research provides a collection of interlinked factors needed to achieve resilience in the context of EM. Therefore, our findings may facilitate future investigations on individual dimensions of EM resilience as well as interdependencies among them as suggested in the following research agenda.

First, creating a common understanding of incident situations or *collective sensemaking* has been considered a foundation of EM resilience. However, only a few studies (Bharosa and Janssen, 2009; Petersen, 2015; Rankin et al., 2013a) have focused on specific tools to improve the collective sensemaking in EM. For example, the role of information management tools used in EM (e.g., incident mapping, event history logging) needs further investigation. Based on the current review, promising research topics for future investigations include: studying differences between centralized control and distributed participation; incorporating multiple incident data into a visually informative form for decision makers (e.g., hazardous conditions); and improving designs suitable for updating information in a timely manner. Widespread commercial collective sensemaking tools such as WebEOC® can also benefit from similar improvements (Robinson et al., 2015; Scholl et al., 2017). Such collective sensemaking tools should be designed to support knowledge-based reasoning commonly required during an emergency (Vicente, 2002) in addition to the current utilization as an information repository (Comfort et al., 2004).

Second, this review has identified that team decisions during an emergency involve coordination among distributed decision-makers. Particularly, *team decision making* in EM is often driven by government protocols (e.g., ICS, NIMS; Son et al., 2018). Consequently, future research should investigate how temporally or spatially distributed decision makers are coordinated to adapt decisions while following such principles in a fluid emergency condition. While a few team decision support systems have been developed and documented (Mendonça et al., 2001; Mendonça and Wallace, 2002), findings pertaining to the effects of such support systems on the EM team's resilient performance are somewhat inconclusive (Mendonça et al., 2006). Future efforts should, therefore, focus on developing more effective support systems that help EM teams quickly recognize adverse events and adapt to changing or unexpected conditions. These systems should also support perception and integration of incident information, as well as complex problem-solving under time-pressure.

Third, bridging the gap between *WAI* (e.g., pre-emergency plans) and *WAD* (e.g., implemented actions) has long been a challenging quest in response to emergency events (Buck et al., 2006). The fact that emergency procedures cannot cover all the possible scenarios and that such procedures may not be implemented exactly as imagined (Hollnagel, 2017) should be acknowledged in the first place. Specifically, the current review provided different dimensions where such discrepancies could occur such as roles of emergency responders (Mendonça et al., 2014; Webb, 2004). Hence, it is imperative to develop emergency operators' ability to devise and implement adaptive actions to changing conditions while meeting the overall goals during an incident (de Carvalho et al., 2018). As indicated by Son et al. (2019b), it would be necessary to incorporate such temporary improvisational actions into formal emergency training programs or emergency operations plans. To that end, the gaps between emergency operating procedures and their actual implementation would be reduced.

Fourth, our review has found that *interaction and coordination* among EM personnel is an essential factor that renders other aspects of EM resilience possible. In reality, it has been a recurring challenge to create supportive and value-added interaction and coordination among distributed EM personnel (Comfort et al., 2004b). Considering the prevalence of a team-oriented environments in emergency operations, future studies along the interaction and coordination dimension can take two approaches. One approach is to investigate actions that EM team members carry out, for example, temporary assembly of sub-teams to reach a decision for specific problems (Domeneghetti et al., 2018; Gomes et al., 2014) in order to identify what type of interactive and coordinative actions occur in the EM team setting and how such actions contribute to collective sensemaking or team decision making. Another approach can be taken from a team composition perspective. Given the common practice of ad hoc teaming and role changing patterns in EM (Pramanik et al., 2015; Trnka et al., 2016), additional attention should be paid to the formation of EM teams when necessary roles are not filled (Rankin et al., 2013b), or when expertise of team members is disparate (Franco et al., 2009). From a methodological standpoint, many studies have sought to descriptively explain how the interaction and coordination occurs in EM; nonetheless, complex interaction patterns of the EM personnel have rarely been analyzed, and quantitative assessment methods are largely absent. Hence, future studies may benefit from analytical methods suitable for complex and dynamic interactions such as social network analysis (Roberts et al., 2019), recurrence quantitative analysis (Demir et al., 2019), and interaction episode analysis (Son et al., 2020).

4.3. Developing technical tools to support resilience in EM

This paper presents a summary of five common technical tools used to support individual operators and organizational processes during emergencies. While advanced technologies often provide better opportunities to increase resilience of socio-technical systems, they may also result in brittleness, as opposed to resilience, when poorly designed (e.g., clumsy automation; see Patriarca et al., 2017; Woods, 2017). Several opportunities and challenges associated with each of the common technical tools, in terms of the four key factors of resilience in EM need to be discussed (Table 5).

First, the *mapping tools* offer a rich geospatial overview of incident operations regarding what events are occurring where. Such representation show how planned tasks occur in real life which may contribute to informed decisions. Also, multiple mapmakers can use the mapping tool as a joint platform for collaboration. However, it may be challenging to integrate multiple geospatial data entered at different times and from different locations. An *event history log* provides notable events and actions in a chronological order. Although the event history log is mostly based on text that conveys less information compared to maps, the logs can better trace what has occurred in the past, which helps identify patterns of event occurrence. Since the log lists such individual events as a separate input, it may be difficult and time-consuming to pinpoint a specific entry. *Mobile communication applications* are promising as they enable multilateral and simultaneous communication even with unplanned users and can support other functions such as visual mapping. By expediting the sharing of common incident information, mobile communication applications may reduce the discrepancies between decisions made at different sites or different organizational levels. However, additional care should be taken to control the ad hoc access and to validate data entered by unplanned users. *Integrated information management systems* are emerging in the field of EM (Neville et al., 2013). These systems support the information management cycle of EM systems–that is, searching, processing, and disseminating incident information–and thus provide a common operating picture (COP). Moreover, additional advanced functions such as potential risk estimation and role assignment may be provided. Nevertheless, it should be also noted that participating organizations may require customized scope and type of information rather than a single, big picture (Son et al., 2019a). Lastly, *decision support tools* (DSTs) can be useful when the need for generation of alternative decisions emerges. Therefore, DSTs can complement a formal and analytical, and often lengthy, planning process usually taking place in the EM field. In addition, ensuring the same information to be available in DSTs may facilitate negotiation among multiple decision makers. However, over-reliance on DSTs or over-creativity of the alternative decisions should be eschewed.

4.4. Emergency simulation to facilitate future research efforts

Despite the widespread use of emergency simulation exercises as a study setting, extant knowledge regarding the effect of scenario design factors and role-playing conditions on resilience of EM organizations is quite limited. Thus, future studies should place more efforts on devising emergency simulations, being not only realistic but also amenable to the investigation of resilience. First, such simulations need to reflect the dynamic and uncertain nature of an emergency incident. This can be achieved by varying tempo (slow vs fast progression), intensity (low vs high consequence), and uncertainty (expected vs. unexpected events) of simulated events (Field et al., 2011). Second, actual operating processes of EM organizations should be incorporated into the simulation settings. For instance, the simulation needs to consider multiple, different roles (e.g., incident data collector, mapper, event logger) involved in the information management and decision-making process. In addition, providing real-time feedback about the status of the incident and the EM organizations via 'injects' (Trnka et al., 2016) can be used to increase the fidelity of simulated exercises.

5. Conclusion

The current review was focused on summarizing and integrating findings from the literature on resilience in EM. The evaluation of definitions indicated that resilience is intertwined with two other concepts, namely adaptation and improvisation, but also showed differences across three categories: temporality (proactive vs. reactive performance), expectancy (expected vs. unexpected disruptions), and means for managing disruptions. This paper also documented four essential and interrelated factors of resilience in EM: collective sensemaking, team decision making, harmonizing WAI and WAD, and interaction and coordination. Regarding the key factors, future research areas were suggested to address associated limitations identified in this review. Considering the EM system as a socio-technical system, five types of technology used to support EM resilience were identified. Further, possible opportunities and challenges that such technology might bring were also discussed. Lastly, our review indicated that simulation exercises can be an effective way to investigate EM resilience and thus we provided guidelines for designing emergency simulations.

Given the complexity of emergency management in recent disasters, resilience in emergency management has emerged as a core agenda both in research and practice. However, addressing challenges that impede resilience in EM remain a critical research gap. By integrating diverse theoretical and empirical findings, this review would serve as a foundation for further efforts to engineer resilience into EM systems from various perspectives, such as supporting collective sensemaking, reconciling WAI and WAD, and adaptive team decision making through interaction and coordination between EM systems.

5.1. Limitations of the present review

First, the scope of the present review was confined to the domain of emergency and disaster research. Thus, the findings and discussions may

Table 5
Opportunities and challenges of technical tools for resilience in EM.

	Opportunities				Challenges
	Collective Sensemaking	Team Decision Making	Harmonizing WAI and WAD	Interaction and Coordination	
Mapping tool (Bharosa and Janssen, 2009; Petersen, 2015)	Providing rich and current geographical information.	Informing decision makers of up-to-date overview of status.	Understanding how planned tasks are currently happening.	Allowing for collaborative efforts from multiple mapmakers.	Multiple data may be entered at different times from multiple sites.
Event history log (Comfort et al., 2004a; Rankin et al., 2013a; Tveiten et al., 2012)	Storing notable events and actions in a sequential order.	Providing a track of past events to identify patterns of occurrence.	Showing how actual events occurred regarding expected scenarios.	Serving as a common warehouse for individuals to retrieve past records.	Difficulty of locating a specific entry as the list gets longer.
Mobile communication application (de Carvalho et al., 2015; Reuter et al., 2014; Robinson et al., 2015)	Enabling multilateral communication (i.e., many-to-many).	Reducing variability of decisions made at different sites.	Accommodating ad hoc participation of unplanned individuals.	Providing enhanced interoperability among different organizations.	Extra efforts to control access and ensure the validity of data.
Integrated information management system (Comfort et al., 2004a; Neville et al., 2013)	Supporting information management cycle and providing COP.	Suggesting potential risks to inform future actions to be taken.	Re-assigning roles of participating members.	Reducing discrepancies of knowledge shared among multiple organizations.	Different entities may require customized type and level of information.
Decision support tool (Mendonça et al., 2001, 2006)	Feeding the same information basis to multiple decision makers.	Generating alternative decisions to achieve incident objectives.	Complementing formal, analytical planning process.	Facilitating negotiation among multiple decision makers.	Over-reliance on suggested alternative decisions and over-creativity of the decisions.

not be directly applicable to resilience of other socio-technical domains. However, previous reviews were largely focused on resilience engineering literature rather than a broad scholarly work of resilience in a disaster context. Hence, the current review may fill the gap that exists in such comprehensive RE reviews. Second, while the current review utilized established systematic review methodologies under the supervision of a librarian at a tier-one research-intensive university and with an advanced screening support tool (i.e., Rayyan), we acknowledge that developing sets of exhaustive search terms (e.g., controlled terms, free-text terms) was a difficult undertaking and it is possible that several relevant papers might have been missed. Third, to mitigate the coders' biases in eliciting emergent factors of resilience, future research is required to develop a set of criteria for which agreement between multiple coders can be assessed. Fourth, although we summarized study designs (e.g., theoretical, qualitative, quantitative) of the included literature, we did not appraise the quality of evidence, which may offer further value of the review and thus is recommended as future inquiry.

Declaration of competing interest

We have no conflict of interest to report.

Acknowledgements

This review was supported by an internal award from Mary Kay O'Connor Process Safety Center and the National Science Foundation EAGER Grant (#1724676). The sponsors had no involvement in the conduct of the research. The authors would like to thank Margaret Foster for her guidance on systematic literature review methods and Jacob M. Kolman for his editing and proofreading support.

Appendix A

Table A
Summary of extracted findings from the included literature (n = 55)

Authors (year)	Publication type	Research focus	Research design	Study methods	Type of event studied	Study Utrecht location
Abbasi et al. (2010)	Conference	Examining the relationship between incident management team members' coordination and their adaptive behavior	Qualitative	Survey	Wildfire	Australia
Aguilera et al. (2016)	Journal	Describing how functional variability in planning, execution, and resources impacts nuclear emergency response activities.	Qualitative	Observation, interview, audio-visual recording	Chemical spill	Brazil
Bergström et al. (2008)	Conference	Investigating whether non-domain specific training improves crisis management team's ability to handle emergency situations.	Qualitative	Observation	Maritime incident	Sweden
Bharosa and Janssen (2009)	Conference	Identifying types of adaptive capabilities in disaster information management.	Qualitative	Observation, interview, document analysis	Flooding, chemical spill	The Netherlands
Brown and Eriksson (2008)	Journal	Discussing limitations of emergency plans and proposing ways to develop the plans that support resilient operations.	Theoretical			
Caldwell (2014)	Journal	Proposing a concept of resilience boundary framing for managing large-scale emergency events.	Theoretical			
de Carvalho et al. (2015)	Conference	Describing how an integrated command and control center responded to a civil disturbance during a major sports game.	Qualitative	Observation, interview	Sports event	Brazil
de Carvalho et al. (2018)	Journal	Comparison between WAI represented in SOPs and WAD identified from simulated emergency training for firefighter captains.	Qualitative	Observation, interview, audio-visual recording	Railroad incident	Brazil
Comfort (2002)	Journal	Developing a model of auto-adaptation aimed at improving inter-governmental performance in extreme events.	Qualitative	Case study, document analysis	Terrorism	USA
Comfort (2007)	Journal	Claiming that cognition is essential to adaptive performance in emergency management jointly with communication, coordination, and control.	Theoretical			
Comfort et al. (2004a)	Journal	Designing integrated spatial information system and reporting findings from its demonstration in a local jurisdiction.	Qualitative	Observation, interview	Hazardous material release	USA
Domeneghetti et al. (2018)	Journal	Identifying the relationship between pre-established action plans and mid-incident decision making based on expertise for mass protection.	Qualitative	Observation	Nuclear incident	France
Field et al. (2011)	Conference	Suggesting necessary elements for emergency training scenarios to foster adaptive skills.	Theoretical			
Franco et al. (2009)	Conference	Evaluating the effect of improvisational behaviors (e.g., changing roles, authority, or communication flow) on decision making team's performance.	Quantitative	Experiment	Six different cases	USA
Frye and Wearing (2016)	Journal	Describing the role of bushfire responders' metacognition in adapting to changing conditions.	Qualitative	Interview, survey, document analysis	Wildfire	Australia
Gomes et al. (2014)	Journal	Describing sources of resilience and brittleness in a simulated nuclear incident.	Qualitative	Observation, audio-visual recording	Nuclear incident	Brazil
Harrald (2006)	Journal	Arguing that both agility (e.g., adaptability, improvisation) and discipline (e.g., command, control) can be achieved during disaster response.	Theoretical			
Hermelin et al. (2019)	Journal		Qualitative	Group discussion, survey	Five different cases	Sweden

(continued on next page)

Table A (*continued*)

Authors (year)	Publication type	Research focus	Research design	Study methods	Type of event studied	Study Utrecht location
		Describing how generic resilience training concepts are applied to specific contexts of a regional medical command and control team.				
Hollnagel and Sundström (2006)	Book chapter	Describing a state-space model of a resilient system in escalating events.	Theoretical			
Hunte (2017)	Book chapter	Providing characteristics of resilient behaviors of an emergency department in response to a large civil disorder.	Qualitative	Case study	Sports event	Canada
Klimek et al. (2019)	Journal	Developing quantitative measures of resilient organizational behavior using social network analysis.	Quantitative	Document analysis	Storm	Hungary
Longstaff and Yang (2008)	Journal	Analyzing the relationship between trust and communication in the face of crisis surprise.	Quantitative	Document analysis	82 various cases	USA
Lundberg et al. (2012)	Journal	Proposing a model for describing resilience in emergency management using disturbance, sensemaking, and control variety.	Qualitative	Observation, audio-visual recording	Storm	Sweden
Lundberg and Rankin (2014)	Journal	Identifying types of role improvisation in small response teams and their negative effects.	Qualitative	Interview, group discussion	Tsunami, warfare	Sweden
Mendonça (2007)	Journal	Identifying requirements for designing a computer-based system that supports improvisation in emergency events.	Qualitative	Interview, group discussion, document analysis	Terrorism	USA
Mendonça (2008)	Book chapter	Developing and evaluating a set of measures for resilience in critical infrastructure restoration.	Qualitative	Interview, survey, document analysis	Terrorism	USA
Mendonça and Hu (2007)	Book chapter	Investigating the role of event severity on cognitive and decision processes in an emergency management team setting.	Quantitative	Experiment	Maritime incident	The Netherlands
Mendonça et al. (2014)	Journal	Analyzing cognitive and behavioral improvisations in two major terrorism events.	Quantitative	Document analysis	Terrorism	USA
Mendonça et al. (2001)	Journal	Proposing a concept of blackboard-based decision support systems for improvisation in emergency response.	Qualitative	Interview, survey, document analysis	Maritime incident	The Netherlands
Mendonça et al. (2006)	Journal	Evaluating the effect of a group decision support system for improvisational decision making behaviors of emergency response teams.	Quantitative	Experiment	Maritime incident	The Netherlands
Mendonça and Wallace (2007)	Journal	Developing a cognitive model of improvisation in emergency management using a theory of jazz music.	Theoretical			
Neville et al. (2013)	Conference	Identifying strengths and weaknesses of commercial decision support tools for flexible multi-agency coordination.	Qualitative	Document analysis	Public health events	European countries
Petersen (2015)	Conference	Comparing and contrasting centralized and distributed mapmaking approaches toward collective sensemaking.	Qualitative	Observation, interview	Wildfire	USA
Pramanik et al. (2015)	Journal	Investigating whether higher familiarity and expectation of future cooperation increases the likelihood of working with other organizations.	Quantitative	Experiment, interview	Storm	Sweden
Rankin et al. (2013a)	Journal	Analyzing factors that hamper role adaptation in information and communication flow in a crisis management team.	Qualitative	Observation, audio-visual recording, document analysis	Wildfire	USA
Rankin et al. (2014)	Book chapter	Developing a framework for sharp-end adaptations and analyzing a crisis management team's response to a reduced team size.	Qualitative	Case study	Wildfire	USA
Reuter et al. (2014)	Journal	Examining how inter-organizational collaboration is supported by a mobile geospatial system.	Qualitative	Observation, interview, group discussion	Storm	Germany
Righi et al. (2016)	Conference	Identifying sources of resilience and brittleness in a crisis management exercise in relation to emergency SOPs.	Qualitative	Case study, observation, audio-visual recording	Railroad incident	Brazil
Robinson et al. (2015)	Conference	Describing issues associated with emergency information and communication technology and strategies to overcome them.	Qualitative	Interview	Landslide	USA
Rose et al. (2015)	Conference	Examining key decision making skills required for emergency managers to respond to unexpected incidents.	Qualitative	Interview, survey	Terrorism	USA
Roux-Dufort and Vidaillet (2003)	Journal	Examining conditions that hinder resilient behavior in multidisciplinary and divergent team environments.	Qualitative	Case study, interview, document analysis	Chemical fire	France
Son et al. (2018)	Journal	Modeling information management and team decision making based on interaction among team components.	Qualitative	Observation, audio-visual recording	Storm, terrorism	USA
Stachowski et al. (2009)	Journal	Distinguishing patterns of changing interaction (number and complexity) between high- and low-performing teams.	Quantitative	Audio-visual recording	Nuclear incident	USA
Trnka et al. (2016)	Journal	Identifying types of situations where role improvisations are manifested and suggesting how a	Qualitative			Sweden

(*continued on next page*)

Table A (*continued*)

Authors (year)	Publication type	Research focus	Research design	Study methods	Type of event studied	Study Utrecht location
		simulation exercise can be designed to prompt the role improvisations.		Observation, interview, group discussion, audio-visual recording, document analysis	Tsunami, warfare, wildfire	
Tveiten et al. (2012)	Journal	Finding out challenges and opportunities for resilient emergency management with respect to advanced technology and distributed response organizations.	Qualitative	Group discussion	Chemical spill	Norway
Vecchiola et al. (2013)	Journal	Providing design principles for resilient disaster information systems and applying them to a public firefighting organization.	Qualitative	Case study	Wildfire	Canada
Voshell et al. (2008)	Conference	Assessing challenges in coordination between urban firefighting teams.	Qualitative	Observation, interview, audio-visual recording	Urban fire	USA
Webb (2004)	Journal	Classifying role improvisations by the type of disasters: natural, technical, or civil incident.	Quantitative	Interview, document analysis	304 various cases	USA
Webb and Chevreau (2006)	Journal	Suggesting characteristics of organizations that impede flexibility in responding to a crisis.	Theoretical			
Weick (1993)	Journal	Proposing potential sources of resilience in a firefighting crew's response to a wildfire.	Qualitative	Interview, document analysis	Wildfire	USA
Westrum (2006)	Book chapter	Suggesting a typology of resilient organizations during emergency events.	Theoretical			
Woltjer et al. (2006)	Conference	Investigating how role-playing exercises influence resilient performance of an emergency management team.	Qualitative	Observation, interview, audio-visual recording, document analysis	Wildfire, blackout	Sweden
Woods and Branlat (2011)	Book chapter	Describing basic patterns in the failure of adaptive systems in the context of urban firefighting.	Qualitative	Observation, interview, document analysis	Urban fire	USA
Wybo et al. (2006)	Conference	Understanding the role of observers in an emergency simulation in capturing resilient behaviors of an organization.	Qualitative	Observation	Road incident	France
Zhuravsky (2018)	Book chapter	Examining core resilience capabilities in a regional emergency medical team's response to an earthquake disaster.	Qualitative	Case study	Earthquake	New Zealand

References

Abbasi, A., Hossain, L., Hamra, J., Owen, C., 2010. Social networks perspective of firefighters' adaptive behaviour and coordination among them. IEEE/ACM Int. Conf. Green Comput. Commun. Int. Conf. Cyber Phys. Soc. Comput. 819–824. https://doi.org/10.1109/GreenCom-CPSCom.2010.57.

Aguilera, M.V.C., Fonseca, B.B.d., Ferris, T.K., Vidal, M.C.R., de Carvalho, P.V.R., 2016. Modelling performance variabilities in oil spill response to improve system resilience. J. Loss Prev. Process. Ind. 41, 18–30. https://doi.org/10.1016/j.jlp.2016.02.018.

Alexander, D.E., 2013. Resilience and disaster risk reduction: an etymological journey. Nat. Hazards Earth Syst. Sci. 13 (11), 2707–2716. https://doi.org/10.5194/nhess-13-2707-2013.

Alias, M., Suradi, Z., 2008. Concept mapping: a tool for creating a literature review. In: At the 3rd International Conference on Concept Mapping. Finland, Helsinki. Paper presented.

Bergström, J., Petersen, K., Dahlström, N., 2008. Securing organizational resilience in escalating situations development of skills for crisis and disaster management. In: At the 3rd Resilience Engineering Symposium. Juan-les-Pins, France. Paper presented.

Bergström, J., van Winsen, R., Henriqson, E., 2015. On the rationale of resilience in the domain of safety: a literature review. Reliab. Eng. Syst. Saf. 141, 131–141. https://doi.org/10.1016/j.ress.2015.03.008.

Bharosa, N., Janssen, M., 2009. Reconsidering information management roles and capabilities in disaster response decision-making units. In: At the 6th International Conference on Information Systems for Crisis Response and Management. Paper presented, (Gothenburg, Sweden).

Bigley, G.A., Roberts, K.H., 2001. The incident command system: high-reliability organizing for complex and volatile task environments. Acad. Manag. J. 44 (6), 1281–1299. https://doi.org/10.5465/3069401.

Boin, A., McConnell, A., 2007. Preparing for critical infrastructure breakdowns: the limits of crisis management and the need for resilience. J. Contingencies Crisis Manag. 15 (1), 50–59. https://doi.org/10.1111/j.1468-5973.2007.00504.x.

Boin, A., Comfort, L.K., Demchak, C.C., 2010. The rise of resilience. In: Comfort, L.K., Boin, A., Demchak, C.C. (Eds.), Designing Resilience: Preparing for Extreme Events. University of Pittsburgh Press, Pittsburgh, PA, pp. 1–12.

Braun, V., Clarke, V., 2006. Using thematic analysis in psychology. Qual. Res. Psychol. 3 (2), 77–101. https://doi.org/10.1191/1478088706qp063oa.

Brown, C., Eriksson, K., 2008. A plan for (certain) failure: possibilities for and challenges of more realistic emergency plans. Int. J. Emerg. Manag. 5 (3), 292–310. https://doi.org/10.1504/IJEM.2008.025099.

Buck, D.A., Trainor, J.E., Aguirre, B.E., 2006. A critical evaluation of the incident command system and NIMS. J. Homel. Secur. Emerg. Manag. 3 (3), 1–27. https://doi.org/10.2202/1547-7355.1252.

Caldwell, B.S., 2014. Cognitive challenges to resilience dynamics in managing large-scale event response. J. Cognit. Eng. Decis. Making 8 (4), 318–329. https://doi.org/10.1177/1555343414546220.

Cañas, A.J., Hill, G., Carff, R., Suri, N., Lott, J., Gómez, G., Carvajal, R., 2004. CmapTools: a knowledge modeling and sharing environment. In: At the 1st International Conference on Concept Mapping. Paper presented, (Pamplona, Spain).

Chuang, S., Ou, J.-C., Ma, H.-P., 2020. Measurement of resilience potentials in emergency departments: applications of a tailored Resilience Assessment Grid. Saf. Sci. 121, 385–393. https://doi.org/10.1016/j.ssci.2019.09.012.

Comfort, L.K., 2002. Managing intergovernmental responses to terrorism and other extreme events. Publius 32 (4), 29–50. https://doi.org/10.1093/oxfordjournals.pubjof.a004970.

Comfort, L.K., 2007. Crisis management in hindsight: cognition, communication, coordination, and control. Publ. Adm. Rev. 67, 189–197. https://doi.org/10.1111/j.1540-6210.2007.00827.x.

Comfort, L.K., Kapucu, N., 2006. Inter-organizational coordination in extreme events: the world trade center attacks, september 11, 2001. Nat. Hazards 39 (2), 309–327. https://doi.org/10.1007/s11069-006-0030-x.

Comfort, L.K., Dunn, M., Johnson, D., Skertich, R., Zagorecki, A., 2004a. Coordination in complex systems: increasing efficiency in disaster mitigation and response. Int. J. Emerg. Manag. 2 (1–2), 62–80. https://doi.org/10.1504/IJEM.2004.005314.

Comfort, L.K., Ko, K., Zagorecki, A., 2004b. Coordination in rapidly evolving disaster response systems: the role of information. Am. Behav. Sci. 48 (3), 295–313. https://doi.org/10.1177/0002764204268987.

de Carvalho, P.V.R., Arce, Diana, Passos, Claudio, Huber, Gilbert J., Borges, Marcos, Gomes, J.O., 2015. A participatory approach to improve resilience in command and control (C2) systems: a case study in the Rio de Janeiro C2 system. In: At the 6th Resilience Engineering Symposium. Paper presented, (Lisbon, Portugal).

de Carvalho, P.V.R., Righi, A.W., Huber, G.J., Lemos, C.d.F., Jatoba, A., Gomes, J.O., 2018. Reflections on work as done (WAD) and work as imagined (WAI) in an emergency response organization: a study on firefighters training exercises. Appl. Ergon. 68, 28–41. https://doi.org/10.1016/j.apergo.2017.10.016.

Demir, M., McNeese, N.J., Cooke, N.J., 2019. The evolution of human-autonomy teams in remotely piloted aircraft systems operations. Front. Commun. 4, 50. https://doi.org/10.3389/fcomm.2019.00050.

Domeneghetti, B., Benamrane, Y., Wybo, J.-L., 2018. Analyzing nuclear expertise support to population protection decision making process during nuclear emergencies. Saf. Sci. 101, 155–163. https://doi.org/10.1016/j.ssci.2017.08.017.

Field, J., Rankin, A., van der Pal, J., Eriksson, H., Wong, W., 2011. Variable uncertainty: scenario design for training adaptive and flexible skills. 29th Annu. Eur. Conf. Cognit. Ergon. 27–34. https://doi.org/10.1145/2074712.2074719.

Franco, Z.E., Zumel, N., Holman, J., Blau, K., Beutler, L.E., 2009. Evaluating the impact of improvisation on the incident command system: a modified single case study using the DDD simulator. In: At the 6th International Conference on Information

Systems for Crisis Response and Management. Paper presented, (Gothenburg, Sweden).
Frye, L.M., Wearing, A.J., 2016. A model of metacognition for bushfire fighters. Cognit. Technol. Work 18 (3), 613–619. https://doi.org/10.1007/s10111-016-0372-4.
Gelo, O., Braakmann, D., Benetka, G., 2008. Quantitative and qualitative research: beyond the debate. Integr. Psychol. Behav. Sci. 42 (3), 266–290. https://doi.org/10.1007/s12124-008-9078-3.
Gomes, J.O., Borges, M.R.S., Huber, G.J., Carvalho, P.V. R.d., 2014. Analysis of the resilience of team performance during a nuclear emergency response exercise. Appl. Ergon. 45 (3), 780–788. https://doi.org/10.1016/j.apergo.2013.10.009.
Grøtan, T.O., Størseth, F., Rø, M.H., Skjerve, A.B., 2008. Resilience, adaptation and improvisation–increasing resilience by organising for successful improvisation. In: At the 3rd Resilience Engineering Symposium. Paper presented, (Juan-les-Pins, France).
Harrald, J.R., 2006. Agility and discipline: critical success factors for disaster response. Ann. Am. Acad. Polit. Soc. Sci. 604, 256–272. https://doi.org/10.1177/0002716205285404.
Hermelin, J., Bengtsson, K., Woltjer, R., Trnka, J., Thorstensson, M., Pettersson, J., Jonson, C.-O., 2019. Operationalising resilience for disaster medicine practitioners: capability development through training, simulation and reflection. Cognit. Technol. Work 1–17. https://doi.org/10.1007/s10111-019-00587-y.
Hollnagel, E., 2011a. Epilogue: RAG - the resilience analysis grid. In: Hollnagel, E., Paries, J., Woods, D.D., Wreathall, J. (Eds.), Resilience Engineering in Practice: A Guidebook. Ashgate Publishing, Surrey, UK, pp. 275–296.
Hollnagel, E., 2011b. Prologue: the scope of resilience engineering. In: Hollnagel, E., Paries, J., Woods, D.D., Wreathall, J. (Eds.), Resilience Engineering in Practice: A Guidebook. Ashgate Publishing, Surrey, UK, pp. xx–xxxix.
Hollnagel, E., 2017. Why is work-as-imagined different from work-as-done?. In: Wears, R.L., Hollnagel, E., Braithwaite, J. (Eds.), Resilient Health Care, vol. 2. Ashgate Publishing, Surrey, UK, pp. 279–294.
Hollnagel, E., Sundström, G., 2006. States of resilience. In: Hollnagel, E., Woods, D.D., Leveson, N. (Eds.), Resilience Engineering: Concepts and Precepts. Ashgate Publishing, Aldershot, UK, pp. 339–346.
Hollnagel, E., Woods, D.D., 2005. Joint Cognitive Systems: Foundations of Cognitive Systems Engineering. CRC Press, Boca Raton, FL.
Hollnagel, E., Woods, D.D., Leveson, N., 2006. Resilience Engineering: Concepts and Precepts. Ashgate Publishing, Aldershot, UK.
Hosseini, S., Barker, K., Ramirez-Marquez, J.E., 2016. A review of definitions and measures of system resilience. Reliab. Eng. Syst. Saf. 145, 47–61. https://doi.org/10.1016/j.ress.2015.08.006.
Hunte, G.S., 2017. A lesson in resilience: the 2011 Stanley Cup riot. In: Wears, R.L., Hollnagel, E., Braithwaite, J. (Eds.), Resilient Health Care, vol. 2. CRC Press, Boca Raton, FL, pp. 31–40.
Institute for Human & Machine Cognition, 2017. CmapTools (Version 6.03) [computer software]. IHMC, Pensacola, FL. Retrieved from. https://cmap.ihmc.us/.
Jenuwine, E.S., Floyd, J.A., 2004. Comparison of medical subject headings and text-word searches in MEDLINE to retrieve studies on sleep in healthy individuals. J. Med. Libr. Assoc. 92 (3), 349.
Kendra, J.M., Wachtendorf, T., 2003. Elements of resilience after the World Trade Center disaster: reconstituting New York City's emergency operations centre. Disasters 27 (1), 37–53. https://doi.org/10.1111/1467-7717.00218.
Klimek, P., Varga, J., Jovanovic, A.S., Székely, Z., 2019. Quantitative resilience assessment in emergency response reveals how organizations trade efficiency for redundancy. Saf. Sci. 113, 404–414. https://doi.org/10.1016/j.ssci.2018.12.017.
Longstaff, P.H., Yang, S., 2008. Communication and trust: keys for building resilience to "surprises" such as natural disasters, pandemic flu and terrorism. Ecol. Soc. 13 (1).
Lundberg, J., Rankin, A., 2014. Resilience and vulnerability of small flexible crisis response teams: implications for training and preparation. Cognit. Technol. Work 16 (2), 143–155. https://doi.org/10.1007/s10111-013-0253-z.
Lundberg, J., Tornqvist, E., Nadjm-Tehrani, S., 2012. Resilience in sensemaking and control of emergency response. Int. J. Emerg. Manag. 8 (2), 99–122. https://doi.org/10.1504/IJEM.2012.046009.
McHugh, M.L., 2012. Interrater reliability: the kappa statistic. Biochem. Med. 22 (3), 276–282.
Mendonça, D., 2007. Decision support for improvisation in response to extreme events: learning from the response to the 2001 World Trade Center attack. Decis. Support Syst. 43 (3), 952–967. https://doi.org/10.1016/j.dss.2005.05.025.
Mendonça, D., 2008. Measures of resilient performance. In: Hollnagel, E., Nemeth, C., Dekker, S. (Eds.), Resilience Engineering Perspectives, vol. 1. Ashgate Publishing, Aldershot, UK, pp. 43–62.
Mendonça, D., Hu, Y., 2007. Cognitive underpinnings of resilience: a case study of group decision in emergency response. In: Nemeth, C., Hollnagel, E., Dekker, S. (Eds.), Resilience Engineering Perspectives: Preparation and Restoration, vol. 2. Ashgate Publishing, Surrey, UK, pp. 179–204.
Mendonça, D., Wallace, W.A., 2002. Development of a decision logic to support group improvisation: an application to emergency response. 35th Annu. Hawaii Int. Conf. Syst. Sci. 2882–2888. https://doi.org/10.1109/HICSS.2002.994269.
Mendonça, D.J., Wallace, W.A., 2007. A cognitive model of improvisation in emergency management. IEEE Trans. Syst. Man Cybern. Syst. Hum. 37 (4), 547–561. https://doi.org/10.1109/TSMCA.2007.897581.
Mendonça, D., Beroggi, G.E.G., Wallace, W.A., 2001. Decision support for improvisation during emergency response operations. Int. J. Emerg. Manag. 1 (1), 30–38. https://doi.org/10.1504/IJEM.2001.000507.
Mendonça, D., Beroggi, G.E.G., van Gent, D., Wallace, W.A., 2006. Designing gaming simulations for the assessment of group decision support systems in emergency response. Saf. Sci. 44 (6), 523–535. https://doi.org/10.1016/j.ssci.2005.12.006.
Mendonça, D., Webb, G., Butts, C., Brooks, J., 2014. Cognitive correlates of improvised behaviour in disaster response: the cases of the Murrah building and the World Trade Center. J. Contingencies Crisis Manag. 22 (4), 185–195. https://doi.org/10.1111/1468-5973.12057.
Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Ann. Intern. Med. 151 (4), 264–269. https://doi.org/10.7326/0003-4819-151-4-200908180-00135.
Nemeth, C., Cook, R., 2007. Healthcare IT as a source of resilience. IEEE Int. Conf. Syst. Man Cybern. 3408–3412. https://doi.org/10.1109/ICSMC.2007.4413721, 2007.
Neville, K., Doyle, C., Sugrue, A., Muller, J., 2013. Supporting cross border emergency management decision-making. In: At the 21st European Conference on Information Systems. Paper presented, (Utrecht, the Netherlands).
Ouzzani, M., Hammady, H., Fedorowicz, Z., Elmagarmid, A., 2016. Rayyan—a web and mobile app for systematic reviews. Syst. Rev. 5 (1), 210. https://doi.org/10.1186/s13643-016-0384-4.
Patriarca, R., Gravio, G.D., Costantino, F., Tronci, M., Severoni, A., Vernile, A., Bilotta, F., 2017. A paradigm shift to enhance patient safety in healthcare, a resilience engineering approach: scoping review of available evidence. Int. J. Healthc. Technol. Manag. 16 (3–4), 319–343. https://doi.org/10.1504/IJHTM.2017.10009752.
Patriarca, R., Bergström, J., Di Gravio, G., Costantino, F., 2018a. Resilience engineering: current status of the research and future challenges. Saf. Sci. 102, 79–100. https://doi.org/10.1016/j.ssci.2017.10.005.
Patriarca, R., Di Gravio, G., Costantino, F., Falegnami, A., Bilotta, F., 2018b. An analytic framework to assess organizational resilience. Saf. Health Work 9 (3), 265–276. https://doi.org/10.1016/j.shaw.2017.10.005.
Perry, R.W., 2007. What is a disaster? In: Rodriguez, H., Quarantelli, E., Dynes, R. (Eds.), Handbook of Disaster Research. Springer, New York, NY, pp. 1–15.
Petersen, K., 2015. Visualizing risk: making sense of collaborative disaster mapping. In: At the 12th International Conference on Information Systems for Crisis Response and Management Kristiansand. Paper presented, (Norway).
Pramanik, R., Ekman, O., Hassel, H., Tehler, H., 2015. Organizational adaptation in multi-stakeholder crisis response: an experimental study. J. Contingencies Crisis Manag. 23 (4), 234–245. https://doi.org/10.1111/1468-5973.12094.
Rankin, A., Dahlbäck, N., Lundberg, J., 2013a. A case study of factor influencing role improvisation in crisis response teams. Cognit. Technol. Work 15 (1), 79–93. https://doi.org/10.1007/s10111-011-0186-3.
Rankin, A., Lundberg, J., Woltjer, R., Rollenhagen, C., Hollnagel, E., 2013b. Resilience in everyday operations: a framework for analyzing adaptations in high-risk work. J. Cognit. Eng. Decis. Making 8 (1), 78–97. https://doi.org/10.1177/1555343413498753.
Rankin, A., Lundberg, J., Woltjer, R., 2014. A framework for learning from adaptive performance. In: Nemeth, C., Hollnagel, E. (Eds.), Resilience Engineering in Practice, vol. 2. Ashgate Publishing, Surrey, UK, pp. 79–95.
Reuter, C., Ludwig, T., Pipek, V., 2014. Ad hoc participation in situation assessment: supporting mobile collaboration in emergencies. ACM Trans. Comput. Hum. Interact. 21 (5), 1–26. https://doi.org/10.1145/2651365.
Righi, A.W., Saurin, T.A., Wachs, P., 2015. A systematic literature review of resilience engineering: research areas and a research agenda proposal. Reliab. Eng. Syst. Saf. 141, 142–152. https://doi.org/10.1016/j.ress.2015.03.007.
Righi, A.W., Huber, G.J., Gomes, J.O., de Carvalho, P.V.R., 2016. Resilience in firefighting emergency response: standardization and resilience in complex systems. Int. Feder. Aviat. Contr. Pap. Online 49 (32), 119–123. https://doi.org/10.1016/j.ifacol.2016.12.200.
Roberts, A.P., Stanton, N.A., Fay, D.T., Pope, K.A., 2019. The effects of team co-location and reduced crewing on team communication characteristics. Appl. Ergon. 81, 102875 https://doi.org/10.1016/j.apergo.2019.102875.
Robinson, J.J., Maddock, J., Starbird, K., 2015. Examining the role of human and technical infrastructure during emergency response. In: At the 12th International Conference on Information Systems for Crisis Response and Management. Paper presented, (Kristiansand, Norway).
Rose, C., Seater, R., Norige, A., 2015. Analysis of decision making skills for large scale disaster response. IEEE Global Humanit. Technol. Conf. 240–247. https://doi.org/10.1109/GHTC.2015.7343979.
Roux-Dufort, C., Vidaillet, B., 2003. The difficulties of improvising in a crisis situation: a case study. Int. Stud. Manag. Organ. 33 (1), 86–115. https://doi.org/10.1080/00208825.2003.11043675.
Rowley, J., Slack, F., 2004. Conducting a literature review. Manag. Res. News 27 (6), 31–39. https://doi.org/10.1108/01409170410784185.
Salmon, P.M., Goode, N., Archer, F., Spencer, C., McArdle, D., McClure, R.J., 2014. A systems approach to examining disaster response: using Accimap to describe the factors influencing bushfire response. Saf. Sci. 70, 114–122. https://doi.org/10.1016/j.ssci.2014.05.003.
Saurin, T.A., Wachs, P., Righi, A.W., Henriqson, E., 2014. The design of scenario-based training from the resilience engineering perspective: a study with grid electricians. Accid. Anal. Prev. 68, 30–41. https://doi.org/10.1016/j.aap.2013.05.022.
Scholl, H.J., Ballard, S., Carnes, S., Herman, A., Parker, N., 2017. Informational challenges in early disaster response: the massive Oso/sr530 landslide 2014 as case in point. 50th Hawaii Int. Conf. Syst. Sci. https://doi.org/10.24251/hicss.2017.302.
Shakou, L.M., Wybo, J.-L., Reniers, G., Boustras, G., 2019. Developing an innovative framework for enhancing the resilience of critical infrastructure to climate change. Saf. Sci. 118, 364–378. https://doi.org/10.1016/j.ssci.2019.05.019.
Shirali, G.A., Motamedzade, M., Mohammadfam, I., Ebrahimipour, V., Moghimbeigi, A., 2016. Assessment of resilience engineering factors based on system properties in a process industry. Cognit. Technol. Work 18 (1), 19–31. https://doi.org/10.1007/s10111-015-0343-1.

Son, C., Sasangohar, F., Peres, S.C., Neville, T.J., Moon, J., Mannan, M.S., 2018. Modeling an incident management team as a joint cognitive system. J. Loss Prev. Process. Ind. 56, 231–241. https://doi.org/10.1016/j.jlp.2018.07.021.
Son, C., Sasangohar, F., Peres, S.C., Moon, J., 2019a. Orchestrating through whirlwind: identified challenges and resilience factors of incident management teams during Hurricane Harvey. Proc. Hum. Factors Ergon. Soc. Annu. Meet. 63 (1), 899–903. https://doi.org/10.1177/1071181319631265.
Son, C., Sasangohar, F., Rao, A.H., Larsen, E.P., Neville, T., 2019b. Resilient performance of emergency department: patterns, models and strategies. Saf. Sci. 120, 362–373. https://doi.org/10.1016/j.ssci.2019.07.010.
Son, C., Sasangohar, F., Neville, T.J., Peres, S.C., Moon, J., 2020. Evaluation of work-as-done in information management of multidisciplinary incident management teams via interaction episode analysis. Appl. Ergon. 84, 103031 https://doi.org/10.1016/j.apergo.2019.103031.
Stachowski, A.A., Kaplan, S.A., Waller, M.J., 2009. The benefits of flexible team interaction during crises. J. Appl. Psychol. 94 (6), 1536–1543. https://doi.org/10.1037/a0016903.
Trnka, J., Lundberg, J., Jungert, E., 2016. Design and evaluation of a role improvisation exercise for crisis and disaster response teams. Int. J. Inf. Technol. Manag. 15 (3), 251–271. https://doi.org/10.1504/IJITM.2016.077348.
Tveiten, C.K., Albrechtsen, E., Waero, I., Wahl, A.M., 2012. Building resilience into emergency management. Saf. Sci. 50 (10), 1960–1966. https://doi.org/10.1016/j.ssci.2012.03.001.
Vecchiola, C., Anjomshoa, H., Bernstein, Y., Dumitrescu, I., Garnavi, R., Von Kanel, J., Wightwick, G., 2013. Engineering resilient information systems for emergency management. IBM J. Res. Dev. 57 (5).
Vicente, K.J., 2002. Ecological interface design: progress and challenges. Hum. Factors 44 (1), 62–78. https://doi.org/10.1518/0018720024494829.
Voshell, M., Trent, S., Prue, B., Fern, L.C., 2008. Cultivating resilience in urban firefighting: supporting skill acquisition through scenario design. Proc. Hum. Factors Ergon. Soc. Annu. Meet. 52 (4), 423–427. https://doi.org/10.1177/154193120805200447.
Waugh, W.L., Streib, G., 2006. Collaboration and leadership for effective emergency management. Publ. Adm. Rev. 66 (s1), 131–140. https://doi.org/10.1111/j.1540-6210.2006.00673.x.
Webb, G., 2004. Role improvising during crisis situations. Int. J. Emerg. Manag. 2 (1–2), 47–61. https://doi.org/10.1504/IJEM.2004.005230.
Webb, G.R., Chevreau, F.-R., 2006. Planning to improvise: the importance of creativity and flexibility in crisis response. Int. J. Emerg. Manag. 3 (1), 66–72. https://doi.org/10.1504/IJEM.2006.010282.
Weick, K.E., 1993. The collapse of sensemaking in organizations: the Mann Gulch disaster. Adm. Sci. Q. 38 (4), 628–652.
Westrum, R., 2006. A typology of resilience situations. In: Hollnagel, E., Woods, D.D., Leveson, N. (Eds.), Resilience Engineering: Concepts and Precepts. Ashgate Publishing, Aldershot, UK, pp. 55–65.
Wheeldon, J., Faubert, J., 2009. Framing experience: concept maps, mind maps, and data collection in qualitative research. Int. J. Qual. Methods 8 (3), 68–83. https://doi.org/10.1177/160940690900800307.
Wise, C.R., 2006. Organizing for homeland security after Katrina: is adaptive management what's missing? Publ. Adm. Rev. 66 (3), 302–318. https://doi.org/10.1111/j.1540-6210.2006.00587.x.
Wolbers, J., Boersma, K., 2013. The common operational picture as collective sensemaking. J. Contingencies Crisis Manag. 21 (4), 186–199. https://doi.org/10.1111/1468-5973.12027.
Woltjer, R., Trnka, J., Lundberg, J., Johansson, B., 2006. Role-playing exercises to strengthen the resilience of command and control systems. In: 13th European Conference on Cognitive Ergonomics, pp. 71–78. https://doi.org/10.1145/1274892.1274904.
Woods, D.D., 2006. Essential characteristics of resilience. In: Hollnagel, E., Woods, D.D., Leveson, N. (Eds.), Resilience Engineering: Concepts and Precepts. Ashgate Publishing, Aldershot, UK, pp. 21–34.
Woods, D.D., 2017. On the origins of cognitive systems engineering: personal reflections. In: Smith, P.J., Hoffman, R.R. (Eds.), Cognitive Systems Engineering: the Future for a Changing World. CRC Press, London, UK.
Woods, D.D., Branlat, M., 2011. Basic patterns in how adaptive systems fail. In: Hollnagel, E., Paries, J., Woods, D.D., Wreathall, J. (Eds.), Resilience Engineering in Practice: A Guidebook. Ashgate Publishing, Surrey, UK, pp. 127–144.
Woods, D.D., Hollnagel, E., 2006. Joint Cognitive Systems: Patterns in Cognitive Systems Engineering. CRC Press, Boca Raton, FL.
Wreathall, J., 2006. Properties of resilient organizations: an initial view. In: Hollnagel, E., Woods, D.D., Leveson, N. (Eds.), Resilience Engineering: Concepts and Precepts. Ashgate Publishing, Aldershot, UK, pp. 275–286.
Wybo, J.-L., Jacques, J.-M., Poumadere, M., 2006. Using simulation of accidents to assess resilience capacities of organizations. In: At the 2nd Resilience Engineering Symposium. Sophia Antipolis, France. Paper presented.
Zhuravsky, L., 2018. When disaster strikes: sustained resilience performance in an acute clinical setting. In: Hollnagel, E., Braithwaite, J., Wears, R.L. (Eds.), Delivering Resilient Health Care. Routledge, London, UK, pp. 199–209.