Being Prepared to be Unprepared: Meaning Making is Critical for the Resilience of Critical Infrastructure Systems

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Abstract: Infrastructure is essential to provision of public health, safety, and well-being. Yet, even critical infrastructure systems cannot be designed, constructed, and operated to be robust to the myriad of surprising hazards they are likely to be subject to. As such, there has been increasing emphasis in Federal policy on enhancing infrastructure *resilience*. Nonetheless, existing research on infrastructure systems often overlooks the role of individual decision-making and team dynamics under the conditions of high

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ambiguity and uncertainty typically associated with surprise. Although evidence suggests that human factors correlating with resilience and adaptive capacity emerge in later stages of psychological development, there is an acute need for new knowledge about the human capacity to comprehend increasing levels of complexity in the context of rapidly evolving technological, ecological, and social stress conditions. Sometimes, it is this developmental capacity for meaning-making that is the difference between adaptive and maladaptive response. Thus, without a better understanding of the human capacity to develop and assign meaning to complex systems, unquestioned misconceptions about the human role may prevail. In this work, we examine the dynamic relationships between human and technological systems from a developmental perspective. We argue that knowledge of resilient human development can improve system resilience by aligning roles and responsibilities with the developmental capacities of individuals and groups responsible for the design, operation, and management of critical infrastructures. Taking a holistic approach that draws on both psychology and resilience engineering literature facilitates construction of an integrated model that lends itself to empirical verification of future research.

Keywords: Human development, human resilience, infrastructure, resilience, resilience engineering.

Introduction

National policies and guidelines for critical infrastructure resilience effectively acknowledge the complex, multi-organizational, and sociotechnical integration of people and technical systems (DHS, 2013; The White House, 2013). These policies support the concept of critical infrastructure resilience as a function of coupled social and technical systems' physical and functional characteristics (Madni & Jackson, 2009), which includes the dynamic relationships between systems (Hollnagel, Woods, & Leveson, 2006). The physical and functional characteristics are often considered in a context of spatial and temporal dimensions. These are standard dimensions for analysis using traditional systems theory and other deterministic methods well suited for technological systems. For example, the factors related to spatial and temporal dimensions of a power system failure can impact assessments of community resilience (Munzberg, Wiens, & Schultmann, 2016) in response to disruption. However, the incorporation of human systems requires an additional dimension of symbolic meaning be included (Holling & Gunderson, 2002) together with space and time. In an analysis of the scholarly literature comparing the theme of resilience in social psychology, ecology, planning, and engineering disciplines, Fleming (2016) found that engineering scholarship focused predominantly on the "highly technical" side of "natural systems," and tends to ignore social systems. Though perhaps not surprising, this is problematic.

The meaning-making dimension accounts for the dynamic properties of complex adaptive human systems embedded within technological systems and operating environments proximal to physical infrastructure. That is, the human capacity to assign meaning and to dynamically interpret events and information relevant to critical infrastructure operation and management in response to disruption can impact the resilience of human coupled infrastructure systems. While many systems are designed to limit or minimize the role of human interaction, human ingenuity may sometimes be relevant to successful adaptation. Therefore, without a better understanding of the human capacity to construct meaning, reductionist views of resilience and tacit assumptions about the complex roles of humans interacting with infrastructure will prevail.

For example, disasters such as the Three Mile Island accident in 1979, the Challenger explosion in 1986, and the New Orleans Levee breakdowns in 2005 illustrate how the complexity of human interactions with technology can amplify failures in coupled systems (Perrow, 2011). By contrast, events like the ditching of US Airways Flight 1549 in the Hudson River on 15 January 2009 (NTSB, 2010) and the safe return of Apollo 13 in 1970 (Madni & Jackson, 2009) demonstrate how human ingenuity and adaptation can overcome surprising technological system breakdowns. Each situation required unanticipated changes in operational complexity and performance and although these examples are extreme, other similar scenarios play out across multiple domains and scales that go unnoticed by the public or academia. In a worst case scenario, unexpected and unknown changes can lead to catastrophic system failures propagating across spatial and temporal dimensions and operating domains such as the Fukushima power plant disaster in 2011 (Park, Seager, & Rao, 2011). In each case, the people involved make decisions and take actions based on mental models – psychological renderings of perceived or imagined conditions (Olson, Arvai, & Thorp, 2011) – that may no longer be relevant when subject to surprise. This means mental models can fail when faced with unanticipated emergent phenomena requiring an adaptive response to ambiguity and uncertainty (Sweet et al., 2014). Therefore, disasters can create conflict between preconceived conditions and direct experience (Hollnagel, Paries, Woods, & Wreathall, 2011) that can impact human interactions with technological systems.

The unanticipated differences between actual and preconceived experience of a person in a disaster scenario may be incompatible with their designated roles and responsibilities corresponding to thoughts, actions, and behaviors. As such, effective adaptation can require dynamic adjustment of individual roles to accommodate unknown or unexpected conditions. In the examples above, human lives were dependent on the ability of the pilots, crew, operators, engineers, and others interacting with the relevant technical systems to comprehend the situation and adjust to maintain viable system performance levels. Responding to adversity with incompatible preconceived responses can amplify failures and make conditions worse (Hollnagel & Fujita, 2013; Hollnagel et al., 2011), which means the roles played by humans can be pivotal to critical infrastructure resilience. In other words, human ingenuity can either enhance or diminish resilience because the intentions, motivations, and judgments of a single individual can influence infrastructure meta-systemic (whole-system) dynamics and outcomes. Moreover, while it may seem apparent why "preparing a large population for any kind of disaster will require a developmental perspective on human resilience, risk, and vulnerability" (Masten & Obradovic, 2010, p-11) the dichotomy of possible roles played by humans in disaster scenarios highlights this important point.

From a resilience engineering perspective, resilient outcomes are a factor of the recursive processes describing the capacities of intentional systems – sensing, anticipating, adapting, and learning (Park, Seager, Rao, Convertino, & Linkov, 2013). Thus, the resilience processes involved with navigating actual versus preconceived experience are partly determined by the complex interactional dynamics between humans and technical systems striving to restore and maintain viable operating levels. Dynamic adjustments to roles and responsibilities can require reinterpreting existing information while giving rational meaning to new and sometimes conflicting information in response to unanticipated or previously inconceivable events (Hollnagel et al., 2011). With potential near-term outcomes ranging from widespread environmental contamination to loss of life, the cascading impacts of disasters can have long lasting social and economic consequences that are less apparent (Cardona, 2003). For example, the human ability to adapt to climate change is a long time scale event with broad impacts linking complex relationships reflecting values, ethics, and world views (Adger et al., 2009) with human development (O'Brien & Hochachka, 2010) and built infrastructure.

Although humans behave like complex adaptive systems, resilience research linking the dynamic interactions between humans and infrastructure is limited (Seager et al., 2017). As a result, it is difficult to communicate complex resilience concepts and collaborate across disciplinary boundaries like psychology and engineering. Moreover, the meanings and interpretations of knowledge, operational dynamics, and events influence human perspectives of system performance, which can vary across people and cultures involved. Other factors include the context of certain roles and responsibilities for a given scenario and corresponding environmental conditions. Thus, in addition to the epistemological perspectives representing multiple ways of knowing coupled systems across relevant spatial and temporal dimensions, critical infrastructure resilience must integrate epistemological diversity to form a holistic perspective reflecting how different human systems comprehend and interact with technological systems. This approach requires understanding how humans assign meaning and interpret knowledge, which includes experience in relation to infrastructure resilience operations and management and how the processes can change across time.

Human psychological development contributes to a body of knowledge and understanding about how people make meaning of the world and interpret experience. Disaster events identify knowledge gaps between the relationships of human resilience, development, and the ability of people to respond and recover (Masten & Obradovic, 2010), which is dependent on critical infrastructure. Although human agency influences behaviors, actions, and interactions with other systems (Brown & Westaway, 2011; Nelson, Adger, & Brown, 2007), there is little research integrating resilience and adult human development perspectives with the resilience of critical infrastructure operations and management. Although less is known about how resilience appears in adults given a significant research focus on youth (Campbell-Sills, Cohan, & Stein, 2006), progress in adult human development research has advanced and offers new insights about adult resilience. A growing body of research describes how human development endures well into adulthood and throughout a lifespan (Cook-Greuter, 2004; Kegan, 2002; Kohlberg, 1973; Loevinger, 1976; Vincent, Ward, & Denson, 2015).

In this paper, we address a gap in the resilience engineering and infrastructure resilience literature to consider how the psychological meaning-making of humans interacting with infrastructure operations and management can influence factors related to perceptions and interpretations of resilience. To accomplish this, we apply a holistic approach that allows for simultaneous perspectives drawing on the resilience engineering, psychology, and human development literature. We review multiple frameworks, synthesize diverse concepts, and propose a conceptual model for investigating the relationships between the developmental capacity of meaning-making and critical infrastructure resilience. The model effectively integrates the socio-technical resilience processes – sensing, anticipating, adapting, and learning – with human developmental capacities. Our analysis suggests that each stage of human development brings new psychological resources contributing to the capacity to comprehend and respond to increasing levels of complexity and uncertainty thereby enhancing the effectiveness of the socio-technical resilience processes. We contribute a conceptual model as a guide for future research. We argue that progressive stages of human development corresponding to more complex forms of meaning-making bring new qualities and capabilities for designers, operators, and managers that can strengthen and enhance critical infrastructure resilience.

A Holistic Perspective of Resilience Engineering Processes

A holistic approach incorporates epistemological diversity to understand the complexity and uncertainty of maintaining a viable operating performance level for critical infrastructure (Thomas, Eisenberg, & Seager, 2018). Whereas a focus on anticipating known failures related to operational disruptions and human interactions with infrastructure can enhance risks mitigation efforts (Cardona et al., 2012), preparing to be unprepared may require circumventing deterministic preparations and responses (Park et al., 2013). Moreover, the adaptive capacities of people, organizations, and engineered systems are interdependent on an ability to accommodate unknown *internal* and *external* changes (Hollnagel et al., 2011). In other words, adaptation to unpredictable system shocks may sometimes require abandoning prescriptive actions while dynamically constructing novel solutions. With regard to human systems, interactions and feedback loops maintain a sense of (rational) equilibrium by forming psychological structures that either filter incoming data to fit existing worldviews or creating new worldviews (John Manners & Durkin, 2000). Thus, a holistic framework of critical infrastructure resilience must integrate the endogenous human factors corresponding to the adaptive capacity of people and working groups interacting (proximal) with technology in addition to sensing, anticipating and learning (Thomas et al., 2018). Without consideration of human dynamics and developmental predispositions, which includes how people interpret and make meaning of information and events, even seemingly comprehensive analyzes of coupled social and technical systems risk offering partial solutions by ignoring critical dependencies.

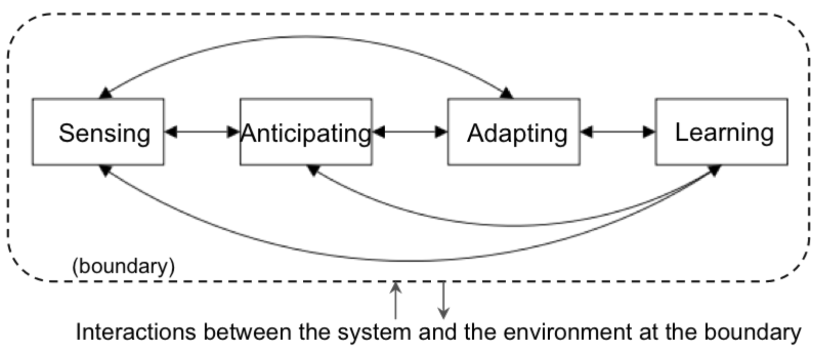

Figure 1. Sociotechnical resilience processes – sensing, anticipating, adapting, and learning (SAAL).[2]

[2] The feedback loops represent the recursive and reciprocal relationships between processes. The boundary condition represented by the dashed line defines the physical and functional areas of consideration for a given scenario. The resilience processes interact with the proximal environment at the boundary (Seager et al., 2017; Thomas, Eisenberg, Seager, & Fisher, 2019).

The 'SAAL' processes (Figure 1) describe four abilities of resilient systems: sensing, anticipating, adapting, and learning (Hollnagel, 2014; Park et al., 2013). Sensing is the ability to detect system state variables; anticipating is the ability imagine changes in system conditions and state variables; adapting is the ability to adjust system performance while maintaining viable operation; learning is the ability to absorb, retain, and access knowledge from experience. The processes represent the recursive and reciprocal relationships between complex socio-technical systems that influence resilience. Taken together, the SAAL processes provide a coupling mechanism for linking dynamic interactions between humans and critical infrastructure (Park et al., 2013). For example, in addition to planning and preparation, humans are integral to the management and operational response to disasters and catastrophic events (Madni & Jackson, 2009). Moreover, officials and civil servants as individuals, teams, and organizations must coordinate and maintain critical infrastructure technical mitigation and recovery (and adaptation) policies and resources (Labaka, Hernantes, & Sarriegi, 2016) while also providing a diversity of rescue (recovery) and support services across other systems, (e.g. public health and safety). The four abilities are a way to describe the resilience of the coupled human–infrastructure system. Thus, the SAAL processes provide a means for describing the dynamic relationships between people and infrastructure (Thomas et al., 2019). In addition to adaptive behaviors, the relationships can also include maladaptive behaviors (Masten & Obradovic, 2010), as observed with events like Hurricane Katrina (Westrum, 2005).

The catastrophic consequences of Hurricane Katrina revealed numerous latent human inadequacies during the recovery efforts, including physical deficiencies, personnel failures, organizational failures, and bureaucracy failures (Westrum, 2005). Multiple breakdowns across operational domains exposed a myriad of individual and organizational deficits including poor leadership, poor judgment, and criminal behavior of officials. Over 200 civil servants either deserted or were absent without official leave including 25 police officers who quit while on duty at areas of intense stress and two officers who committed suicide (Westrum, 2005). "It seemed as if no one was in control. In a very real sense this was true" (Westrum, 2005, p. 5). In other words, there was a catastrophic breakdown in the human component of recovery management in multiple overlapping operating domains within the city of New Orleans. Beginning with a profound lack of preparation cited just a year earlier (Laska, 2008), a "social catastrophe" ensued (Cutter & Emrich, 2006) along with a complete loss of power, loss of the levees system, loss of communications, and a loss of civil obedience among numerous officials (Westrum, 2005). A capstone to the emergency management breakdowns in New Orleans in response to hurricane Katrina, the mayor of New Orleans when the hurricane hit in 2005 was sentenced to federal prison in 2014 (Murphy & Peristein, 2014) for corruption and gaff during and after the hurricane struck the city.

In contrast to the diminished moral capacity prevalent among a cross section of civil servants, there were also examples of exceptional human performance during Hurricane Katrina. Admiral Thad Allen, the commander of the U.S. Coast Guard gained high regard for his leadership during the recovery efforts (Sullenberger & Century, 2012). His rapid response was unscripted and credited with saving thousands of people. Allen was appointed Director of the Federal Emergency Management Agency at a time of organizational dysfunction. His ability to articulate and enact a set shared values among staff, was recognized as exceptional leadership in a most difficult of circumstances.

Moral development is relevant to critical infrastructure resilience engineering for two reasons. First, moral maturity is related to human resilience (Kumpfer, 1995), which means it is embedded in any consideration of infrastructure resilience that includes people. Second, because an individual's capacity for moral reasoning may be viewed as a protective factor for people (Stokols, Lejano, & Hipp, 2013), moral development is interrelated to the dynamic interactions between and among humans, technical systems, and environments.

Given the complex, interdependent, and interconnected nature of infrastructure systems, certain critical roles (e.g., managers and operators) require individuals to make sense of systems in complex ways that can involve high degrees of ambiguity and uncertainty. Evidence from research in developmental psychology suggest that human factors such as interpersonal awareness, the capacity to consider alternative perspectives, complex systems thinking, and adaptive capacities emerge and advance in later stages of human development (Cook-Greuter, 2004; Vincent, 2015). Moreover, research by Cook-Greuter (1999) supports the notion that capacities for complex systems thinking are rare human traits only accessible after passing through a sequence of developmental stages. Other evidence suggest that individuals are often discouraged from developing by existing educational institutions and management structures (Torbert et al., 2004). Furthermore, Cook-Greuter's data (n=4,510) indicates that fewer than 20% of the adult population arrive at the later (postconventional) stages of development (Cook-Greuter, 1999). As a result, certain catastrophic infrastructure breakdowns may exceed the capacity of some individuals to effectively function and cope with high degrees of complexity and uncertainty. The developmental stages support a holistic structure for linking diverse concepts of resilience involving human interactions with – operating and managing – infrastructure. Thus, in addition to the potential to enhance anticipation of potential threats and outcomes, a key benefit of a holistic framework integrating human development and critical infrastructure resilience processes is to align operations and management roles and responsibilities with individual strengths and adaptive capacities of people.

Human Development Theoretical Framework and Potential Implications for Infrastructure Resilience

Human development theory incorporates epistemological diversity to account for differences in how people make meaning and interpret knowledge in different contexts across time. That is, the way in which individuals experience resilience concepts and how those concepts and definitions influence relationships and proposed solutions over time correspond to the human capacity to develop more complex ways of interpreting and interacting with their environment. In this section, we examine different human development theories to identify one able to support a holistic framework for critical infrastructure management applications.

Early Developmental Theories

Jean Piaget (1954) is considered to have developed the first structural model of cognitive development (called "genetic epistemology"). He created a comprehensive empirical method to assess the capacity for rational thought and describe how patterns or stages of cognition emerge in developing children and adolescents. Piaget identified the important transition from "concrete" to "formal" cognitive capacities that allow for abstract concepts, logical reasoning, and the rigorous imagination of possibilities/alternatives.

Building on Piaget's work Lawrence Kohlberg developed a theory of moral development describing six types of moral reasoning in children and adults (Kohlberg, 1969, 1973). The six stages appear amongst three tiers – pre-conventional, conventional, and post-conventional (Kohlberg, 1969, 1973). A related pattern was found by William Perry's in his study of "epistemological growth," or how people relate to knowledge and belief – its sources, justifications, and evolution in people and society (Perry, 1970). Pre-conventional stages are not much concerned with either moral principles or how beliefs are justified. Conventional stages look to authorities and peer groups for both valid knowledge and moral rules. Post-conventional individuals have well developed "formal operations" that allow them to think autonomously and critically about both knowledge and ethical principles.

As noted with Hurricane Katrina, moral development is relevant to critical infrastructure resilience engineering partly because an individual's capacity for moral reasoning may be viewed as a *protective factor* for people (Stokols et al., 2013) impacting human resilience and decision making. In other words, moral development may influence the dynamic interactions between and among humans and technical systems. Epistemological sophistication is also relevant to critical infrastructure resilience because in unexpected scenarios the normative procedures may not apply, and critical thinking, reevaluation, and creative problem solving are needed. Importantly, research shows that under stress cognitive capacities can deregulate, which can be viewed as a developmental "down shifting" to earlier levels of complexity capacity (Goleman, 2006; LeDoux, 1996).

Development of Cognitive Complexity

It is now a cliché and truism that we live in a "complex and fast-changing world." Increasingly we understand that real-world situations are "ill-defined" or "wicked," characterized by "vague or broad goals; large volumes of data from many sources; nonlinear, often uncharted analytical paths; no pre-set entry or stopping points; many contending legitimate options; collaborators with different priorities; [and] 'good enough' solutions with no one right answer (Mirel, 2004). Robert Kegan (1994, p. 12) notes that "when we experience the world as 'too complex' we are not just experiencing the complexity of the world. We are experiencing a mismatch between the world's complexity and our own at this moment. There are only two logical ways to mend this mismatch – reduce the world's complexity or increase our own. The first isn't going to happen." This concept links the developmental complexity of the infrastructure managers to the operational complexity of the infrastructure systems.

Developmental stage theories provide a way to understand the relationships between coupled human – infrastructure systems. As described by Gardner (1983), people exhibit "multiple intelligences" – a framework extended by Wilber who articulated over a dozen developmental "lines" studied by researchers (Wilber, 2000). Although researchers differ on the mechanisms, stratification schemes, and definitions of developmental levels, there is a surprising degree of correspondence among dozens of theories as to the general outlines of adult cognitive development. Domains studied include cognitive development (Piaget, 1954; Murray, Hufnagel, Gruber, Vonèche, & Voneche, 1979), moral development (Gilligan, 1982; Kohlberg, 1969), ego development (Cook-Greuter, 2004; Loevinger, 1966, 1976) values development (Beck & Cowan, 2006; Graves, 1970), epistemic development (Perry, 1970), and socio-emotional development (Goleman, 2006). So-called neo-Piagetian theories have also emerged proposing underlying mechanisms involved in all forms of development (Commons & Richards, 1984; Fischer, 1980).

In practice the sub-skills underlying many of these "lines" have common roots and overlapping branches, and we can focus on two broad categories of cognitive development. The first is *cognitive complexity* (using the narrow definition of cognitive as intellectual skill distinct from social/emotional skill); and the second is *meaning-making* capacity, which is Kegan's term for a skill-set that substantially overlaps with Loevinger's construct of ego development (we treat the two as essentially equivalent).

Cognitive complexity refers to the complexity of mental operations applied to some task or problem. More complexity involves more parts, relationships, factors, dynamism, interdependence, and/or unpredictability (Benbya & McKelvey, 2006; Grünwald & Vitányi, 2003). Elliott Jaques, who studied the complexity of tasks, jobs, and cognition, states that “the true source of difficulty in any problem lies in its complexity” (1996, p. 64). Jaques applied his findings to management and organizational theory, finding that “complexity may be defined in terms of the number of variables that have to be dealt with in a given time in a situation, the clarity and precision with which they can be identified, and their rate of change" (ibid). He developed methods for matching task and job complexity to an individual's cognitive complexity. Coming to conclusions compatible with those of Commons, Jaques identified two fundamental elements of cognitive complexity (Jaques, 1989). First, understanding in an area develops from simply recognizing or defining things and working with one variable at a time ("declarative"), to understanding simple relationships among them ("cumulative"), to understanding more complex relational and cause/effect chains ("serial"), to inter-related co-causal relationships and whole systems that coordinate multiple relational chains ("parallel"). Second, this entire sequence of increasing complexity happens first for semi-concrete (and symbolic) information, and then it reiterates for abstract systems of information.

Our increasingly complex world requires increasingly complex cognition to understand it – and *humans* and human systems are among the most complex objects we must think about. Meaning-making capacity can be understood as the application of cognitive complexity to domains involving human emotions, interiors, groups, and knowledge. Intellectual skills by themselves are understood to apply to the domain of "it" or external objects, but these skills can be applied to, not *some* idea, but *my/your/our/their* ideas (or needs, values, etc.).

Loevinger and Wessler (1970) say that "conceptual complexity has proven to be an important clue to [stage of ego development]" (v. I, p. 115); and Kegan's model describes how underlying "cognitive, interpersonal, and interpersonal" structures ("lines") develop in parallel. These theories were developed to understand how the average person understands "the world," including self and other, but since our context includes the technical and engineering domains involved in infrastructure resilience, we need to clarify that the complexity we will focus on is “meaning-making” complexity, which includes intellectual (strictly cognitive) complexity, but only to the degree needed to understand "the world" at a given level of sophistication. It seems self-evident that one can have a high degree of complex intellectual knowledge about a system yet not have the ego development or meaning-making sophistication to, for example: question whether one is over-confident in one's knowledge, seek alternative perspectives, or flexibly adapt one's knowledge when it is proven inadequate. Strictly cognitive skills are important for routine (even advanced) engineering, design, and problem solving work, but in social-technical situations involving rapid change, multiple perspectives, or unpredictability, meaning-making skills are critical.

Constructive Developmental Theories

Researchers including Robert Kegan (1980, 1982) and Jane Loevinger (1979, 1983; 1970) created theories of "meaning making" (called "ego development" by Loevinger) that incorporate all of the above mentioned modalities – cognitive, epistemological, and ethical (including social/emotional) reasoning – into a single construct and framework. These theories are *holistic* – integrating cognitive, affective, and behavioral elements. Furthermore, these three core dimensions align with prior work relating human and technical resilience capacities through the SAAL socio-technical processes (Thomas et al., 2019).

A central tenet of these "constructive-developmental" theories is that people construct and interpret meaning and identity in an ongoing manner to understand and adapt to changing life conditions and experiences. The developmental perspective shifts the focus on human understanding from *behavior* and *what* people think to *how* people think – i.e. to underlying cognitive structures that influence how complex problems are perceived and approached and how solutions are proposed and justified (Cook-Greuter, 1999; Kegan, 2002).

The gradual accumulation of new interpretations and ways of making meaning constructs an invariant sequence of psychological structures identified as levels or stages of development representing increasingly complex, nuanced, and creative ways of interpreting and navigating life conditions and experiences (Cook-Greuter, 1999; Kegan, 1982; Kohlberg, 1969; Loevinger, 1983). Each level brings new capacities while strengthening and building on existing capacities. As the complexity and uncertainty of life conditions and environments increases, developing individuals are challenged to build more comprehensive psychological meaning-making systems (Cook-Greuter, 2004) and an increasing capacity for positive adaptation (Hauser, 1999).

Meaning making (or ego) development spans a spectrum from black-and-white, narcissistic, impulsive, us-vs-them, short-sighted, and simplistic thinking into increasingly complex, nuanced, flexible, adaptive, reflective, expansive, empathic, and pro-social thinking. Vincent notes that as meaning-making develops "each shift in stage offers greater cognitive complexity, a more integrated perspective, greater self and interpersonal awareness, responsibility and personal autonomy, decreasing defensiveness and increasing flexibility, reflection and skill in interacting with the environment" (2015, p. 3). Here the reader can recognize the close connection between the research in developmental science and the need for adaptive and resilient approaches to socio-technical systems.

A developmental perspective on human resilience offers a better understanding of what type of adaptive responses may be possible when critical infrastructure resilience includes human factors. Because developmental theories outline specific levels and detailed skill progressions, questions of resilience capability can be translated from vague notions or binary categories (is or is not resilient) into a more detailed and discriminating framework composed of multiple levels that have already been researched. A consideration of human development may assist, for example, with aligning management roles and responsibilities of people holding critical positions in emergency response networks. It can also help managers assess matches of tasks and situation complexity to human capacity in any situation, and especially in changing or uncertain contexts.

The Ego Development Theories of Loevinger & Cook-Greuter

Though Kegan's and Loevinger's theories cover very similar territory, we will focus on Loevinger's ego development theory (though "meaning making" development may still be a more apt term) because (1) it has been more used and validated, and (2) its assessment method, the sentence completion test (SCT) is more practical and also more strongly validated.

The literature drawing on Loevinger's ego development model is so extensive that it includes a number of meta-analysis and critical overviews, substantially supporting its validity and usefulness (Cohn & Westenberg, 2004; Holt, 1980; Jespersen, Kroger, & Martinussen, 2013; Manners & Durkin, 2001; Novy & Francis, 1992; Vincent, Ward, & Denson, 2013). According to an overview by Cohn & Westenberg (2004) the SCT has very strong psychometric properties, having "indicated excellent reliability, construct validity, and clinical utility" (p. 596). As of their 2004 article, "findings of over 350 empirical studies generally support critical assumptions underlying the ego development construct" (p. 485). Blumentritt (2011, p. 153) says that "more than 1,000 articles and book chapters have been published examining nearly every conceivable aspect of the construct and measurement of ego development [showing an overall] substantial support" for the theory and measurement.

Translated into over ten languages (Cohn & Westenberg, 2004), the SCT has been used to study personality differences (Westenberg & Block, 1993), leadership (B. C. Brown, 2011; Vincent et al., 2013), management and organizational development (Torbert et al., 2004), and individual resilience (Gralinski-Bakker, Hauser, Stott, Billings, & Allen, 2004; Hauser, 1999). Pfaffenberger (2011, p. 10) says that "the face validity of the SCT is demonstrated by the sheer fact that it has been used in more than 300 research studies [including] such diverse topics as parenting behaviors, managerial effectiveness, and the effects of meditation on recidivism rates." Numerous studies have shown that ego development is distinct from but correlated with general intelligence (about a 30% correlation) and verbal fluency, and, as expected, like IQ, it correlates with socioeconomic status (Cohn & Westenberg, 2004; Crammer, 1999; Manners & Durkin, 2001). Pfaffenberger (2011, p. 10) says "the SCT correlates with education, socioeconomic status, and complexity of work, which has been shown to hold true across international samples" (emphasis added).

Cook-Greuter's research enhanced and extended the seminal work of Jane Loevinger at the postconventional levels (Cook-Greuter, 1999). Cook-Greuter's research showed that the 'Strategist' stage or structure in Loevinger's model appears as two distinct stage structures. Data collected from 4,510 participants over a period of 15 years were used to characterize an additional post-conventional level and to verify adjustments to the SCT measurement instrument

(Cook-Greuter, 1999). Table 1 identifies the "action logics" system of meaning making, and central focus for each stage along with the distribution of stages among research subjects. The dashed lines identify the stages most relevant to the present research and are discussed in more detail in the next section. The research also provided new details about the post-conventional stages such as an enhanced capacity to cope with complexity and uncertainty and an improved ability to adapt to change (Cook-Greuter, 1999; John Manners & Durkin, 2000; Vincent et al., 2015). These considerations can have both causal and prognostic implications for the resilience of infrastructure systems within which human systems are embedded.

Table 1. Ego-development Stages, Action Logics, and Central Focus.[3]

Stage Name	**Action Logic**	**Central Focus**	**% Adults** (N=4,510)
Preconventional			
Opportunist	Needs rule impulses	Own immediate needs, opportunities, self-protection	4.3
Conventional			
Diplomat	Norms rule needs	Socially expected behavior, approval	11.3
Expert	Craft logic rules norms	Expertise, procedure and efficiency	36.5
Achiever	System effectiveness rules craft logic	Delivery of results, effectiveness, goals, success within a system	29.7
Post-conventional			
Individualist	Relativism rules single-system logic	Self in relation to system, interaction to system	11.3
Strategists	Most valuable principles rule relativism	Linking theory and principles with practice, dynamic systems interactions	4.9
Alchemist	Deep processes and inter-systemic evolution rules principles	Interplay of awareness, thought, action, and effects; transforming self and others.	2.0

Cook-Greuter's framework was extended further by O'Fallon in her STAGES model (Murray, 2017; O'Fallon, 2011). STAGES formalizes and extends Cook-Greuter's original notion of a sequence of "person-perspectives" into a sequence of six person-perspective transformations (i.e. first, second, third...sixth person-perspective). It proposes an underlying set of generative

[3] Stage names by Cook-Greuter (and Torbert); Action Logics are meaning-making systems with increasing complexity; Central Focus describes a psycho-social disposition or frame of reference dominant for each stage; % Adults are the results of a 15 year study involving 4,510 adults across a broad range of demographics. (Cook-Greuter, 2004; Torbert et al., 2004).

parameters that give rise to the entire developmental sequence, including growth from concrete to increasingly abstract (or "subtle") objects of awareness, advancing cognition from individual objects to collectives and systems of objects, and moving from receptive to more active and reciprocal orientations to knowledge. O'Fallon's SCT scoring method is much less dependent on the content of the sentence completions (i.e. is more focused on underlying structure) and thus her method is more extensible to new domains.

Both the theoretical model and the assessment method described above apply to critical infrastructures whereby roles and responsibilities are impacted by the resilient development of the designers, operators, and managers involved as noted earlier with the contrasting management responses to Hurricane Katrina. That is, psychological meaning-making structures supporting the different ways of interpreting events, experiences, and changes associated with stages of development can impact how people interact with and influence the resilience of complex technological systems like infrastructure.

Ego Development Applied to Infrastructure Resilience Management

Studies Linking Human Resilience and Development

Related studies of human development focus on how children and young adults learn and grow (develop) in different support-and-challenge contexts. These studies offer valuable insight to human development by emphasizing a behavioral perspective of the interactions of individuals exposed to different environments such as risk and adversity (Masten, 2001), social ecology and diversity (Bronfenbrenner, 1999; Ungar, Ghazinour, & Richter, 2013), and cultural tensions (Ungar, 2006). In general these studies show that supportive social networks enhance an individual's resilience, and that resilient personalities withstand stressful situations more favorably (Masten & Obradovic, 2008). Within the Loevinger lineage we can note two longitudinal studies relating human development and resilience.

In the first study, data gathered at the beginning and end of a nine-year period showed a strong positive relationship between measurements of ego-resiliency and ego-development (Westenberg & Block, 1993). Empirical evidence suggests that ego resiliency and ego-development are interrelated, and that development may occur at different rates among individuals within the same age group (Westenberg & Block, 1993). Ego-resiliency, which describes “flexible and resourceful adaptation” was divided into three subdomains, and each proved interrelated to ego development. Although the relationship between ego-resiliency and ego-development did not contrast or change among ego stage transitions, a strong, coherent relationship was apparent. Another important finding relevant to our paper is the anticipated and observed strong positive relation between interpersonal integrity and ego development. Interpersonal integrity, which describes a capacity for authentic relations, was subdivided into two subdomains, and each revealed a strong, coherent relationship with ego-development.

Although the age range of the participants does not represent middle-aged managers, this study is most relevant to the work herein because it provides evidence of the interrelatedness between concepts of human resilience and human development. The data suggest that the properties that correlate with the resilience of a person also correlate with patterns of ego development. A potential application to infrastructure resilience is the alignment of short and long-term roles and responsibilities with consideration of individual human strengths and growth opportunities.

In the second study, multiple sets of data collected over a 20 year period found associations between ego-development and a set of themes characterizing a group of people demonstrating resilient outcomes in young adult life despite extreme adversity in childhood (Gralinski-Bakker et al., 2004; Hauser, 1999). The research posits a perspective of resilience as the positive adaptation in response to adversity (Masten, Best, & Garmezy, 1990) and includes measurements and assessments of both internal states of being *and* observed actions and outcomes (Gralinski-Bakker et al., 2004; Hauser, 1999). The research findings are relevant to our integration of human resilience and development with critical resilience for two reasons.

First, whereas the research described above reviewed data collected at the end points of a nine-year period, this longitudinal study collected data over a period of 20 years, in addition to the endpoints, including adolescence and young adulthood. Although single cross-sectional or time-point assessments can yield valuable insights, longitudinal research is vital to understanding potential trajectories of resilient development in humans (Gralinski-Bakker et al., 2004; Hauser, 1999), technical systems (Igor Linkov et al., 2013; Park et al., 2013), and social systems (Brown & Westaway, 2011; Walker, Holling, Carpenter, & Kinzig, 2004).

The second reason this study is relevant to the present work is the comprehensive research approach, tools, and methods used. The instruments, which included Loevinger's ego development test, provided reliable and repeatable measurements of the protective factors, which were later used as predictors of outcomes (Gralinski-Bakker et al., 2004) in the third phase of data collection. The factors characterize a perspective of resilience as an *internal* state of being and positive adaptation to adverse events and changing life and environmental conditions (Hauser, 1999). In other words, the research included both endogenous and exogenous measures and assessments of resilient human development. The rigor of data collection, analysis, and published findings of Hauser's research supports our conceptual framework for integrating a perspective of resilient human development with critical infrastructure resilience.

Ego-Development Stages Influence on the SAAL processes

Although ego stages may be viewed as coherent personality structures, Loevinger considered ego as a reference frame or a "lens" influencing an individuals' perceptions of the world (Cohn & Westenberg, 2004). Whereas "the depth, complexity, and scope of what people notice can expand throughout life," (Cook-Greuter, 2004, p4), protective factors like resilience and adaptive capacity are particularly enhanced in *later* stages of development (Gralinski-Bakker et al., 2004; Hauser, 1999; Westenberg & Block, 1993).

We emphasize the four stages in Table 2 as a focus of our human development framework for two reasons. First, the distribution of stages in Cook-Greuter's data suggests that over 80% of the sample represent a stage at or below the conventional tier. Other researchers report similar findings whereby the majority of the adult population appear to reside at either the expert or achiever stages (Manners & Durkin, 2000; Vincent, 2015). We have excluded the Opportunist and Diplomat stages based on our assumption that individuals at these stages are not likely found in infrastructure design, operation, and management environments.

Table 2. Ego-development stages considered with the present work.[4]

Stage Name	Methods of influence	Response to feedback
Conventional		
Expert	Gives personal attention to detail and seeks perfection, argues own position and dismisses other' concerns	Takes feedback personally, defends own position, dismisses feedback from those who are not seen as experts in the same field
Achiever	Provides logical arguments, experience, makes task/goal-oriented contractual agreements	Accepts feedback, especially if it helps them to achieve their goals and to improve
Post-conventional		
Individualist	Adapts or ignores rules where needed, or invents new ones, open to discussion of issues and airs differences	Welcomes feedback as necessary for self-knowledge, and to uncover hidden aspects of their own behavior
Strategists	Leads to reframing, reinterpreting situation, so that decisions support overall principle, strategy and foresight	Invites feedback for self-actualization, conflict is seen as an inevitable aspect of viable and multiple relationships

Second, post-conventional stages appear to reveal qualities of people associated with enhanced human resilience and adaptive capacity, which can have positive influence on the SAAL processes in relation to infrastructure resilience. Thus, there is an opportunity for growth and expansion from conventional to post-conventional ways of interpreting experience and interacting with complex systems. Individuals at post-conventional stages can more readily adapt to more complex environments and changes because they are more flexible and have more personal resources available to them. For example, these individuals have the ability to perceive another person's frame of reference and are more likely to respond in a way that is most effective to the task at hand by adapting their message to best be received by the other (Cook-Greuter, 1999, 2004; Vincent et al., 2015).

Many of the properties of post-conventional stages have been correlated with leadership effectiveness across a range of studies reporting similar findings (Cook-Greuter, 2004; Manners, Durkin, & Nesdale, 2004; Torbert et al., 2004; Vincent et al., 2015). Common themes and characteristics include a higher toleration for ambiguity and uncertainty, increased ability to

[4] Column list stage names by Cook-Greuter and Torbert. 'Methods of influence' characterize how individuals at a given stage tend to interact with others when seeking influence. 'Response to feedback' indicates how individuals are able to receive and integrate information and critique from others (Cook-Greuter, 2004; Torbert et al., 2004).

comprehend complexity, and a greater capacity to manage multiple and conflicting perspectives and emotions. These factors are relevant to certain roles and responsibilities in an infrastructure environment whereby people are interacting with other people and with technological systems, and where people and/or groups might be holding different priorities and assumptions. The dynamic interactions can influence potential resilient pathways and outcomes. Whereas the current stage for a given individual represents established psychological structures that can be measured, transitions to later stages are pathways of development representing a potential for growth that can be anticipated and thereby enhance critical infrastructure resilience.

How do the developmental levels relate to job situations likely to arise in infrastructure disaster scenarios? At Conventional (Diplomat and Expert) levels safety and acceptance come through pleasing authorities and merging/complying with "the crowd" of one's peers on the job. These individuals are more likely to: keep one’s head down; stay out of trouble, don't rock the boat, look good to one's supervisor, just follow the given rules, do their very best to master a defined task.

At the Achiever level individuals are more likely to take initiative, propose novel ideas, understand abstract and complicated systems, map out a rigorous field of possibilities, and search for the most efficient or effective methods.

At later post-conventional stages (Individualist and above) one is more likely to realize that even our best rational efforts are flawed, that human and natural systems are fundamentally unpredictable, and that one should be both open to and prepared for surprise. Moreover, ego development theory suggests that these individuals may be more capable of holding conflicting perspectives and possibilities without stress and moving into "sense and respond" vs. "plan and control" mode when situations are dynamic.

Although individuals tend to operate at a dominant stage (or "center of gravity"), measurements reveal a Gaussian (or normal) distribution among test items. Developmental theories in general draw on Vygotsky's "zone of proximal development" model in assuming that people demonstrate a range of developmental levels across tasks and situations, such that they perform more poorly in challenging or stressful contexts, and perform at their leading edge in familiar and/or supported (also called "scaffolded") contexts (Fischer & Pruyne, 2002; Vygotsky, 1980).

This is particularly important in the domain of critical infrastructure resilience. First, as mentioned, systems failures and unexpected shocks to normal expectations can create stressors that "downshift" an individual's developmental capacity. Second, complex socio-technical systems require collaborative/collective efforts, in which each person's tasks and knowledge is scaffolded by others. In times of complexity, uncertainty, and/or stress, social and communications relationships can degrade, which means that the performance of each individual who relies on others may further degrade. This implies that trust and other forms of social capital actually protect against degradation of both individual and group performance in times of stress.

Discussion and Future Research

A developmental perspective of resilience can have broad application to large-scale natural or man-made disaster scenarios (Masten & Obradovic, 2010). Disaster scenarios and catastrophic events include disruptions to infrastructure critical to public health, safety, and well-being that supports conditions for development to occur. Thus, we propose a method for investigating the relationships between human resilience, development, and critical infrastructure resilience.

The framework proposed combines conceptual frameworks of human resilience, development, and critical infrastructure resilience to form a single meta-framework. The SAAL processes are adapted from resilience engineering concepts and frameworks representing the resilience of a socio-technical system (Hollnagel, 2014; Park et al., 2013; Woods, 2015) as applied to critical infrastructure (Thomas et al., 2019). Common theoretical foundations consisting of cognitive, emotional, and behavioral dimensions of resilience (Mischel & Shoda, 1995; Reich, Zautra, & Hall, 2010) and human development (Cook-Greuter, 1999) serve as a basis for linking the frameworks. Moreover, data from prior research revealing a strong, coherent relationship between resilience and development in adults (Gralinski-Bakker et al., 2004; Hauser, 1999; Westenberg & Block, 1993) further supports our rationale for research linking frameworks. With an emphasis on coupled social and technological systems, we offer a conceptual model a starting point to operationalize an integrated framework of resilient human development and critical infrastructure.

The proposed framework is shown in Figure 2 below. The rows are the four stages of development identified earlier, and the columns represent the four social-technical processes, which are dynamically coupled to human resilience and critical infrastructure resilience (Thomas et al., 2019). The SAAL processes serve as a coupling mechanism linking infrastructure resilience concepts with human development concepts and structures. We posit that endogenous and exogenous properties and processes corresponding to sensing, anticipating, adapting, and learning are progressively differentiated for each stage of development as identified in the first column of Figure 2. Each stage reveals capacities for sensing, anticipating, adapting, and learning that are more enhanced, complex, and integrated compared to the prior stages. We also posit the differences between stages can have a significant influence on critical infrastructure resilience. For example, as an individual's development unfolds from conventional to post-conventional, there is a shift in capacity toward greater autonomy, and a higher tolerance of ambiguity and uncertainty (Cook-Greuter, 2004). The shift can impact how individuals interpret and respond to high degrees of complexity such as catastrophic system failures and disasters. Moreover, a capacity to comprehend complex systems is emergent at the post-conventional levels (Cook-Greuter, 1999), which can impact critical infrastructure resilience.

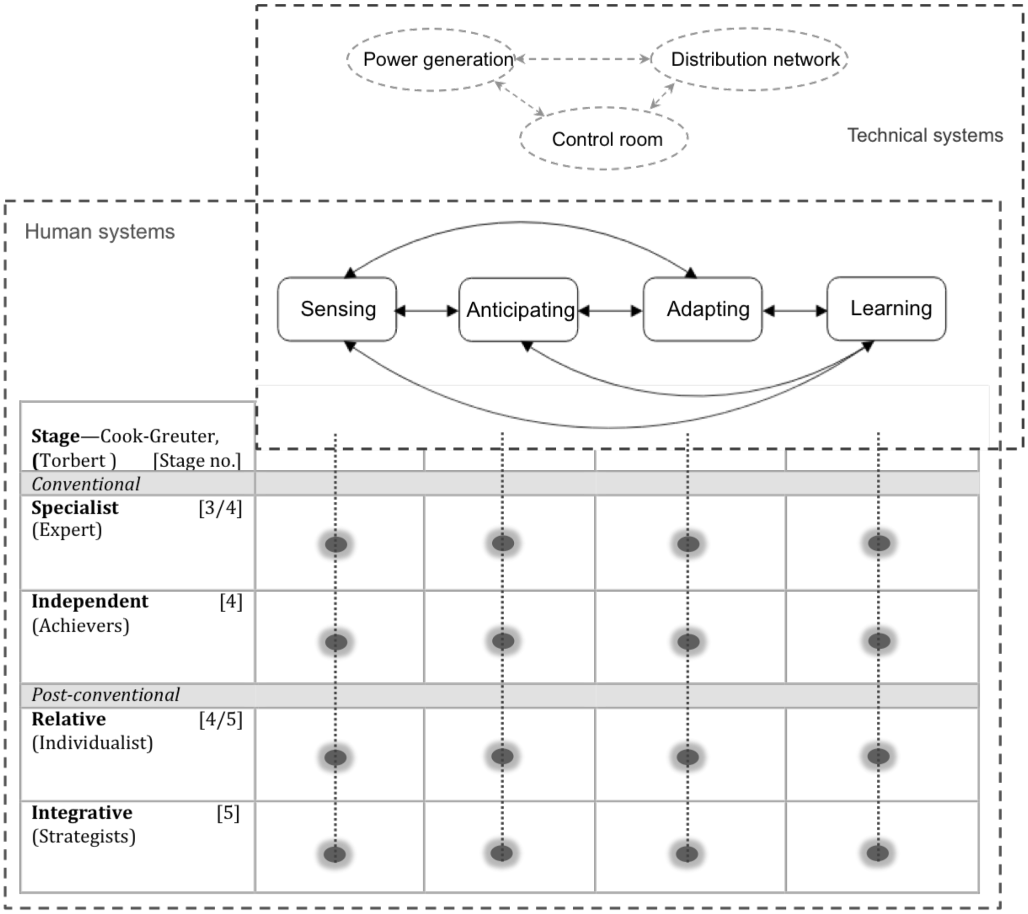

Figure 2.[5] A framework integrating technical systems' resilience capacities with human meaning-making via the SAAL sociotechnical processes.[6]

At this early stage of arguing for a marriage of developmental theories with infrastructure resilience scholarship we can only begin to map out the potential applications and implications. Clearly there is no extant research that demonstrates that, for example, individuals at or above a given developmental level will perform well at specific infrastructure-related jobs, or respond flexibly to systems failures and other unexpected situations. Here we can only (1) argue that the capacities required for resilient responses map well to the skills articulated more thoroughly in existing developmental theories (in particular meaning-making and ego-development models); (2) show that developmental theories and their assessment instruments have proven to be robust and valid in many applications and contexts.

How are each of the SAAL components effected by developmental factors? To review: *Sensing* is the ability to detect system state variables; *anticipating* is the ability imagine changes in system conditions and state variables; *adapting* is the ability to adjust system performance

[5] **Note:** The stage names in bold represent changes in labels Cook-Greuter made to her model in 2015.
[6] As development moves from the Expert toward the Strategist stage, each cell describes the internal and external developmental properties representing the SAAL sociotechnical processes – sensing, anticipating, adapting, and learning.

while maintaining viable operation; *learning* is the ability to absorb, retain, and access knowledge from experience. Below we illustrate how each of these elements relates to developmental factors – but keep in mind that here one's "developmental level" is not simply one's ordinary "center of gravity," but includes the dynamic of the how one actually behaves and thinks in any given moment and situation. For example, a person who normally is open to receiving feedback may be more emotionally "shut down" and defensive in times of stress – exhibiting a lower developmental capacity. Later developmental levels will be better able to monitor both self and social-systems to notice stressor effects, and make efforts to protect against or compensate for them – resulting in a type of meta-resilience that tries to maintain optimal levels of psycho-social resilience in the face of extreme stressors. In terms of each of the SAAL elements:

- **Sensing:** Earlier stages may be less capable of perceiving novel information and may "keep their head down" focused on tasks and be less likely to scan for unusual signs. And they may stay silent and defer to authorities or consensus opinion in the face of novel or conflicting information. Conversely, later levels may notice nuances and novel signals, be able to perceive come complex patterns in novel data, be more likely to speak up in dissent from authorities or peers; and they may notice more nuanced signals and patterns in interpersonal and social dynamics.

- **Anticipating:** Earlier levels are less likely to imagine possibilities or scenarios that differ from past experience (or codified procedures); they are less likely to consider the types of complex interactions and feedback loops that lead to unpredictable and chaotic outcomes; they are less likely to take the initiative to actively seek out new information and perspectives. Conversely, later levels are more likely to anticipate more unusual and/or complex scenarios; be more active in seeking diverse perspectives on a topic; and will have the capacity to plan or imagine further into the future, and over wider social and geographic scales.

- **Adapting:** Earlier levels will stick to accepted and well-practiced protocols, fearing punishment, public shaming, or disorientation if they diverge from norms and authoritarian expectations. Conversely, later levels will adapt routine protocols more readily, and have better feedback mechanisms (sensing and anticipating) for continuous fine-tuned adjustment of their actions and plans.

- **Learning:** Earlier levels are more geared to learn from explicit instruction, and from observing and/or imitating others; they are more resistant and defensive to changing their minds or mental models or to receiving corrective feedback. The types of complexity they can learn is limited, for example, to simple associations and linear methods. Conversely, later levels are more eager to learn, improve, and excel; ego's are less threatened by challenges, and corrective feedback is not only appreciated it is sought after. In addition, more complex mental models can be learned, such as complex dynamic systems, ecologies, recursive and fractal structures, etc.; and more complex interpersonal and socio-cultural dynamics can be appreciated and accommodated to.

We posit knowledge of the properties that appear at each stage of development assist with aligning strengths and capacities of individuals with roles and responsibilities for designers, operators, and managers thereby improving critical infrastructure resilience. Moreover, because stages emerge in an invariant sequence over time (Cook-Greuter, 1999; Loevinger, 1976), knowledge of how the properties change at each stage can serve as a predictor of potential outcomes correlating with the SAAL processes representing critical infrastructure resilience. Thus, knowledge of how a person is capable of responding and interacting with complex systems can improve critical infrastructure resilience by providing a more effective allocation of resources. For example, possible responses to varying levels of complexity and uncertainty related to infrastructure disruptions can be informed by an individual's stage of development thereby increasing the potential of aligning resilient system requirements for sensing, anticipating, adapting, and learning with human resilience and developmental capacities.

Similar to the adaptive properties of other human coupled systems that are unpredictable due to novelty and uncertainty introduced by humans (Holling & Gunderson, 2002; Martin-Breen & Anderies, 2011), we posit that meaning-making offers an important dimensional perspective of resilient social-technical systems like critical infrastructure. Thus, another reason for incorporating ego-development in our framework linking people and technical systems is that ego-development theory and model rely on measurement of adult capacity for meaning-making. Moreover, Cook-Greuter's (1999) evolution of Loevinger's (1976) model and O'Fallon's extension (2011) offers a comprehensive and validated method for measuring the adult capacity for meaning-making relevant to the present application. Because stages of development correspond to structures of adult meaning-making, we argue that ego-development is an effective way to account for the third dimension of resilience, in addition to space and time, influencing complex adaptive systems like critical infrastructure.

Further work could propose how each SAAL element breaks down by each of the four developmental levels in Table 2, but the level of specificity we give above, in terms of general trends, better matches the early state of research and scholarship in applying developmental theory to workplace and infrastructure resilience. How might we apply this marriage of the SAAL framework and developmental theory? Again, we can only be suggestive at this early stage, and additional research is warranted.

- Our framework can be used to better articulate the factors that go into techno-social systems (1) design; (2) training; and (3) post-event analysis. The framework supports the consideration of internal (endogenous) and social factors, such as feelings (e.g. confidence, fear, resistance, surprise, trust, respect), expectations, values, and flows of information/communication.

- Post-disaster analysis data could be re-analyzed in the terms of our model. For example each context could be rated according to whether each of the four SAAL elements was early, middle, or late according to the trends we suggest above. This could be done for successful responses and unsuccessful responses, with the hypothesis that successful responses would demonstrate later level SAAL elements.

- The assessment of developmental levels (directly or indirectly) can inform both the expectations placed on workers and stakeholders, and also the appropriate types and goals for trainings and educational opportunities afforded.

- Developmental assessment might be used to inform which individuals are given the reigns and which groups are asked to collaborate closely in response to disasters. The theory suggests that in dynamic scenarios trying to coordinate conventionally-oriented groups with post-conventional groups would only pile on additional tensions.

Here we must add a caution often included when such developmental or cognitive tests are used for "high stakes" decision-making. A single assessment has a margin of error, and any single measurement can capture the complexity of a human being. Such assessments should not be used as the only source of decision making; extreme precautions are warranted when decisions are focused on individuals (e.g. job placement); and more robust results are expected when assessment results are applied over groups, e.g. in assessing the average ability of a team to respond to a critical situation. Moreover, as research indicates that diversity of various sorts is important for team performance (Horwitz & Horwitz, 2007; Nederveen Pieterse, Van Knippenberg, & Van Dierendonck, 2013), relying on any single psychological construct can contribute towards cultural or epistemic 'mono-culture' (Bennett, 2015; Mignolo, 2011)

Conclusion

Human resilience, development, and critical infrastructure resilience can have reciprocal influence on one another. The holistic model shown in Figure 2 links resilience and development with technical systems by incorporating the endogenous and exogenous factors influencing the resilience of complex systems like infrastructure. The endogenous properties include the cognitive, emotional, and behavioral factors linking ego-development and human resilience. These factors form a developmental basis for human intentions, motivations, and agency that subsequently influences and informs social-technical processes of sensing, anticipating, adapting, and learning. The endogenous and exogenous properties are both recursive and reciprocal in nature, which means each system can interact and exchange influence in a repetitive manner, and each system can influence the resilience of other coupled systems. Future research designed to identify, apprehend, and validate the theoretical and conceptual frameworks presented herein with empirical data is recommended. Knowledge of the properties and processes corresponding to sensing, anticipating, adapting and learning for each stage of development will ground the theoretical and conceptual frameworks in practical research. A proven operational model can elucidate how each stage of resilient human development contributes unique qualities and capabilities needed by designers, operators, and managers to ensure the resilience of infrastructure critical to public health, safety, and well-being.

Data Availability Statement

No data, models, or code were (Cook-Greuter, 2004)generated or used during the study (e.g., opinion or data-less paper).

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