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Dynamic criticality for infrastructure prioritization in complex environments

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Abstract

As infrastructure confront rapidly changing environments, there is an immediate need to provide the flexibility to pivot resources and how infrastructures are prioritized. Yet infrastructures are often categorized based on static criticality framings. We describe *dynamic criticality* as the flexibility to reprioritize infrastructure resources during disturbances. We find that the most important prerequisite for dynamic criticality is organizational adaptive capacity characterized by flexible goals, structures, sensemaking, and strategies. Dynamic capabilities are increasingly important in the Anthropocene, where accelerating conditions, uncertainty, and growing complexity are challenging infrastructures. We review sectors that deployed dynamic management approaches amidst changing disturbances: leadership and organizational change, defense, medicine, manufacturing, and disaster response. We use an inductive thematic analysis to identify key themes and competencies and analyze capabilities that describe dynamic criticality. These competencies drive adaptive capacity and open up the flexibility to pivot what is deemed critical, depending on the particulars of the hazard. We map these competencies to infrastructure systems and describe how infrastructure organizations may build adaptive capacity toward flexible priorities.

1. Introduction

Infrastructure organizations increasingly struggle to respond to accelerating and increasingly uncertain environments, such as extreme weather events (Helmrich and Chester 2020, Markolf *et al* 2021b, Kim *et al* 2022), changing demands, pandemics (Carvalhaes *et al* 2020), and cyber warfare (Chester and Allenby 2020). These changing environments produce a decoupling between what infrastructures can do and what communities need them to do (Allenby and Chester 2018). The diversity of novel hazard dynamics raises questions about whether static framings of *critical* infrastructures (CI) are appropriate (Carlson and Doyle 2002, Gilrein *et al* 2019, Chester and Allenby 2019b, Markolf *et al* 2022). For example, should infrastructure managers prepare for extreme weather-related events in the same way as a pandemic? Do current framings of criticality provide the flexibility to reprioritize resources across various hazards? Throughout this paper, *infrastructures* refer to engineered systems as physical technologies and their associated organizations and governance unless otherwise stated. Furthermore, the *environment* will refer to the many external forces that affect infrastructures, including the natural environment, politics, cyber warfare, disruptive technologies, economic pressures, etc.

Static approaches have long characterized prioritization and resilience strategies for CI (Humphreys 2019). Since 9/11, many governmental actions, such as presidential directives, congressional acts, and federal department policies, have attempted to inspire greater awareness for critical infrastructure protection and prioritization (Humphreys 2019). The seminal definition of critical infrastructure came from the Patriot Act and is still used by the Department of Homeland Security (DHS) (CISA 2019). Multiple lists of prioritized national CIs have been created and contain a mix of traditional civil infrastructures (i.e. those systems thought of as 'utilities') and some social and ecological systems. There does not appear to be a concerted effort to support rapid transitions of resources to different infrastructures sensitive to the hazard. DHS and the Cyber Security and Infrastructure Security Agency (CISA) use a two-tiered priority system for CI but do not have a dynamic prioritization process for when disturbances change (Moteff 2015). Static framings continue to be standard practice for infrastructure organizations (Moteff 2015, Clark *et al* 2018, CISA 2019).

Infrastructure organizations often lack the competencies to dynamically prioritize critical systems with quickly changing environments (Helmrich and Chester 2022). As disasters unfold, managers need the competencies to make sense of the impacts and the most vulnerable services. COVID-19 is a valuable case study. Whereas energy, water, and other lifeline systems were largely uncompromised, parks (to house and socially distance the homeless) and digital communications became critical to health and well-being (Andrew 2020; criticality and prioritization for infrastructure may change conditionally (Clark *et al* 2018), Montgomery *et al* 2021). Infrastructure managers need insight into how their organizations should prepare to morph and bend to chaotic events, identify changing environmental conditions, and rapidly pivot priorities. We refer to this as *dynamic criticality*, where a system can contextually adjust to environmental disturbances, dynamically prioritize resources, and balance robustness and adaptability (Roli *et al* 2018).

Many CI sectors have diverse operational requirements, so a framework for dynamic criticality must be broadly applicable and focus on infrastructure organizational management and not specific engineered systems. Toward this end, we start by reviewing the competencies of other sectors that appear to be able to pivot how they focus as hazards change, cross-compare these competencies, and then apply them to engineered infrastructures.

2. Methodology

Cross-industry sectors that appear to have dynamic criticality capabilities were reviewed to improve the capabilities to dynamically define CI and pivot resources depending on specific hazard contexts. Five sectors were selected and analyzed: (1) leadership and organizational change; (2) military and defense; (3) medical emergency and triage; (4) manufacturing; and (5) disaster response. Literature was collected based on keyword searches to identify competencies that enable sectors to have the flexibility to reprioritize critical systems and pivot resources accordingly when faced with disturbances. Keywords included dynamic, criticality, edge of chaos, self-organization, decision-making, and priorities. The search used metadata academic journal search engines (ASCE, Google Scholar, Crossref, WorldCat, etc) and identified 29 sources across journal publications, book chapters, and government reports.

An inductive approach was used to describe common themes to identify sector competencies that support dynamic criticality. Inductive thematic analysis is a qualitative process whereby papers or texts are analyzed to develop common concepts and themes (Corbin and Strauss 1990, Boyatzis 1998, Thomas 2006). The goal was to evaluate how the sectors prioritize critical systems and resources amidst dynamic environments. The inductive analysis followed three steps: content review, theme generation, and validation (Thomas 2006). In reviewing the literature, themes about the research objectives were identified, labeled, and defined. The themes were analyzed for similarities, subtopics, and associations toward synthesizing them into a generalized framework for infrastructure (Creswell 2002, Thomas 2006). Methodologies, vernacular, and lexicons differ between the sectors, but common themes emerged, resulting in a framework with four overarching themes. Lastly, group-sample analysis was used to validate the results (Thomas 2006).

3. Sector review

The five sectors identified were examined for their dynamic capabilities. While *Leadership and Organizational Change* reveals generalizable capabilities across many domains, *Military and Defense, Medical Emergency and Triage, Manufacturing*, and *Disaster Response* show capabilities specific to their industries.

3.1. Leadership and organizational change

Leadership and organizational change literature transcends specific industries and describes organizations' cultures, priorities, and structures. Organizations have experienced significant transitions in the past century, such as the shift from production orientation to knowledge-production and the associated technological revolutions (Davenport 2001, Manville and Ober 2003, Uhl-Bien *et al* 2007). These transitions are entangled with tensions such as supply chain disruptions by logistics or dwindling resources and changing consumer demands (e.g. increased awareness of corporate social responsibility to the latest technology). The transitions also include the restructuring of workplace dynamics (e.g. dispersion of power to remote work) and competition which pressures the speed of innovation within an organization. These tensions interact unpredictably and destabilize organizations (Sterman 1989, Uhl-Bien and Arena 2018). Organizations have responded to this complexity with adaptability, recognizing they will be operating with some degree of chaos and disruption, utilizing responses such as dynamic decision-making (DDM) (Edwards 1962, Brehmer 1992, Gonzalez *et al* 2005). Organizations also developed principles like contextual ambidexterity (March 1991, Papachroni *et al* 2016, Uhl-Bien and Arena 2018) and leadership priorities that emphasize innovation (Uhl-Bien *et al* 2007). Complexity leadership theory (CLT) describes balancing bureaucratic leadership (during times of stability) with more entrepreneurial leadership that emphasizes innovation in the face of chaos. CLT emphasizes the ability of the organization to pivot between efficiency (stability) and resilience as innovation during instability.

3.2. Military and defense

Defense organizations must effectively operate across stable (peacetime) and chaotic (wartime) contexts and have embraced several techniques for assessing the criticality of resources and threats dynamically. The strategic and competitive nature of the military may inspire more proactive planning and decision-making. These techniques include dynamic force employment (DFE), creating scalable and context-specific capabilities to deploy resources in an increasingly chaotic and diverse landscape (DoD 2018, Wetzel 2018). Mission command has also adopted decision-making techniques that encourage collaboration and bottom-up formation of relationships, create a continuous dialogue toward a shared understanding, and provide clear command guidance and empowerment for autonomous decision-making (Deployable Training Division 2020). The core tool that has emerged for assessing threats and responses and how those change with context is center of gravity (COG) analysis (Mcfadden 2014, Schnaubelt *et al* 2014). COG is the entity capable of achieving or enabling an objective or capability and can represent physical assets (weapons systems or financial institutions), people (individuals or groups), or ideologies (Perez 2012, Kornatz 2016). Defense organizations have centered COG as a framework for assessing threats (e.g. physical armies, financial networks, or ideologies) in differing contexts and surgically deploying responses. COG analysis involves first identifying crucial capabilities (crucial enablers for a COG to function). Next, it identifies critical requirements, i.e. essential conditions, resources, or means for a critical capability to be fully operational. Lastly, COG describes critical vulnerabilities where neutralization, interdiction, or attack will create decisive or significant effects on the COG. The COG analysis guides the operational response, including lines of operation (actions or events that must unfold in a particular sequence) and lines of effort (the linking together of tasks to determine how they will lead to an objective) (Schnaubelt *et al* 2014, Kornatz 2016).

3.3. Medical emergency and triage

Originally conceived in the 1700s out of necessity to make rapid decisions for wounded soldiers in wartime, medical systems began formally developing triage frameworks in the 1970s (Dippenaar 2019). Emergency departments require decision-making tools to prioritize groups and individuals during medical emergencies. For triaging groups of patients, the sort, assess, life-saving interventions, treatment, and transport and simple triage and rapid treatment methods focus on sorting and diagnosing. During sorting, these methods quickly place patients into three categories: (1) unresponsive or life-threatening injuries; (2) can respond purposefully; (3) can walk, despite injuries. Based on this sorting, medical providers can prioritize limited resources to assess and care for patients, including life-saving interventions, further care, and transportation. Notably, if providers determine that the patient is unlikely to survive due to the severity of their injuries, they may move on to other urgent patients. While certainly not devoid of ethical conflicts, these frameworks help medical providers rapidly determine criticality and respond accordingly (Aacharya *et al* 2011).

Triage for individuals leaves out the ‘sorting’ step and presumes the emergency department is experiencing a steady flow of patients to prioritize. With individuals, an E.R. physician must first assess how quickly a patient needs attention and then how to administer proper care. For example, the emergency severity index (ESI) assesses the patient’s condition with a series of questions: (1) immediate life-saving required; (2) high risk, confused/lethargic/disoriented, severe pain/distress; and (3) the number of resources required. ESI combines these questions with vital measurements (heart rate, respiration rate, and oxygen levels). The output is a priority level from 1 to 5, with level 1 requiring immediate medical attention and level 5 requiring medical attention within 120 min (Aacharya *et al* 2011).

Worldwide triage frameworks exhibit thematic commonalities in determining criticality, despite practical application differences, often driven by culture (Dippenaar 2019). In general, medical providers quickly identify patients that require immediate care, administer life-saving interventions for stabilization, and then assess the remaining patients with less urgency. Moreover, the individual patient assessment provides a specific checklist of critical body systems and symptoms, which points the medical team toward the type of care needed (Aacharya *et al* 2011). Ultimately, triage frameworks save time, energy, and lives when employed properly (Dippenaar 2019).

3.4. Manufacturing

The globalization of markets has increased demand volatility, forcing manufacturing companies away from mass production toward mass customization. Prioritizing market competition and profitability, companies have shifted to designing unique products for individuals at smaller volumes (Hu 2013). Simultaneously, new technologies have aided manufacturing adaptations, such as advanced sensor systems reducing equipment-based disturbances so manufacturers can focus more on market analysis and the associated manufacturing pivots (Frankowiak *et al* 2005). Reconfigurable manufacturing systems (RMSs) have been a pivotal adaptation that has increased the ability to manage the market volatility toward rapid customization. RMSs are individually reconfigurable machines that can be added, removed, or adjusted to customize products to customer needs. The goal of RMSs is to minimize the response time to unpredicted market shifts while still allowing for traditional machine and system-level optimization (Yelles-Chaouche *et al* 2021). During the development of RMSs, a new set of organizational requirements emerged: scalability, convertibility, diagnosability, customization, maximizing tasks given to machines, and balancing maintenance for optimal throughput and reliability (Koren *et al* 2018). Manufacturers developed methods to detect market disturbances, designing, selecting, and pivoting to new configurations. Two priorities drive these configurations: resource availability (i.e. tools and machines) and throughput requirements (production volumes) (Mabkhot *et al* 2020). In general, the frequent and rapid pivots that RMSs must undergo highlight key capabilities: disturbance detection, coupled with a quick redesign and driven by critical priorities.

3.5. Disaster response

The complexity of disaster response arises from shifting climatic conditions in hazard prediction, coordination of limited resources for response and recovery activities, and varying adaptive capacity and vulnerability of affected populations (O'Sullivan *et al* 2013). The stress of chaotic environments underscores the importance of heuristics in decision-making (Sterman 1989) and thoughtfully crafted and practiced response plans (O'Sullivan *et al* 2013, FEMA 2021). During disaster response, institutions identify critical assets for protection in terms of importance, value, sensitivity, associated resource requirements, and interdependencies (FEMA 2018, Hempel *et al* 2018). Traditionally, deterministic methods have dominated disaster response decision-making based on historical data, experiences, and judgment without considering future uncertainties. Some critical values (e.g. water level or flood return period) can provide indices for decision-making. More recently, hazard prediction models use probability and uncertainty modeling (e.g. the relationship between dam failure probability and fatality). Probabilistic approaches can be combined with a real-time hazard assessment to reduce the uncertainty in the decision during disasters but require more information and an iterative process to improve the models, which can potentially delay the decision (Peng and Zhang 2013).

4. Thematic analysis results

Several commonalities emerged across the sectors. The thematic analysis revealed four generalizable themes. First, many sectors showed methods for describing *goals* when dynamically shifting priorities. Second, several sectors exhibited capabilities toward configuring organizational *structures* to implement the goals. Third, a common theme of *sensemaking* appeared across sectors: making sense of an environment to open up decision-making (Weick 1995). Fourth, organizations developed specific *strategies* for implementing flexibility amidst changing conditions. These four themes and their competencies are shown in figure 1 and are discussed at length in this section. These results and figure 1 will guide the following discussion.

4.1. Theme 1: goals

Establishing *goals* was pivotal for sectors to implement dynamic criticality. Goals guide organizations toward responding to disturbances or chaos, which leads organizations to change structures, sensemaking, and strategies accordingly. Goals appear foundational for strategy development. The six competencies that emerged from the goals fell into two primary categories as shown in figure 1. The first was a *rapid adaptation* to changing environments. Rapid adaptation includes self-organizing adaptability, requisite variety, and quick detection and reaction to disturbances. The first category of goals focused on *enabling quick decision-making*, including prioritization of resources during emergencies, identifying critical requirements for mission accomplishment, and building organizational relationships to facilitate DDM.

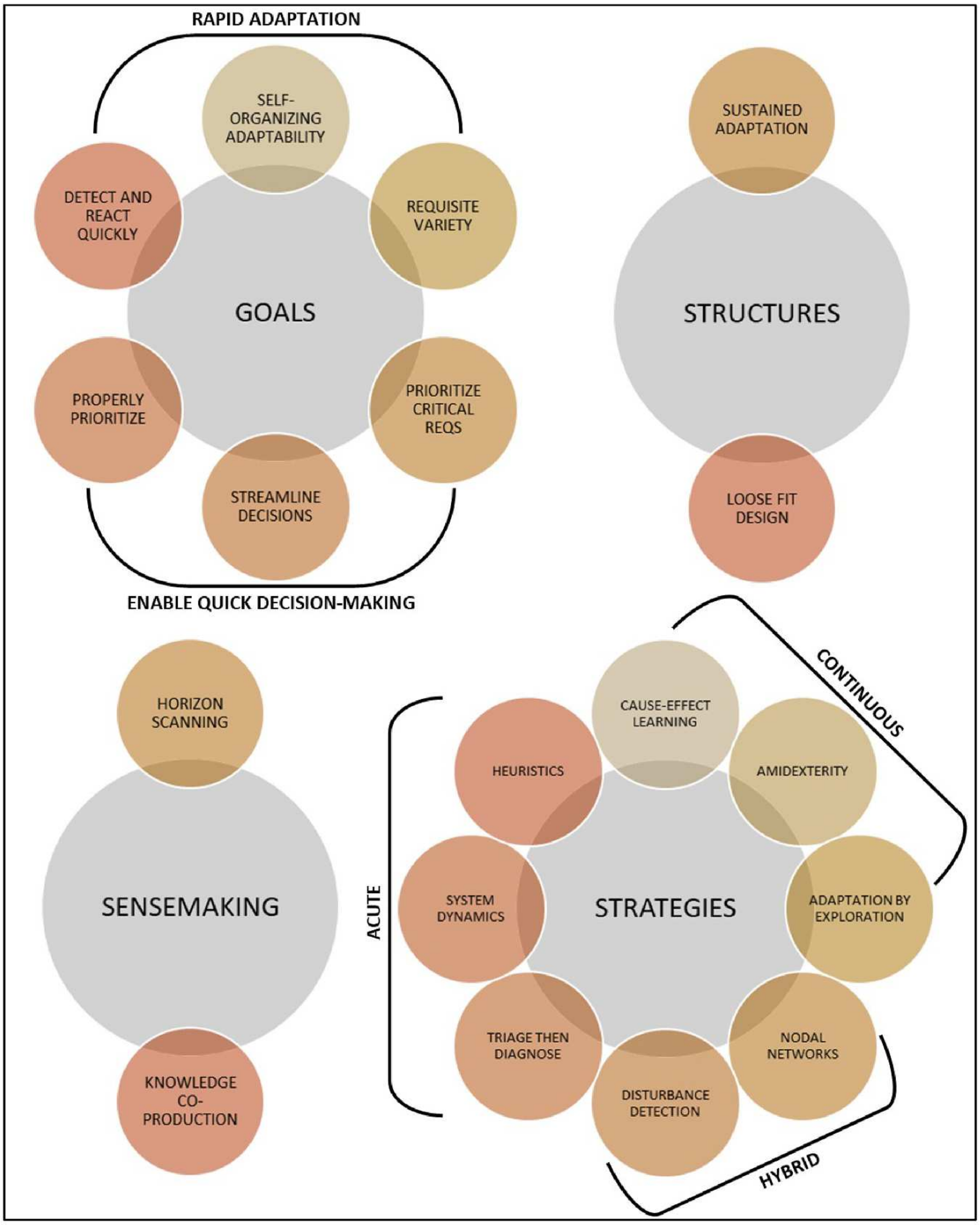

Figure 1. Summary of the resulting themes and competencies. The four are equal in importance for dynamic criticality. But organizational structures and goals should be established first before moving toward strategy development/execution and sensemaking.

When organizations set goals for rapid adaptation, this nudges the organization toward dynamic criticality, often indirectly. First, organizations with goals toward dynamic criticality *select priorities* more efficiently than others (Manville and Ober 2003). Similarly, dynamic environments alternate unpredictably between stability and instability. In response, organizations should develop exploitative efficiency and explorative innovation. Exploitation focuses on efficiency, which is effective during periods of stability, and exploration is more effective during instability. This ambidexterity makes an organization efficient, agile, and flexible (March 1991, Uhl-Bien and Arena 2018). Second, *requisite variety* commonly appeared in both military and manufacturing goals. Requisite variety describes how systems in changing environments must have a repertoire of responses sufficient for their environment complexity (Naughton 2017, Chester and Allenby 2022). The military changed its operations to incorporate randomness for the timing and movement of forces which simultaneously confuses adversaries and builds adaptability and readiness for deployment

(DoD 2019). In manufacturing, RMSs match market needs and the pace of change (Koren *et al* 2018, Khalil *et al* 2020). Rapid adaptation goals have also led manufacturing to use sensors, process monitoring, and analysis tools to detect and react to process and equipment disturbances (Frankowiak *et al* 2005). For disaster response, the variability of disaster outcomes makes it unrealistic to standardize prioritization methods (such as in medical triage). Thus, disaster planners set general goals toward quick contextual discernment of criticality and speed of response (Applied Technology Council 2016, DHS 2019b). Although the goals found within the thematic analysis were different, they were generally oriented toward rapid adaptation. Ultimately, this appeared to inform organizational priorities, preventing reflexive decision-making. Goals that supported making faster decisions also improved dynamic criticality. The sectors showed many of the same principles for decision-making that (Brehmer 1992) cites for the theory of DDM, such as decisiveness, delegation, taking responsibility, and avoiding fixation. In medical triage frameworks, the goal of appropriately prioritizing patients during emergencies is paramount to establishing decision criteria so medical staff can dynamically sort and prioritize patients specific to the scenario without time-consuming analysis, testing, or judgment (Aacharya *et al* 2011, Storm-Versloot *et al* 2011). Secondly, several sectors set a goal to clarify the requirements needed to meet specific objectives. Military COG analysis uses critical requirements, vulnerabilities, and assets to select priorities for mission accomplishment (Perez 2012, Schnaubelt *et al* 2014). Similar to how military planners need to identify various critical attributes, disaster response planners also must prioritize specific assets and resources during a response (O'Sullivan *et al* 2013, DHS 2019a). As per (Clark *et al* 2018), disaster planning seeks to isolate the most critical assets and then shift those priorities dynamically. Also, the military realized that micro-management and lack of trust slowed the decision-making process. So, senior military commanders set goals to streamline the decision-making process. They built organizational relationships that empowered local commanders to prioritize and make decisions swiftly by creating a culture of trust, communication, and deep mutual understanding (Deployable Training Division 2020).

4.2. Theme 2: structures

The ability of organizations to change their governance models and processes to respond to changing conditions emerged across the sectors. Novel methods for transitioning governing structures appear to enable organizations to see game-changing disruptions and pivot resources more clearly in response. Two competencies emerged, as shown in figure 1: (1) a commitment to sustained adaptation where the organization recognizes that its environment is in flux and structures itself to adjust course as needed, and (2) instituting processes that enable dynamic organizational structures and adaptive planning, referred to as 'loose fit design.' In CLT, organizations can pivot between efficiency and innovation governance models, the latter suitable for periods of instability (Uhl-Bien and Arena 2018). RMSs are more flexible at handling demand and disruption shocks, adjusting the systems' orientation in response. RMSs achieve this flexible state through convertibility (capable of adaptation to new products), diagnosability (design quality assurance with the system, and not as an afterthought), customizability (designed around a family of products, and not just one), and scalability (cost-effective adaptation to future market demand). The loose-fit design has several associated properties. First, horizontal governance—shifting resources and decision-making authority to front-line workers who can coordinate and better sense change—creates organizational capabilities to diagnose and respond appropriately to chaos and change quickly. Formally, dynamic planning involves avoiding fixation—remaining focused on a set of increasingly obsolete challenges—and committing to a continuous cycle of reassessment of environmental conditions relative to organizational goals and processes (Brehmer 1992, FEMA 2016).

Like how goals inform decisions, organizational structures provide a foundation for sound decision-making. Organizations that confront frequent dynamism have streamlined processes and aligned their formal and informal structures to be more flexible as the environment changes. To maintain readiness, they must suppress natural apathy within structures during periods of equilibrium and maintain energy toward adaptability (Pascale 2006).

4.3. Theme 3: sensemaking

Dynamic environments forced organizations to develop new ways of understanding and interpreting the environment. In doing so, they are exercising *sensemaking*: taking in new knowledge, structuring it using novel techniques, and ultimately opening up decision-making opportunities (Weick *et al* 2005). In the thematic analysis, sensemaking presented two distinct competencies, shown in figure 1: (1) the search for weak signals that may indicate changing environmental conditions in a process called *horizon scanning*; and (2) focusing on organizational *co-production of knowledge*. For DFE, the military collects and interprets data to understand the operational environment, enabling it to alter its force structure dynamically (DoD 2019). Similarly, disaster response planners for communities spend significant time understanding the dynamic environment within their area of responsibility to anticipate how different disturbances may affect the community (O'Sullivan *et al* 2013, FEMA 2021). Additionally, manufacturing systems constantly scan within their system to detect weak signs of equipment/process failure (Frankowiak *et al* 2005) and also scan outside their systems (i.e. markets) to see hints of market changes that may trigger shifts in production or design (Khalil *et al* 2020). Organizational co-production of knowledge supports dynamic criticality primarily through network and collaboration. CLT creates informal social networks in organizations, allowing for a freer flow of ideas and collaboration, thus increasing innovation during disorder when old priorities suddenly become irrelevant and new ones must be identified (Uhl-Bien and Arena 2018).

Similarly, managers of knowledge workers have shifted focus from task oversight toward knowing the capabilities of subordinates and building networked teams, creating more effective organizational knowledge toward shifting priorities during disturbances (Davenport 2001). Indeed, the military has also identified this need for knowledge co-production with the concept of mission command. Senior commanders have a greater understanding of the strategic environment, while subordinate commanders have a better contextual awareness. Thus, mission command also shifts focus from oversight. The focus on building trust between the higher and lower ranks empowers and supports. The continuous dialogue toward shared understanding establishes trust and liberates senior commanders to focus on giving clear guidance and intent. Subordinate commanders are then empowered to swiftly decide and prioritize without asking for additional guidance (Deployable Training Division 2020). Collectively, horizon scanning and co-production of knowledge during disturbances seek to combine information collection and synthesis with robust abilities to quickly and efficiently convert that information into relevant priorities.

4.4. Theme 4: strategies

The goals, structures, and sensemaking culminated in the creation of *strategies*. Eight strategies emerged from the review, describing acute (short-term), continuous (long-term), and hybrid decision-making timeframes. Acute strategies address disturbances with an apparent beginning and end (e.g. medical triage). Other sectors used continuous strategies oriented toward cyclical and ongoing problems (e.g. global military competition). Some sectors use hybrid strategies for scenarios with a clear beginning and end but require reassessment (e.g. lifeline disaster response). The three types are grouped and labeled accordingly in figure 1.

The three acute strategies came from the triage and disaster response sectors. Time constraints of medical emergencies and disaster scenarios focus on rapid decision-making using pre-established frameworks, which requires deep systems knowledge to do dynamic criticality. In medical triage, this situational urgency requires *prioritization* via *predetermined critical information heuristics.* Action and priority-based thresholds are predetermined for efficiency, so a paramedic or triage nurse is not responsible for analyzing the patient's condition. They are trained for condition determination and prioritization via prescribed metrics, charts, data, and sensors (Aacharya *et al* 2011), with some flexibility for tacit knowledge and experience to account for framework simplicity (van Pijkeren *et al* 2021). Sometimes, medical triage encounters situations where professionals must do *initial sorting and emergency interventions and then detailed evaluation/ determinations*—such as in a mass casualty situation. Medical professionals begin with simple visual heuristics for prioritization: unresponsive, responsive, or walking. While simple, it is the most expedient strategy in the results. It displays how organizations can simplify a chaotic environment for tiered criticality prioritization. Emergency managers also found that *in-depth knowledge of the system, connections, capabilities*, and *dependencies* was an effective strategy to cut through the complexity and chaos during disasters. This knowledge enables decision-makers to make quick but contextualized decisions for prioritization (O'Sullivan *et al* 2013, FEMA 2021). While building and maintaining this knowledge is a continuous process, this strategy is acute when the knowledge is applied toward rapid prioritization, reducing waiting time and ambiguity.

Next, the continuous strategies shifted priorities during disturbances via a mixture of *structures* and *sensemaking* practices. Paradoxically, organizations that use continuous strategies appear to exist in a constant state of change where disturbances become a form of equilibrium. Business organizations have found that *ambidexterity and organic, networked adaptation* are necessary strategies for survival. Organizations intentionally vacillate between exploitation and exploration, building adaptability and DDM and eliminating dependence on fragile and inaccurate market forecasts. Moreover, pursuing informal networks in organizations creates organic adaptation, which is more desirable when constantly engaging disturbances (Papachroni *et al* 2016, Uhl-Bien and Arena 2018). Also, toward continuous DDM, people unconsciously fixate during stress and chaos. Intentional decision-makers must measure, analyze, and compare marginal gains for each action, allowing for iterative priority adjustments (Brehmer 1992). This *cause-effect learning toward improved decision-making* helps decision-makers maintain a state of dynamic criticality. Similarly, the U.S. military continuously adapts to a rapidly changing global environment. DFE and competition continuum doctrine emphasize *adaptation by exploration* through continuous change, inserting temporal and physical randomness in force movement (DoD 2018), and dynamic engagement levels (i.e. peacetime, cooperation, and combat operations) (DoD 2019). This proactive strategy seeks to constantly develop new 'forms' that the organization can adopt to outpace competitors, focusing on attaining an adaptive state rather than seeking specific outcomes. These strategies all target the deep development of organizational adaptive capacity, the ability to reform and reshape when faced with new challenges.

Last, the military COG analysis, RMSs, and the Federal Emergency Management Agency (FEMA) community lifeline support frameworks were hybrids of acute and continuous strategies. They used continuous processes to achieve dynamic criticality, but disturbances also had a clear beginning and end. The military uses COG to derive priorities from critical attributes of the environment (e.g. financial systems, physical targets) linked to the mission's desired outcome. These *nodal networks* are used for single and continuous objectives (e.g. a long campaign or operation), constantly identifying new priorities and updating old ones. COG uses a network that maps capabilities, vulnerabilities, assets, and the COGs they orbit around. The top priorities are the network attributes connected to the desired end state (i.e. the target COG). Critical priorities shift if the end state shifts (Perez 2012, Schnaubelt *et al* 2014, Kornatz 2016). Next, *disturbance detection, adaptation identification, monitoring*, and *remembering* is a cyclical process that RMS and FEMA use for individual disturbances. The RMS process detects market disturbances, develops manufacturing system adaptations, and monitors market conditions' relevance. Key to this adaptation process is a rich archive of past disturbances and adaptations and the ability to recall them for reuse—simplifying future adaptation development (Khalil *et al* 2020). Similarly, emergency support management applies a cyclical process for restoring essential CIs (e.g. water, electricity, shelter) after a disruption. When an incident occurs, this triggers assessments, prioritizations, logistics, and responses, a process that loops until CIs are stabilized. Emergency managers also apply their archive/remember/recall process while updating plans so that emergency response goals are relevant to the environment (DHS 2019b).

5. Discussion: infrastructure dynamic criticality

Having described the themes and their competencies in the results and in figure 1, we turn to how infrastructure systems can use these capabilities to practice dynamic criticality. These themes can support infrastructure systems to detect disturbances early, pivot priorities, and balance robustness and adaptability. The thematic analysis showed that organizations that successfully confront chaos tend to engage disturbances in three phases: prior, during, and post-disturbance (FEMA 2016). The (Park *et al* 2013) framework for sensing, anticipating, adapting, and learning (SAAL) closely aligns with this process. Before chaos, infrastructure managers should probe, sense, and respond to the environment (Chester and Allenby 2019a). The thematic analysis shows that most work toward dynamic criticality happens before chaos. In alignment with the four main themes, *goals* are set for adaptability and quick decision-making. Dynamic and flexible *structures* are formed. Organizations will practice sensemaking for past, present, and future environments and develop adaptable *strategies* to engage disturbances. Then, organizations must transition during disturbances to more acute and hybrid strategies. During disturbances, they will test sensemaking capabilities, execute plans, and rapidly innovate. After the disturbance is over and stable conditions return, organizations should shift toward expanding resilience for the future. It is time for organizations to learn, produce knowledge from the experiences, archive and remember, and change adaptations and plans for future chaos cycles. This learning component is a looped cycle that links all the other components of the adaptation process and thus deserves additional attention (Thomas *et al* 2019). This final section will contextualize the themes and competencies for infrastructure, discussing them relative to the *prior, during*, and *post* phases of disturbance engagement. Henceforth, italicized terms refer to the framework of themes and competencies shown in figure 1.

The primary takeaway from the thematic analysis is that goals toward rapid adaptability and quick decision-making are essential to building capacity for dynamic criticality. In the thematic analysis, adaptable goals focused on capabilities that enabled quick shifts in priorities. Without dynamic criticality as a goal, it is unlikely to permeate the structures and operations of the organization. Goals bring inspiration to changes in organizational structures. For example, goals to exhibit requisite complexity will inspire an organization to look for more forms that an organization can take to fit the increasing forms of the environment (Brose 2020, Brown 2020, Chester and Allenby 2022). After all, addressing complexity is about flux and unpredictability. The environment will always overcome more robust or efficient systems. So, these organizational goals, determined by leadership, will be a product of new governance that has embraced wicked complexity and uncertainty as the new normal (Chester and Allenby 2021).

The thematic analysis indicated that, for more complex organizations, pre-established priority lists are less critical than building the capacity to engage chaos. Overemphasis on efficiency and optimization has led to rigidity and catastrophic failure in infrastructure. Leading up to the 2021 Winter Storm in Texas, electrical utility companies had neglected to upgrade system capacities and improve weatherization, resulting in an unprecedented cascading power outage and highlighting numerous areas where community resilience had been neglected (Markolf *et al* 2022). Dynamic criticality thinking would have encouraged utilities to invest time in developing *loose-fit structures* and build *horizon scanning* capacity for weather-related cascading failure scenarios. With these tools, they may have had the ability to pivot priorities and develop strategies for quick reactions to extreme storms. While prioritizing assets is necessary for developing readiness and strategies to engage disturbances, static priority lists have often been mistaken as a good plan for disturbances (Clark *et al* 2018). This static thinking causes shortfalls when responding to novel or extreme disturbances that exceed historical precedent (Clark *et al* 2018). These shortfalls exemplify how *goals* that focus on foundational requirements (e.g. *requisite variety, detecting/reacting quickly*) enable adaptative *strategies* and specific competencies such as *ambidexterity, disturbance detection*, and *adaptation* via *exploration*. This adaptive capacity gives organizations more tools to confront chaos when it comes (Lichtenstein *et al* 2007, Chester *et al* 2020).

Capacity development for infrastructure must happen in the pre-chaos space. Adaptive capacity is not expanded during chaos as much as used (Woods 2015). Successful organizations spend considerable effort building organizational relationships toward cultures of *sustained adaptation* and practicing reactions to chaos from the *cause-effect learning* that exercises foster. These efforts may differ depending on the type of disturbance (i.e. practicing reactions for a hurricane will look much different than practicing for reactions to seasonal monsoon flooding). Hurricane Katrina showed how neglect of pre-chaos adaptations could hamper responses. Overdependence on robustness for resilience causes infrastructure organizations to undervalue the *knowledge co-production* that comes with intentional cooperation and collaboration. There was no consensus within and between agencies about pivoting priorities when CI failed. Organizational relationships and cooperation quickly deteriorated without firm goals and consensus methods to triage and diagnose priorities (Leavitt and Kiefer 2006). This lesson demonstrates how prior-to-disturbance efforts to build adaptive capacity for infrastructure should focus on leadership to enable *ambidexterity*, flexible *structures*, and *knowledge co-production* necessary to bolster innovation and build capacity (Helmrich *et al* 2021, Helmrich and Chester 2022).

Reimagining infrastructures as knowledge enterprises and shifting to flexible *loose-fit* governance *structures* will grow the capacity to *adapt by exploration* much faster than traditional governance structures (Uhl-Bien and Arena 2018). Infrastructure governance *structures* historically manifest as divisional bureaucracies, characterized by isolated divisions that often lack coordination and collaboration skillsets that may hinder many of the dynamic criticality competencies cited in this framework (Chester *et al* 2020). During the Northeast Blackout of 2003, time-crucial coordination and *sensemaking* between two personnel who worked across the hallway could have prevented the cascading failure in the initial minutes of the disaster (NERC 2004, Pescaroli and Alexander 2016). Thus, two organizational transformations are necessary to shift toward a more adaptable paradigm. The first is to transition to a knowledge enterprise, which focuses less on developing a product (i.e. infrastructure assets) and more on developing knowledge workers (i.e. technicians, operators, and engineers) who are responsible for systems (Chester *et al* 2020, Chester and Allenby 2021). This transformation deemphasizes the importance of supervision and oversight and emphasizes leadership, empowerment, and sharing of knowledge (Davenport 2001, Deployable Training Division 2020), all pieces that bolster *sensemaking* and more adaptable governance *structures*. Therefore, shifting toward these principles may improve dynamic criticality via communication and coordination. Communication and coordination, in turn, increase idea syndication and expand *sensemaking* (Uhl-Bien and Arena 2018). The second transition is to develop *ambidexterity*, switching between hierarchical and decentralized, ad-hoc *structures* during equilibrium and chaos, respectively (Chester *et al* 2020, Helmrich and Chester 2022, Siggelkow and Levinthal 2003). These relationships also display the interconnected relationship between organizational *structures* and *sensemaking*. To this end, infrastructure organizations should practice the discomfort of shifting to emergency response teams, diverse in expertise and empowered to take quick action to *triage and diagnose* disturbances. In doing so, infrastructure organizations will familiarize themselves with scenarios where *structure* shifts are necessary, diminishing lethargic responses that may hinder dynamic criticality (Alderson *et al* 2022). Furthermore, an infrastructure organization that knows when to shift between efficient and resilient structures gains the *requisite variety* to match its environment, which also aids the dynamic prioritization process (Markolf *et al* 2022).

The nature of the disturbance and the outputs of *sensemaking* should guide *strategy* selection and development. Infrastructure needs to practice and exercise disturbance responses, not to be predictive, but to develop familiarity with the discomfort of surprise and intimate knowledge of the *system dynamics*. This practice expands the SAAL skillsets toward the *sensemaking* competencies of *horizon scanning* and *knowledge co-production* (Miller and Munoz-Erickson 2018, Ancona *et al* 2020, Alderson *et al* 2022, Chester and Allenby 2022). Disturbances manifested differently across the sectors of this study, and the diversity of hazards battering infrastructure appears to be doing the same. Practically, low-chaos disturbances may allow for *node-networked* responses with multiple considerations for shifting priorities—much like COG analysis, which uses critical capabilities to determine priorities dynamically. For high-chaos disturbances, reflexive reactions may be more realistic, such as *triaging and diagnosing*—much like how medical professionals sort patients into general categories during mass casualty events. Additionally, multiple strategies could be nested within each other to increase flexibility. An infrastructure control center may develop a COG-like *nodal network* based on triage-like assessments from multiple teams transmitting information, pushing back against the degradation of rationality that often occurs during DDM (Brehmer 1992). When chaos is so high, some organizations have no choice but to simplify the environment—as discussed in *requisite variety* (Boisot and McKelvey 2011). But this simplification must also be balanced with proper *sensemaking*, lest infrastructure managers misdiagnose problems (Chester and Allenby 2022). So, the nesting of strategies may be a reasonable compromise to these problems. Additionally, strategy selection may present an opportunity for human-supervised artificial intelligence systems to assist with sensemaking, reducing confusion and subjective bias while bolstering speed and agility (Markolf *et al* 2021a).

Although most *sensemaking* competencies should be built pre-chaos, they are tested and exercised more intensely during chaos. *Horizon scanning* and *knowledge co-production* remain essential to leading through chaos (Ancona *et al* 2020) and analyzing how the chaos will affect the infrastructure system. The COVID-19 pandemic revealed that infrastructure organizations often neglect *sensemaking* to anticipate hazards (Carvalhaes *et al* 2020). For example, in the summer of 2021, hospitals began to rapidly consume the available supply of liquid oxygen due to the surge in severe COVID patients. Consequently, there was concern that water utilities would run out of the resource—commonly used as a critical water treatment component (Rosen 1973). Until the realization of resource constraints, no one had considered the interdependencies that might have caused liquid oxygen to become the critical priority for the water utility. Managers were forced to revert to simplified decision-making thresholds for water consumption and conservation (Lusk *et al* 2021). But *nodal networked* thinking, *horizon scanning* as a discipline, and *disturbance detection* could have identified this vulnerability before it became a crisis. Making sense of a system requires an in-depth analysis of connections, interdependencies, and stakeholders (O'Sullivan *et al* 2013). It is necessary to keep up with real-time shifts in criticality (Clark *et al* 2018).

Finally, *cause-effect learning* for the future is a best practice for dynamic criticality—although it appears to be among the hardest of competencies to retain (Westrum 2006, Thomas *et al* 2019). When comparing the different sectors of this study, manufacturers appeared to do this more competently. They intentionally archive and recall previous *strategies* when a new market *disturbance is detected*. It saves time and effort in reinventing new *strategies* and helps an organization remain familiar with other competencies for adaptation to disturbances (Khalil *et al* 2020). Additionally, newly developed *strategies* contribute to an ever-growing 'snowball' of remembered potential responses (Sweet *et al* 2014), which continue to grow *requisite variety* and contribute to a *streamlined decision-making* process. Therefore, remembering for infrastructure is foundational to requisite variety because of the interactive feedback loops between *cause-effect learning* and other aspects of *sensemaking* (Clark *et al* 2019). Moreover, remembering is an essential component of organizational cognition (Cooke *et al* 2013), and cognition links to *knowledge co-production* concerning systems and how responses should be tailored accordingly (Miller and Munoz-Erickson 2018). So, infrastructure organizations must practice remembering to practice cognition, which is ultimately necessary for *sensemaking* and *strategy development* for dynamic criticality.

6. Conclusion

Infrastructure organizations must implement practices toward dynamic criticality during times of chaos to remain viable in rapidly changing and increasingly unpredictable environments. Other sectors provide insights into the competencies that enable rapid pivots to reprioritize knowledge and resources. Chaos is not predictable or comprehendible (Chester and Allenby 2019a). Static priorities to engage chaos will remain unknowable, much like an 'event horizon of chaos' for infrastructure. Thus, the results of this study show that if infrastructure organizations wish to approach dynamic criticality amidst disturbances, they should focus on maximizing adaptive capacity. Specifically, during periods of equilibrium, they should set goals for rapid adaptation and quick decision-making. They should alter their formal structures in ways that are friendly to sustained adaptation, which can be dynamic, flexible, and shiftable when disturbances occur. These goals and structures will then enable sensemaking competencies, allowing the organizations to scan the horizon for threats and make sense of increasing information flow (before, during, and after disturbances). These efforts will give way to the final sought-after product: practical strategies for dynamic criticality. Beneficial future research may be the historical analysis of disturbances and how dynamic criticality was or was not achieved by infrastructure organizations. But we urge caution regarding developing specific decision-making frameworks, as they may lead to strategy entrenchment and a decrease in adaptive capacity.

The primary lesson from this work is that strategies are also dynamic and unique to disturbances. Thus, focusing on adaptive capacity will benefit infrastructure organizations more than a rigid list of priorities.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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