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TOPICAL REVIEW

Infrastructure autopoiesis: requisite variety to engage complexity

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Abstract

Infrastructure systems must change to match the growing complexity of the environments they operate in. Yet the models of governance and the core technologies they rely on are structured around models of relative long-term stability that appear increasingly insufficient and even problematic. As the environments in which infrastructure function become more complex, infrastructure systems must adapt to develop a repertoire of responses sufficient to respond to the increasing variety of conditions and challenges. Whereas in the past infrastructure leadership and system design has emphasized organization strategies that primarily focus on exploitation (e.g., efficiency and production, amenable to conditions of stability), in the future they must create space for exploration, the innovation of what the organization is and does. They will need to create the abilities to maintain themselves in the face of growing complexity by creating the knowledge, processes, and technologies necessary to engage environment complexity. We refer to this capacity as *infrastructure autopoiesis*. In doing so infrastructure organizations should focus on four key tenets. First, a shift to sustained adaptation—perpetual change in the face of destabilizing conditions often marked by uncertainty—and away from rigid processes and technologies is necessary. Second, infrastructure organizations should pursue restructuring their bureaucracies to distribute more resources and decisionmaking capacity horizontally, across the organization's hierarchy. Third, they should build capacity for horizon scanning, the process of systematically searching the environment for opportunities and threats. Fourth, they should emphasize loose fit design, the flexibility of assets to pivot function as the environment changes. The inability to engage with complexity can be expected to result in a decoupling between what our infrastructure systems can do and what we need them to do, and autopoietic capabilities may help close this gap by creating the conditions for a sufficient repertoire to emerge.

1. Introduction

The external conditions in which our infrastructure need to function are changing rapidly. Acceleration of climate change (IPCC 2014), acceleration of the integration of cybertechnologies (and with that security concerns) (Chester and Allenby 2020a), hyperpolarization that routinely stifles innovative reform (Pildes 2011), distributed control (with third parties increasingly driving service consumption, e.g., phone navigation software and smart home energy technologies) (Poska *et al* 2021), shifting priorities (e.g., pushes to increase renewables) (The Economist 2021), and new competition (Amazon drone delivery as infrastructure) (Lohn 2017), to name a few, represent dramatic shifts in the environments in which legacy infrastructure need to remain viable. We use the term environment in the broadest of senses including technological, political, social, cultural in addition to environmental change. Modernizing infrastructure for any one of these challenges is difficult enough but tackling all at once is necessary and represents accelerating complexity for infrastructure managers and a new Frontier of tools. Infrastructure have been designed for variability across

some of these external conditions, but (1) are these conditions now or soon going to exceed what the systems are able to respond to, and (2) are infrastructure being adapted too slowly relative to changes in external conditions? If the answer to either question is *yes* then we must recognize that there is an infrastructure viability problem.
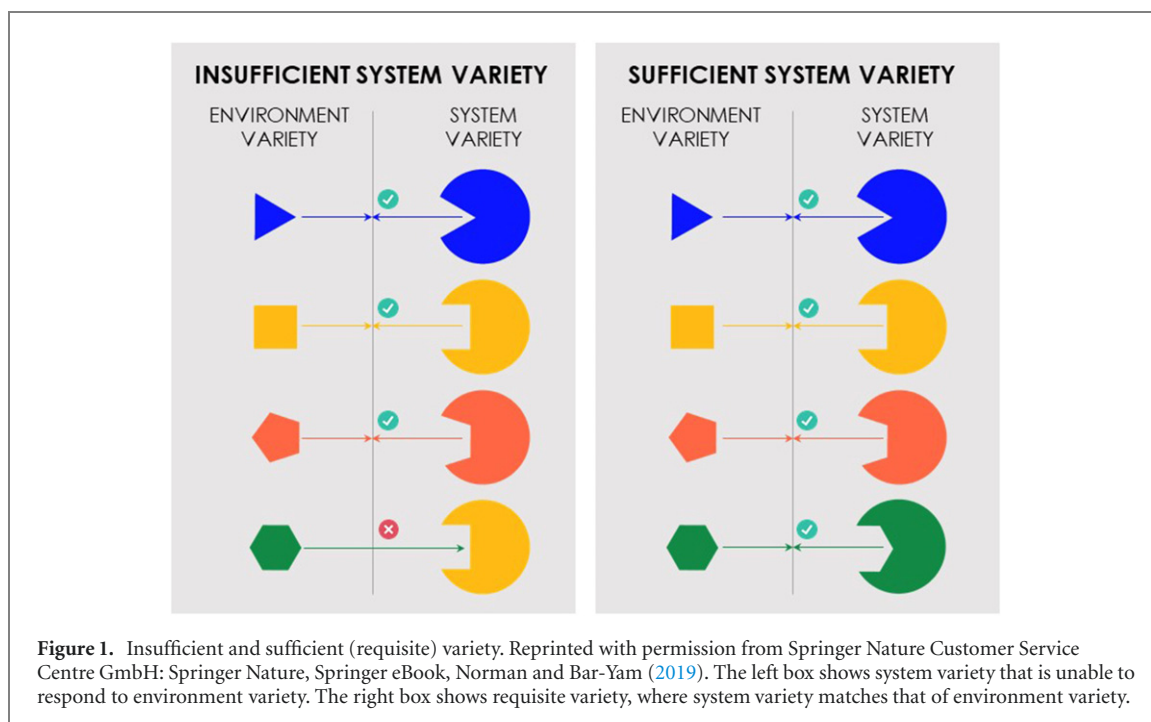
As the scale and scope of human activities have grown, the boundaries between human, built, and natural systems are becoming porous (Allenby 2007, Zalasiewicz *et al* 2011, Allenby 2012, Steffen *et al* 2016, Waters *et al* 2016). Whereas in the past human systems on smaller scales had clearer bounds, the challenges that have emerged with the Anthropocene appear to be unbounded (Allenby 2012). Climate change, for example, is an integration of human, technological, social, cultural, economic, and natural system dynamics, and any mitigation or adaptation strategy must embrace this complexity (Hetherington 2018, Miller *et al* 2018). Infrastructure—design spaces where humans provide basic, lifeline, and critical services through governance structures, physical assets, and mental models informed by educational practices—appear to be at a critical juncture. Serious questions are emerging around what infrastructure are and should do in the future (Allenby 2007, Edwards 2017, Hetherington 2018, Chester and Allenby 2021). This is driven in part by the accelerating capabilities and increasingly global scope of human activities (Steffen *et al* 2015, Steffen *et al* 2016). Infrastructure are generally framed from a local context—city or regional engineered systems that deliver and support services such as water, power, and mobility, in tightly bounded (geography, financing, goals, interdependencies) spaces. But these design spaces (infrastructure) appear increasingly unbounded. For example, carbon capture and storage technologies treat the atmosphere as a managed space, public service and private business operations increasingly rely on data streams hosted and managed by technology firms and warehouses, water provision in the Western US includes the management of continental hydrology, and space (as used by GPS systems) are critical infrastructure for all transportation and routing activities. This deepening integration represents new challenges when contextualized in rapidly changing environments.

Infrastructure adaptation has emerged as a set of responses to rapidly changing environments. Adaptation appears to be heavily rooted in climate preparedness efforts, and for infrastructure conventional risk-based strategies including rebound and robustness are still emphasized (Bassett and Fogelman 2013, Woods and Hollnagel 2017) and strategies such as safe-to-fail, design-making under deep uncertainty, and social-ecological-technological capacity planning are just emerging (Kim *et al* 2019, Helmrich and Chester 2020, McPhearson *et al* 2021). There appears to be a disconnect in infrastructure planning between adaptation strategies and the fundamental capabilities of infrastructure organizers (Chester *et al* 2020a). Adaptation is a set of actions that are predicated on the organization being able to make sense of changing environments (Miller and Muñoz-Erickson 2018). Making sense of the changing environments requires that the organization be willing to engage with complexity and produce a repertoire of responses commensurate to the complexity it faces (Ashby 1956, Boisot and McKelvey 2011, Naughton 2017).

Here, we frame the challenges of modernizing infrastructure in the face of growing complexity as a set of processes that can make sense of and appropriately react to the increasing variety produced in the environment. We contend that infrastructure agility and flexibility fundamentally stem from how the organization and its technologies respond to increasing variety. In establishing this context we draw from the cybernetics, biology, and ecology fields where considerable theory has been developed to describe how systems react to change. We start by establishing the concept of internal–external variety as it relates to infrastructure, as well as how organizations structure themselves to respond to external variety, both sufficiently and insufficiently. Leveraging this theory, we then describe how infrastructure systems should change to be able to respond to increasing complexity in the Anthropocene. Our goal is to help reframe how infrastructure organizations plan for adaptation in the face of unfamiliar Anthropocene conditions. In doing so we position key tenets (sustained adaptation, horizon scanning, horizontal governance, and loose fit design) that infrastructure should advance to engage with complexity. We use the term *infrastructure* as an uncountable (or mass) noun, i.e., as plural.

2. Only variety can absorb variety

To engage with complexity, infrastructure systems will need to understand the processes by which their organizations make sense of changing environments, and how the organization supports or hinders novel ways of sensemaking (i.e., knowledge generation about the system itself and the environment) and service delivery. 'If a system is to be able to deal successfully with the diversity of challenges that its environment produces, then it needs to have a repertoire of responses which is (at least) as nuanced as the problems thrown up by the environment' (Naughton 2017). Variety is not simply change, but the number of states that a system or its environment can achieve (Ashby 1956). This concept is referred to as the law of requisite variety (illustrated in figure 1), and is a valuable starting point when considering whether systems are able to respond to external pressures. How engineered infrastructure respond to external pressures deserves critical examination.

Figure 1. Insufficient and sufficient (requisite) variety. Reprinted with permission from Springer Nature Customer Service Centre GmbH: Springer Nature, Springer eBook, Norman and Bar-Yam (2019). The left box shows system variety that is unable to respond to environment variety. The right box shows requisite variety, where system variety matches that of environment variety.

Infrastructure have been designed with governing principles and bureaucratic processes that emphasize particular bounds around sensemaking. Infrastructure are a product of the historical context inside which they were structured, and the operating goals rooted in that context. This includes the historical normalized goals, cultures, and preferences (Joerges 1988, Sovacool *et al* 2018), as well as perception of the environment (Chester *et al* 2020a, 2020b). When an infrastructure system was created (such as a transportation or water agency) these goals and perceptions became institutionalized and the technologies to support the service became the backbones of system functionality. We are today reconciling how to modernize infrastructure, at the nexus of past norms and future uncertainty. When environment variety outpaces that of the infrastructure system itself, it's not simply that internal variety must be increased, but more so that the appropriate variety must be generated at least as fast as the environment is changing. It's not about explicitly designing internal system variety, as that implies a state of certainty that we don't have with increasing complexity. Instead, we must position infrastructure systems with the agility and flexibility to organically respond at pace. We refer to this as *infrastructure autopoiesis* which we will elaborate on.

2.1. Infrastructure sensemaking processes

The organizations that manage infrastructure are designed to amplify and attenuate particular types of information, and receive conditioned information. This process drives how infrastructure systems make sense of complexity and their ability to respond, and in many situations remains affected by historical goals. An organization engages with environment complexity by managing how and what types of information flow between decisionmakers (Beer 1979, 1981, 1985). Consider that infrastructure management (as management and operations) must interact not only with the physical infrastructure but also governance systems and environments consisting of natural systems and non-governmental human systems (figure 2). Management is not designed to make sense of Environment and Infrastructure complexity (Chester *et al* 2020a); if it did it would be overwhelmed (Beer 1985). As such, it relies on its operational capabilities, which have been explicitly designed to interact with these systems. Operations make sense of demand, changing conditions in weather and climate, resource availability, and other conditions. Decisions must be made in a timely manner and with limited resources, so operations are designed to attenuate environment and infrastructure information to only what is perceived to be needed (reducing away the complexity). Operational processes will also amplify the effects of management, for example, channelizing rivers to control variability, encouraging particular behaviors, or creating increasingly sophisticated systems in response to perceived needs. A similar set of interactions occur between management and operational processes. Management requires attenuated information from operations to make decisions. If operators updated management with every subtask, activity, and day-to-day goings-on management would be overwhelmed. Note that by the time information about the environment reaches management it is attenuated twice. Management sends effector signals to operations amplifying how it thinks the organization should respond to environmental conditions. In doing so management amplifies what it perceives operations must know and eliminates what it perceives to be irrelevant. Human governance

Figure 2. Infrastructure management requisite variety to engage complexity. Variety attenuation is when high variety is cut down to the number of states the receiving entity can handle. Variety amplification is when low variety is enhanced to the number of states that the receiving entity needs. The S (social), E (ecological), and T (technological/infrastructure) labels describe the major systems represented in the SETS framework. The figure is detailed from the perspective of infrastructure management (Markolf *et al* 2018, McPhearson *et al* 2021). Inspired by the concepts described in Beer (1985).

systems are also relevant as they add complexity creating goals, systems, and rule sets, but will receive attenuated information in terms of what the infrastructure system is doing. The relationship between governance and the environment is co-evolutionary (red dotted line), i.e., they are interdependent and change in response to each other.

The relationships are critical to understanding how infrastructure organizations understand and respond to complexity. Environment and infrastructure complexity are intentionally reduced by operations, and in the long run may be especially problematic, as changing conditions may result in obsolete practices by the organization (Beer 1985, Hayward 2004). However, as management tries to reintroduce complexity, first to operations and then in how operations respond to the environment, it may find that its low complexity response is insufficient for the high complexity of the environment (Beer 1985, Hayward 2004). This process is by design and includes rules and norms that were intentionally created based on goals that may reflect legacy priorities. They reflect an organization's mental model of how the environment, and the organization's interactions with it, work.

2.2. Requisite complexity

Recognizing that organizations can try to manage or reduce external complexity with commensurate internal complexity, Boisot and McKelvey (2011) advance Ashby's work as the law of requisite complexity. In doing so they argue that organizations can invest in adaptation in one of two ways: (1) simplify the complexity of incoming stimuli to economize on the resources needed to respond; or, (2) invest extra resources beyond what is deemed necessary to ensure some degree of adaptation. The two options are effectively efficiency versus resilience prioritization, exploitation and exploration (Papachroni *et al* 2016, Allenby and Chester 2020). In the first, organizations run the risk of oversimplifying, reducing external complexity by miscategorizing unfamiliar signals as fitting known patterns. With the second, two risks emerge. The first is associated with expending unnecessarily on complex responses before adaptation occurs (Boisot and McKelvey 2011). There is also, however, the risk of applying outdated assumptions to a changing environment. It's important to recognize that the operational space was engineered from how we perceived complexity in the external system relative to its actual complexity (i.e., organizational mental model). If we perceive the complexity of the external system to change then the organization must change how it invests in adaptation. The requisite perception is in fact a creative interaction between institutional cognition and the external, unknowable (because of complexity) environment. Organizations construct a mental model of their reality (i.e., how the environment works and they interact with it) through a dialogue between what they desire (as possibly mandated by their mission),

Figure 3. The Ashby space. Adapted with permission from Boisot and McKelvey (2011).
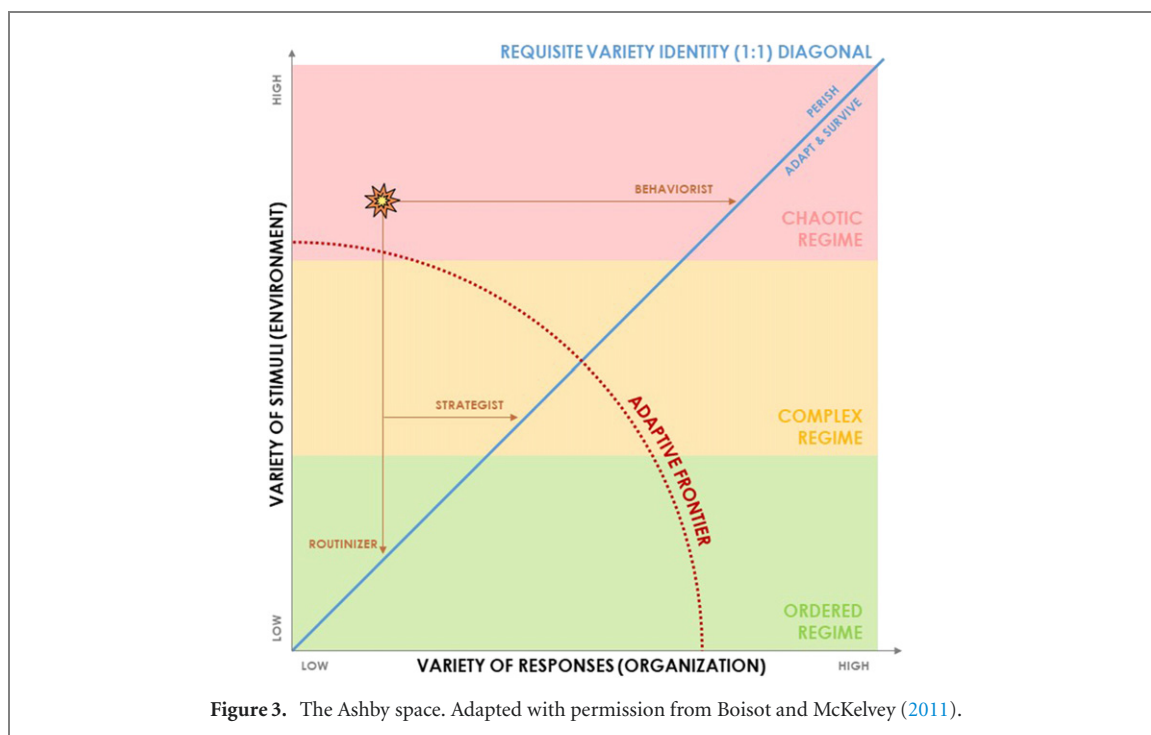
and how they perceive their environment. As such adaptation necessitates mental model shifts, an internal renegotiation by the organization of how it perceives the environment.

Exploring complexity within the context of environment variety relative to internal variety is helpful for understanding response strategies. Figure 3 is the Ashby space (Boisot and McKelvey 2011), where the *x*-axis represents the variety of system responses and the *y*-axis variety of environmental stimuli. The identity (1:1) diagonal delineates between two critical regimes: above being *perish* where the system is producing more variety than the organization can respond to, and below being *adaptive* where the system is being overwhelmed by environment variety. The chart is separated into three regimes: ordered, complex, and chaotic (Gell-Mann 2002 p). In the ordered regime stimuli are relatively unproblematic. In the Cynefin complexity framework, the ordered regime would map to simple and complicated systems, where emergent behaviors are predictable (Snowden and Boone 2007, Chester and Allenby 2019, Helmrich and Chester 2020). In the complex, there is a mix of predictable and unpredictable stimuli, where initiating events, accidents, and non-linear phenomena are obscured by noise. In the chaotic regime extracting useful information appears intractable both because the information and situation are chaotic, making anticipation and prediction impossible. Here operators must either wait for the situation to fully unfold or proceed by trial-and-error. In figure 3 the red dotted line indicates the adaptive Frontier (or budget)—outside of this curve, the organization does not have the resources or capacity to process external environment input and to make appropriate responses. The ontology is helpful when considering how organizations respond to environmental stimuli, the act of trying to manage the organization toward a response capability (i.e., the requisite variety diagonal). If the organization interprets the stimuli as ordered (low variety stimuli) it will follow a path that emphasizes routine responses associated with stable conditions. The organization's adaptive success will depend on whether the routine tools and processes used during stable times are sufficient for the phenomena. If the organization interprets the stimuli as chaotic (high variety stimuli) and tries to match the response with capabilities that don't exist, the organization will exceed its adaptation budget and collapse. The third approach (strategist) becomes critical as it recognizes that trial-and-error is needed in adaptation. Here, the organization interprets the stimuli and attempts to find patterns (moving down the *y*-axis), reducing both the range and variety of stimuli (Boisot and McKelvey 2011). Where no patterns are found the organization develops new patterns (moving to the right along the *x*-axis), all while staying within the adaptation budget. Some stimuli will appear ordered and others chaotic, and the better the organization is at discerning between the two the greater chance it has at staying within its adaptation budget. This is because the organization can economize on tackling the ordered challenges and saving limited resources for trial-and-erroring their understanding and response to the chaotic stimuli.

Codes, regulations, financing, organizational culture, and priorities define the rules and norms that underpin the mental models that infrastructure organizations follow, effectively informal governance. When should organizations challenge these assumption sets to shift their mental models of how the environment works and how their systems need to change to remain viable? The Ashby space and law of requisite complexity provides

Figure 4. Adaptive Frontier. Adapted with permission from Boisot and McKelvey (2011).
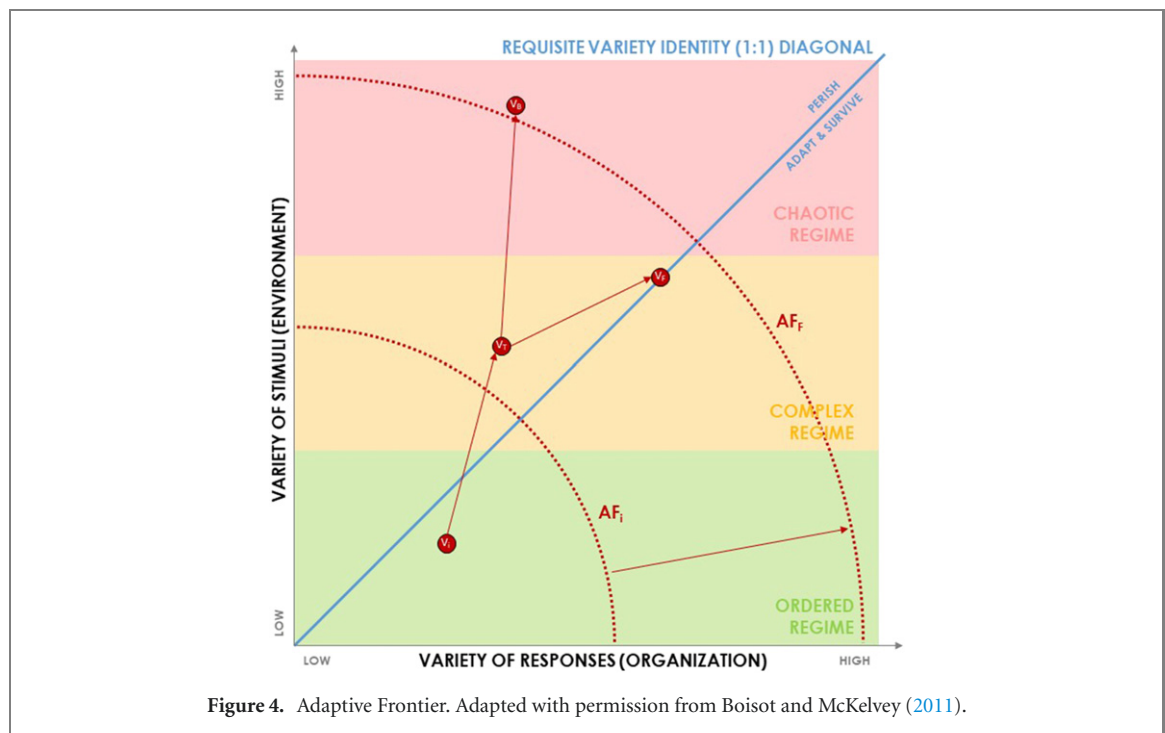
helpful framing. At their inception infrastructure systems may have had a variety of responses greater than that of their environment, as represented in figure 4 as V_i. Today, environmental stimuli have increased significantly, and while our response repertoire has not increased commensurate with changing external conditions (V_T). We find ourselves in the perish space where there is a decoupling between what infrastructure can do and what we need them to do. Infrastructure systems are now outside of their initial adaptive Frontier (AF$_i$) and in a complex regime. Adaptation to greater environment complexity should not necessarily be met by attempting to make sense of increasing stimuli within existing assumption sets and adaptation budgets, but to instead creatively muddle through by moving up the vertical and horizontal axes (V_F) while pushing out the adaptive Frontier (AF$_F$). This is effectively questioning and redefining assumption sets to build new institutional capabilities that give space for adaptation (AF$_F$) and an appropriate repertoire.

In the Anthropocene, the dichotomy between infrastructure and the environment appears to be shrinking (Chester *et al* 2019), and as such changes to infrastructure to increase adaptive capacity should be expected to trigger changes in the environment. This in turn demands new capabilities from the infrastructure. As such variety is subject to both infrastructure and environmental co-adaptation over time, a feedback loop that necessitates a process of sustained adaptation.

Infrastructure systems must effectively engage complexity and this will require a restructuring of how they make sense of changing conditions, provide space for the systems to adapt, and restructure their mental models. We call this process *infrastructure autopoiesis*: the ability of infrastructure systems to maintain themselves in the face of growing complexity by creating the knowledge, processes, and technologies necessary to engage environment complexity.

3. Engaging complexity

We contend that to meaningfully engage with the growing complexity of the Anthropocene infrastructure systems need to (1) have a sufficient repertoire to respond to growing environment variety, and that (2) necessitates restructuring how organizations generate knowledge and make sense of change. In doing so infrastructure systems will need to adopt autopoietic capabilities, i.e., the ability to self-maintain through restructuring in changing environments. These capabilities will need to be primarily rooted in how the organization generates and acts on knowledge.

We must rethink infrastructure systems as knowledge enterprises with the capabilities necessary to constantly assess change, test paths forward, and restructure leadership, education, and technologies in response to change. In doing so we must first recognize that non-competitive environments, while necessary for public service, create disincentives for engaging with complexity.

Infrastructure systems, particularly those aligned with public services, are predicated on conditions associated with non-competitive environments. A city's water utility does not need to concern itself with the prices

of competitors or being pushed out of the market by alternatives. The non-competitive environment emerges from regulation and legislation where providers of lifeline infrastructure services are established to provide services that deliver positive externalities, and where determining a fair price is infeasible as no market mechanism exists to determine an individual's willingness to pay (UK Institute for Government 2015). We argue that this non-competitive environment in which infrastructure as natural monopolies are designed, operated, and governed drives much of our system's rigidity. Without concern that the infrastructure as an organization will fail (e.g., the public cannot do without water), public agencies have fewer incentives to assess their organization's viability into the future. This perspective appears increasingly problematic in a rapidly changing environment, where the conditions of survivability are rapidly changing and the rapid integration of cyber-technologies into legacy infrastructure is creating opportunities for new players to control some aspects of how public services are produced, managed, and consumed.

3.1. Infrastructure autopoiesis

In the Anthropocene, infrastructure systems will need to be able to make sense of change and restructure to respond. Autopoiesis is generally discussed in the context of natural or biological systems where competition and survivability are contingent on adaptive traits in response to changing conditions (Muturana and Varela 1980). Infrastructure as a process of transforming, e.g., water supply or energy sources into potable water and electricity, is *allopoietic* in that the system produces something other than itself. But when governance as knowledge processes is introduced into the infrastructure as a system then we contend that autopoiesis becomes possible. In the Anthropocene, infrastructure must be primarily thought of as knowledge enterprises, and secondarily amalgamations of hardware (Chester *et al* 2020a). Sensemaking is an organizational process that underlies infrastructure cognition, the ability to acquire knowledge about changing conditions, what your systems are and can do, and how to pivot in response to change (Miller and Muñoz-Erickson 2018).

Infrastructure autopoietic capabilities should be in support of closing the gap between the complexity of the environment and the complexity of the organization's repertoire (*adaptive tension*) (Maguire and McKelvey 1999). At the *edge of chaos*—the boundary between order and disorder in a system—organizations tend to emphasize creativity, agility, flexibility, and innovation (Packard 1988, Langton 1997, Levy 2000, Porter 2006, Lambert 2020). This is because to avoid chaos organizational sub-systems must accelerate interactions and restructuring (akin to *near-decomposability*, discussed later). Infrastructure systems appear to exhibit structures and interactions that assume long-term stability and are poorly suited for increasing complexity (Chester *et al* 2020a). The threat of and flirtation with chaos produces self-organizing criticality (Bak 1996), organizations that are able to reflect on how change is occurring and what they need to do to remain viable.
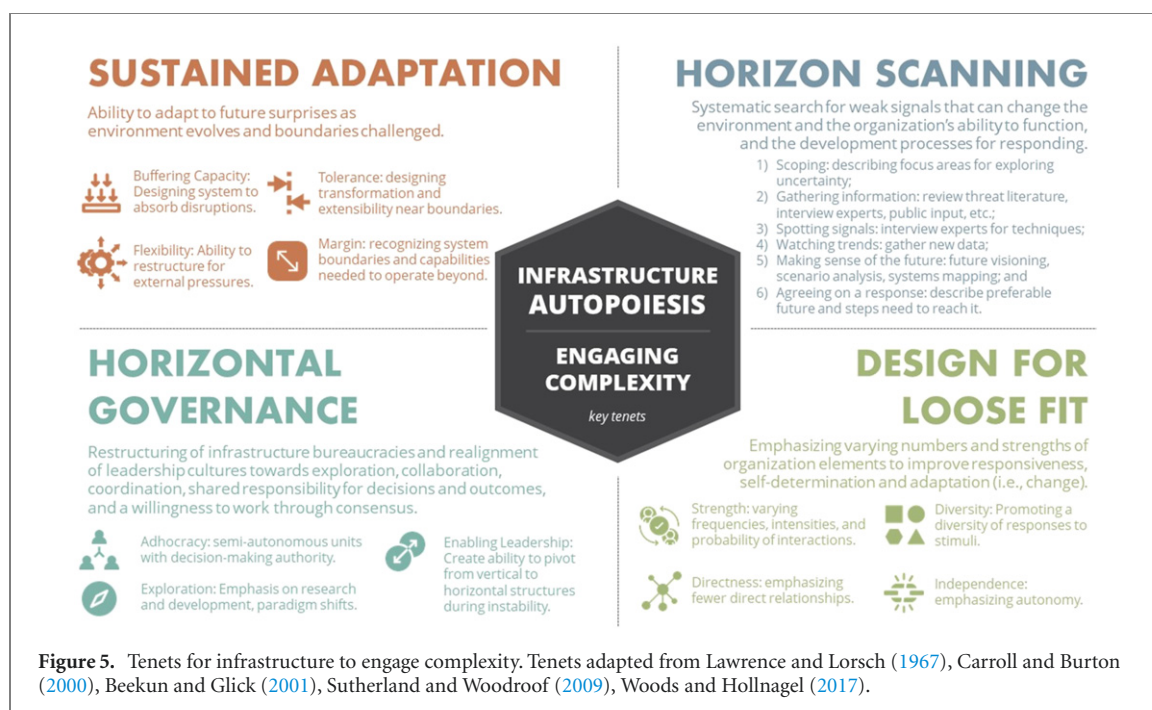
3.2. Agility and flexibility as engaging complexity

We contend that agility and flexibility are the capabilities of infrastructure systems to adapt and transform by operating at the edge of chaos where they negotiate between exploitative (efficiency) and explorative (resilience) activities to generate an internal repertoire that can respond to changing external complexity. In the past, we've framed agile and flexible infrastructure based on characteristics seen in other industries that have shown a propensity to adapt. These characteristics included technical (compatibility, connectivity, modularity, software-for-hardware substitution), governance (roadmapping, design for obsolescence, organic cultures that emphasize change), and education (transdisciplinary) dimensions (Chester and Allenby 2018). We've described how these characteristics support sensemaking, the ability of infrastructure systems to recognize and keep pace with change (Chester and Allenby 2020a, 2020b). We argue here that these characteristics fundamentally describe capabilities associated with sensemaking and generating an internal repertoire to adapt; they are an output of an infrastructure system generating complexity. Going forward we discuss what it means for infrastructure to operate at the edge of chaos, in self-organized criticality where the tension between exploitation and exploration of resources is navigated. To do so we frame four tenets that appear frequently in the Complexity literature (Coyote and Thompson 1967, Lawrence and Lorsch 1967, Weick 1976, Galbraith and Galbraith 1977, Mintzberg 1979, Henderson and Clark 1990, March 1991, Carroll and Burton 2000, Lichtenstein *et al* 2007, Sutherland and Woodroof 2009, Garud *et al* 2011, Woods and Hollnagel 2017). Each of these tenets is described in detail including examples from infrastructure, and figure 5 provides an overview.

3.3. Tenet 1: sustained adaptation

Sustained adaptation describes an organization's commitment to change in the face of destabilizing conditions often marked by uncertainty (Woods 2015), and should become a guiding principle for engaging complexity. Infrastructure as governance and technologies are obdurate, with momentum that carries them along established lines of development (Hughes and Hughes 1983, Sovacool *et al* 2018). This path-dependency results from organizational structures that emphasize efficiency over innovation, commitments to technologies with long lifetimes, assumptions of relatively stable operating conditions, and financial and regulatory processes

Figure 5. Tenets for infrastructure to engage complexity. Tenets adapted from Lawrence and Lorsch (1967), Carroll and Burton (2000), Beekun and Glick (2001), Sutherland and Woodroof (2009), Woods and Hollnagel (2017).

that were structured for past goals (Arthur 1989, Payo *et al* 2016). Massive contingencies are required to disrupt momentum (Hughes and Hughes 1983, Sovacool *et al* 2018). On the contrary, sustained adaptation recognizes that over the life cycle boundary conditions will be challenged, conditions and contexts of use will change, adaptation efforts will at times fall short requiring innovation, and systems will need to stretch when their boundary conditions are exceeded (extensibility) (Woods 2015). The notion that today's infrastructure (a product of legacy technologies and goals) will evolve when needed and will continue to remain viable, without transformative leadership, is foolhardy at best. Instead, we should create the conditions for sustained adaptation to establish as a unifying perspective.

Sustained adaptation will require making space for innovation, and allowing infrastructure governance to renegotiate roles in what the systems do and how they interact with nonincumbent (disruptive) services. It will require a commitment to scanning, asking *what if?*, but most importantly creating the conditions for the organization to shift form and goals. This will require pivoting infrastructure from processes that emphasize reduction of complexity to those that produce a repertoire (variety) to engage with it. Organizations struggle to engage with complexity for several reasons (Garud *et al* 2011). Institutional practices can lock people into 'thought worlds' by reducing or governing their interactions and dampening creative dialogues (Dougherty 1992, Kanigel 2005), emphasize short-term performance metrics at the expense of nurturing long-term ideas, or have cultures that do not benefit from innovative experiences (Tushman and O'Reilly 1996). Sustained adaptation will require negotiating tensions between innovation and process that attenuate complexity.

Infrastructure leadership for engaging complexity should take the perspective of investing in processes that generate novelty. Early organizational complexity leadership focused on generating innovation during periods of stability (Cyert and March 1992) or developing innovation in separate organizational units (Tushman and Nadler 1978, Tushman and O'Reilly 1996, Benner and Tushman 2003). These approaches have since been deemed insufficient for environments of constant change where innovation needs to happen continually for organizational survival (Garud *et al* 2011). They require organizations to reorient frequently at heavy cost, strain management attention, and as new stakeholders and needs are formed produce a divergence between the change the organization perceives and what is actually happening in the environment (Henderson and Clark 1990). Instead, organizations should seek to invest in reaching critical thresholds where change must occur, by investing in dynamic activities and teams as well and their connections (Lichtenstein *et al* 2007). In doing so the 'scaffolding' for innovation is created, and when the organization confronts change its requisite variety is more equipped to match that of the environment. Investments in interactions across the workforce and possibly broader stakeholders are critical, and the rules that govern those interactions should be flexible (Drazin and Sandelands 1992, Axelrod and Cohen 2008). The rules that govern interactions should provide space for improvisation and spontaneity (Stacey 2003). Fundamentally, infrastructure organizations should engage complexity not as something to be analyzed but instead as an unfolding practice that warrants continual investment (Garud *et al* 2011). This investment will require leadership change.

3.4. Tenet 2: horizontal governance

Sustained adaptation will require the restructuring of infrastructure bureaucracies and the realignment of leadership cultures. Research and development should become central to what infrastructure agencies do, and it should focus not just on normal science (research within current thought paradigms), but on paradigm shifts. Infrastructure agencies should recognize that their legacy roles as natural monopolies are being disrupted and that control of how services are delivered and consumed is rapidly becoming distributed (e.g., solar panels and home batteries, sharing economy services, smart thermostats, big-tech cloud-based navigation), resulting in mismatches between what the organization does and the routines it uses (Henderson and Clark 1990, Helmrich *et al* 2021). Instead of full control, infrastructure agencies should begin restructuring themselves as coordinators of multiple players affecting services and driving appropriate change.

Infrastructure are typically structured as divisional bureaucracies with an emphasis on vertical management (up and down layers of the hierarchy) and control, where expertise is siloed and the organization emphasizes efficiency (exploitation) as assessed by measurable performance goals (Chester *et al* 2020a). This rigid structure makes shifting what the organization does challenging (Mintzberg 1979) and adaptation to disruptive change difficult. To manage in the face of complexity *near-decomposability* of organizational units becomes critical. The theory of near-decomposability describes how when systems are perturbed, the smallest sub-units in a hierarchy, if given independence, tend to evolve faster and find stable solutions (Simon 2002). We argue that in the pervasive models that dominate infrastructure bureaucracies today, subunits (e.g., sub-divisions) are not decomposable as they're heavily controlled by management (Chester *et al* 2020a). This top-down control limits the ability of the organization to restructure as chaos ensues by retarding the speed at which the organization needs to respond to a fast-changing environment.

Infrastructure organizations should focus on providing flexibility for self-organization. They should restructure bureaucracies and leadership toward a horizontal governance model where teams coalesce around tasks instead of divisional focus, and autonomy is given to the teams with appropriate resources to scan, test, and make decisions. This requires a pivot from the conventional divisional bureaucracy to an adhocracy where differentiation is encouraged (Mintzberg 1979, Carroll and Burton 2000, Chester *et al* 2020a). Instead of leadership focused on trying to make sense of changing conditions, they should instead focus on providing the integrative pieces for teams (Coyote and Thompson 1967, Galbraith and Galbraith, 1977, Gresov 1989). The separating out of activities means that the organization as a whole is better capable of responding to specific challenges in the environment (Lawrence and Lorsch 1967). In an adhocracy, teams 'comprised of modular units that are partially connected to each other avoid the trap of too much standardization (which creates obstacles to change) and too little coordination (which results in chaos)' (Perrow 1984, Brown and Eisenhardt 1998, Carroll and Burton 2000). The self-organization is loose-coupling (semi-autonomy) that prevents the organization from overreacting to environmental change while increasing the capability of the organization to appropriately and timely react to change (Weick 1976).

Comprehensive reorganization is likely a longer term proposition and in the short term, infrastructure organizations can consider structural ambidexterity, a separate structure within an organization committed to exploration (Raisch and Birkinshaw 2008). The 'skunkworks' satellite structure involves an autonomous sub-division tasked with innovating beyond what the mainstream organization is capable of (Donada *et al* 2021).

US agencies have operated with horizontal governance models, a result of a mandated need for innovation. Examples of public infrastructure agencies operating with horizontal governance models were not identified, likely due to political accountability best served in vertical governance models, and that the divisional bureaucratic form that dominates infrastructure agencies was purposefully adopted from the railroads (Chester *et al* 2020a). Created in 1958, the Defense Advanced Research Projects Agency's (DARPA) goal is to conduct revolutionary and high-payoff research with no specific operational mission. To privilege action and exploration over positional authority, DARPA is structured in a horizontal governance model (specifically, an adhocracy), where transient teams and mobile individuals are brought together to assess US security holes, later to be disbanded so that new teams can form around different challenges (Nieto-Gómez 2011). DARPA accomplishments include major contributes to stealth technologies, the internet, GPS, and unmanned aerial vehicles.

3.5. Tenet 3: horizon scanning

Infrastructure organizations must restructure how they make sense of information about the environment. As previously discussed, infrastructure organizations take in information about the environment attenuating it based on processes and filters designed for normative and generally legacy goals. The attenuated environmental information is analyzed by operations (people and technology) who pass on a further attenuated information stream to managers to make strategic decisions. If the information processing systems used by the organization are not structured for new and changing conditions then they can be expected to miss or misinterpret

critical information about the environment that may affect the viability of the organization. Horizon scanning is the process of systematically searching the environment for opportunities and threats (Sutherland and Woodroof 2009).

Horizon scanning is not simply future thinking; it is the systematic search for weak signals that can change the environment and the organization's ability to function, and the development processes for responding. Infrastructure organizations today are scrambling to respond to climate change and cyberattacks, two destabilizing challenges that have for decades been slowly boiling. Horizon scanning involves: (i) scoping (describing focus areas for exploring uncertainty); (ii) gathering information (review threat literature, interview experts, public input); (iii) spotting signals (interview experts for techniques); (iv) watching trends (gather new data); (v) making sense of the future (future visioning, scenario analysis, systems mapping); and (vi) agreeing on a response (describe preferable future and steps need to reach it) (Sutherland and Woodroof 2009). The goal of horizon scanning is to create plans and strategies that are agile and flexible to a variety of future conditions to aid decision making toward organizational change. It is not simply to pontificate about or to try to predict the future.

A horizon scan developed with the stormwater and wastewater management communities revealed poor preparedness for increasing integration of cybertechnologies into assets and how third parties may increasingly use data from public services (Blumensaat *et al* 2019). Related, a horizon scanning exercise developed for water resources in Russia that identified trends, weak signals, wild cards, and uncertainties identified potential cross-sector demand conflicts and the need for circular economy planning to conserve resources (Saritas and Proskuryakova 2017).

3.6. Tenet 4: design for loose fit

Infrastructure change should embrace loose fit design where assets, processes, and solutions are given the flexibility to work independently or as part of a larger group. Typically, tight fit solutions are deployed for infrastructure where sub-systems have rigidly predetermined functions and interactions with other parts of the system. Put simply, loose fit design enables change, so when the environment or demand changes the asset can pivot to meet the new need. However, underlying loose fit design is the notion of negotiating between exploitation (efficiency) and exploration (innovation) (March 1991).

Creativity flourishes at the edge of chaos because loose fit provides opportunities for exploration, while not being so unstructured as to leak vital information. Infrastructure systems appear to be organized around principles of tightness; they take comfort in the traditional, there is minimal innovation, and they are slow to adjust to changes in their environments. On the contrary, there are industries that constantly innovate as their markets demand so, e.g., Silicon Valley (Pancs 2017). Loose and tight coupling is not simply about innovation, but more fundamentally how connections between sub-systems are structured and function (Weick 1976, Orton and Weick 1990). Infrastructure are coupled systems with *distinct* elements (people, hardware, and software) governed by formal and informal rules that govern the *responsiveness* of elements to each other. Traditionally, infrastructure limit the distinctiveness of elements to pursue standardization; they emphasize tight couplings. Errors of tightness can emerge when organizations constrain their decision making capacity (and as such choice), which can stem from the specialization that comes with being too large. This can produce organizations that are too tight for their technical and strategic contexts (Butler *et al* 1998). Looseness emphasizes both responsiveness and distinctiveness, where elements are given room for self-determination and localized adaptation (Orton and Weick 1990). Looseness is not always preferable. When an organization institutes structures that are too fuzzy then decision making and efficiency can be lost due to power that is too diffuse and nobody with authority to make decisions (Butler *et al* 1998).

Loosely coupled systems are desirable in certain high-risk infrastructure settings. Perrow (1984) describes how loosely coupled organizational decisionmaking processes are more likely to contain sensitive areas should an accident take place. In contrast, tight coupling may make things worse as rigid decisions are more likely to be made despite not having a comprehensive view of the nature of the problem.

Loose fit solutions are needed to respond to growing environment complexity. With increased autonomy, loose fit solutions provide greater sensitivity of elements to sense environment changes. With tight fit solutions elements are more constrained by their organizations or by other elements (interdependencies) and their ability to sense is limited (Weick 1976). The balance between looseness and tightness is driven by Ashby's law of requisite variety; the organization needs sufficient looseness of elements to produce a repertoire that is as large as or exceeds that of the environment.

4. Conclusions

The inability to engage with complexity can be expected to result in a decoupling between what our infrastructure systems can do and what we need them to do, and autopoietic capabilities close this gap by creating

the conditions where a sufficient repertoire can emerge. This decoupling does not necessarily mean a rapid progression to irrelevance. On the contrary, the obdurate and ossified nature of infrastructure technologies and our normative expectations of the institutions that govern them will support their persistence for some time. However, the decoupling will likely create space for innovation by third parties (often driven by advances in connected technologies), and these parties can be expected to exert more and more control over aspects of services, adding complexity to an increasingly complex environment. Instead of trying to hold back these parties (imagine a transportation agency telling Google or Apple that they can no longer navigate traffic through a road network), infrastructure agencies should embrace the increasingly diverse stakeholder environments, and seek to establish their organizations as consensus builders. And infrastructure agencies should restructure toward a model sustained adaptation, with horizontal governance increasingly used as a bureaucratic structure, with horizon scanning that shifts how they make sense of their environment, and around loose fit design. Fundamentally, infrastructure leadership should recognize that changing conditions into the future are likely to represent a new paradigm for the basic and critical services that future generations will rely upon, and rapid innovation is needed to reposition their organizations to thrive.

Acknowledgments

Data availability statement

No new data were created or analysed in this study.

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