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DISCUSSION PAPER



Toward adaptive infrastructure: the Fifth Discipline

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ABSTRACT

Modern infrastructure have been a relatively stable force for decades, ensuring that basic and critical services are met, without significantly changing their core designs or management principles. At the dawn of the Anthropocene it appears that accelerating and increasingly uncertain conditions are poised to result in a paradigm shift for infrastructure, where the environments in which they operate are changing faster than the systems themselves. New approaches are needed in the education, governance, and physical structures that constitute infrastructure systems that can respond in pace. Principles of agility and flexibility appear well suited to help guide how we transform the management and design of infrastructure. In changing how we approach infrastructure we will need to respond to increasingly wicked challenges. Infrastructure must become a Fifth Discipline, focused on learning about the rapidly changing environments and demands in which they operate, and agility and flexibility in both governance and technology reconfiguration.

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1. Introduction

Successful institutions – public or private – adapt to the changing complexity in the environments in which they operate. Adaptability, the capabilities needed to survive and thrive as the environment in which you function changes, has been a topic of study as it relates to human enterprises for decades. It frequently appears as a concept of academic interest in business, management, and computer science (Chakravarthy, 1982; Garlan et al., 2004; Hrebiniak & Joyce, 1985; Ross et al., 2003). However, the infrastructure institutions that manage the technologies and systems that deliver critical and basic services have received remarkably little attention when it comes to adaptability. They are possibly a victim of their own success, in the developed world delivering services with the highest reliability, and have been doing so for decades. At the dawn of the Anthropocene the world appears to be accelerating in many destabilizing ways. The Great Acceleration graphs show changes in key global indicators since 1750, and that since around 1950 there has been an acceleration of human activity and associated impacts. Yet the institutions that manage our infrastructure, including the technological solutions they deploy, remain rigid and obdurate, reflecting the relatively stable conditions of the past. We cannot underestimate how destabilizing these forces are predicted to become. While change has always happened, we appear to be entering an era marked by rapid

acceleration and unpredictability of social, technical, and environmental variables in ways that we as humans have never experienced, and infrastructure are at the center of these trends (Figure 1). Infrastructure are a three-part system consisting of physical assets, institutions for governance, and education, and each is failing to be agile enough given the rapid pace of change.

We are already becoming overwhelmed by the growing complexity that is just beginning to emerge at dawn of the Anthropocene (Allenby, 2012; Senge, 1990; Tainter, 1988). It's important to distinguish between complexity and complicatedness prior to discussing rigidity, agility, and flexibility in the context of adaptation. Here we define complexity as it relates to infrastructure-based primarily on the inability to predict emergent behaviors. Complexity has emerged from the acceleration and growing uncertainty associated with social, technical, and environmental factors, and the combination thereof, and requires fundamentally new approaches to how we deliver services (Arbesman, 2017; Helmrich & Chester, 2020; Snowden & Boone, 2007). Yet infrastructure management remains largely rooted in principles for complicated systems (Chester & Allenby, 2019a). Complexity is about flux and unpredictability, no right answers, and unknown unknowns, thus requiring creative approaches and pattern-based leadership that often test before formalizing solutions. Complicatedness on the other hand is about expert

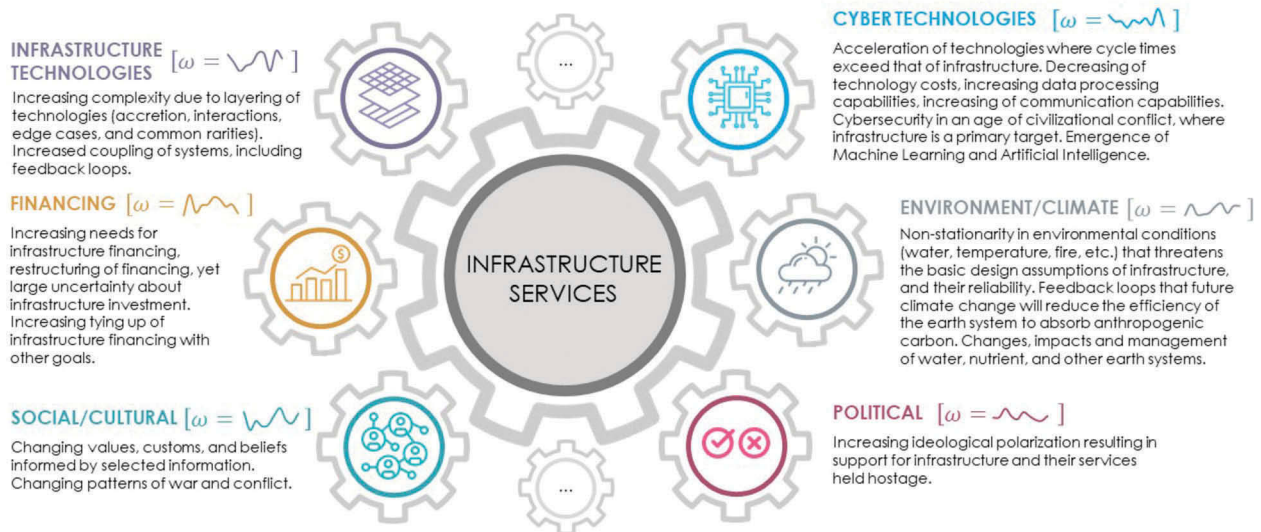


Figure 1. Accelerating, Non-Stationary, and Increasingly Unpredictable Emerging Affecting Infrastructure. Each force is represented as a gear that is moving and affecting the ability to deliver and modernize infrastructure services. These forces are becoming increasingly unpredictable, as represented by different and random rates (ω) by which the gear spins. There are many sources that describe these forces and their trends including (Allenby, 2015; Arbesman, 2017; Friedlingstein et al., 2006; Fukuyama, 2018; Kissinger, 2014; Kurzweil, 2005; Nye, 2011).

diagnosis to assess multiple right answers, known unknowns, and fact-based management that typically emphasizes data collection and analysis to make decisions (Chester & Allenby, 2019a; Snowden & Boone, 2007). Complexity has always existed with human systems in some form, but the rate of change of human activities, technologies, etc., appears to be taking off, resulting in acceleration and scale that is unprecedented (Allenby, 2012; Kurzweil, 2005; Marchant, 2011; Rosenberg & Birdzell, 1986; Syvitski, 2012), and producing a new normal where the predictability of what infrastructure will and should do is diminishing. And new dynamics, such as Asymmetric Warfare that leverages the increasingly cyber connected core systems and lax security, make infrastructure a battlefield in civilizational conflict (Allenby, 2015). We argue that infrastructure and the institutions that manage them must adapt by becoming agile and flexible in response to the changing complexity of the world around them. In doing so they must become a Fifth Discipline, organizations that are focused on learning about the rapidly changing environments and demands in which they must deliver services. The Fifth Discipline concept was developed by Senge (1990) to describe the necessity of organizations to learn in complex environments. The disciplines – 1) continual clarity and deepening is needed to see reality objectively, 2) mental models must be challenged; 3) building shared visions is necessary to foster commitment; 4) team learning requires dialogue; and 5) systems thinking is needed to integrate

the first four – are competencies to make sense of complex environments, precursors to adaptive and transformative capacity.

The design and management of infrastructure continues to emphasize rigidity through well-established models developed over the past century when conditions were much more predictable. We define *rigidity* in the context of infrastructure systems as a highly constrained ability to adapt to changing internal and external conditions. In a functioning infrastructure system, it may arise from physical, institutional, political, or economic factors, including lock-in to other systems that prevent responsive change. It may also arise from an inability to perceive or learn rapidly enough to change appropriately. Rigidity occurs for many reasons including governance models that emphasize predictability in environmental conditions and demand, the use of technologies that hedge risk over long periods under stationarity assumptions, and educational norms that emphasize problem-solving in the complicated domain. As such, infrastructure management emphasizes risk-based models that assume stationarity, do not consider what may happen when the risk management solutions fail, and large and permanent assets that are prone to greater damages when they fail (Kim et al., 2019; Park et al., 2011). This model is in many ways the result of the prevalent form of government that oversees infrastructure, the divisional bureaucracy. This form of infrastructure bureaucracy emerged in the early 1900 s with natural monopolies, first the railroad, and later utilities

(Chandler, 1977; Friedlander, 1995a, 1995b; Friedlander and Initiatives, 1996). It silos functional specialization with multiple layers of management that i) separates strategic visioning from day-to-day operations, and 2) is inimical to interdisciplinary problem solving by creating managerial barriers that work against the exchange of ideas across expertise silos (Chandler, 1977; Edwards, 2003). It was a product of the industrial revolution reflecting the social and technological complexities of the twentieth century. Indeed, the divisional bureaucracy that has managed infrastructure for a century has allowed for some agility and flexibility, but it appears to operate too slow for the accelerating and uncertain change associated with the Anthropocene.

In Chester and Allenby (2019b) we identified the growing challenges associated with the rigid institutional forms and associated technologies that drive our infrastructure today. We explored industries that exhibited agile and flexible characteristics, and synthesized these into a set of competencies that we recommend as useful principles for infrastructure going forward. In Gilrein et al. (2019) we used the competencies to identify real-world examples. The competencies and examples covered both centralized to decentralized, green to gray, and even dumb to smart configurations of infrastructure and technologies. Furthermore, we discussed both technological and institutional competencies. We did not advocate for any particular configuration but instead viewed the challenge of implementing agility and flexibility as one that could deploy any number of approaches.

Saxe and MacAskill (2019) provide a thoughtful response to our work, largely arguing that rigidity in some forms may in itself produce agility and flexibility. Their argument appears to be motivated by an urging of caution that we should not aggressively seek to change infrastructure but instead to look carefully at existing rigid systems that have proven successful. In particular, they argue that 1) rigid infrastructure has provided immense value (we agree) that we can learn from and leverage; 2) planned obsolescence – specifically the shortening of lifetimes of many assets and then continuing their use after their design life – has created a paradigm where many assets are in need of major rehabilitation and are designed for past demand assumptions, and longer lifetimes would obviate some of these challenges; and 3) centralized large-scale infrastructure provide stability, a skeleton that can be built upon and utilized for the long term. We address these counterpoints while expanding our position on the necessity of restructuring infrastructure institutions and the way they deploy technologies at the dawn of the Anthropocene.

We maintain first and foremost that the institutions that manage infrastructure and the technologies they deploy must reflect the rapidly accelerating and uncertain environment in which they operate. As complexity in the world emerges the institutions that operate within it need to change to continue delivering services in those new environments. Infrastructure have for decades, if not centuries, operated in environments that have been relatively stable as compared to today, and the institutions and technologies exemplify this rigidity. Certainly, rigid infrastructure has provided immense value, but this rigidity was able to persist (that is continue delivering services reliably) because the complexity that defined society and technologies was changing at a pace that the infrastructure systems could remain viable. More specifically, changes in demand have for nearly a century been slower than the capacity of the institution to change. As such, the cycle time of infrastructure change and renewal was effectively coupled to the cycle time of change in the external environment. Breakdown in institutional control and effectiveness occurs when the cycle time of the subject matter of the institution exceeds the speed with which the institution can respond (Osinga, 2007). We argue that we are at a point in the acceleration of human systems including technology where infrastructure institutions are going to be unable to keep up to remain viable (both institutionally and in their ability to meet new needs). Similarly, while norms may have shifted to shorter asset lifetimes, and indeed there are benefits to locking in longer lifetime assets, the asset (designed for short or long lifetimes) will only be viable as long as the demands and environment in which it operates remain in a somewhat stable envelope. Evidence mounts that these envelopes are likely to be greatly exceeded, if not become wholly irrelevant into the future (COVID-19 gives us a glimpse into how rigid infrastructure are disrupted when demands change seemingly overnight). Every infrastructure element relies on design constraints and objectives, and many of these are derived from assumptions regarding the state of the external environment within which that infrastructure functions. When those implicit assumptions change, the design becomes obsolete, and sometimes even dysfunctional.

Agility and flexibility differ in their application between physical assets and governance processes. For physical assets they can be met through centralized or decentralized configurations; we imagine future infrastructure having aspects of both. Similarly, we see pathways for increasing agility and flexibility anywhere along the gray to green spectrum, and the physical to cyber spectrum. Indeed, many of the technologies

identified by Gilrein et al. (2019) were decentralized, however, centralized configurations – which we would argue today are often configured towards rigidity – can be managed or designed differently to improve their agility and flexibility. The topic of agility and flexibility in infrastructure governance deserves its own paper; however, we think that they are primarily found in the organizational leadership capabilities needed for both stable and unstable environments, and transitioning between. Infrastructure institutions are structured around *Administrative* leadership for stable conditions (the management of bureaucratic function through the structuring of tasks, planning, vision building, resource acquisition, crises management, and organizational strategy). *Adaptive* leadership describes learning processes (that renegotiates roles, goals, and ideas, sometimes through the clashing of ideas and technologies) while *Enabling* leadership is the ability to shift between Administrative and Adaptive leadership as environments change, and consists of facilitating the movement of information, creating the pressure to act, and providing resources for creativity (Uhl-Bien et al., 2007).

While there are indeed lessons to be learned from cities and infrastructure that have persisted for centuries, we argue that any potential to use these solutions into the future must be rooted in their capacity to address increasing complexity, not simply because evidence suggests they are better than other solutions absent of any consideration of the environment they must function in. Again, we can conceive of pathways where dense urban form that promotes active transport (walking, biking, and transit) and locks in other infrastructure (e.g., power and water) towards agility and flexibility. These pathways must embrace the accelerating climate, technology, and social forces that will drive the viability of infrastructure at the nexus of supply and demand. We urge caution in trying to emulate desirable urban forms that exist elsewhere without consideration of the growing complexity that is the new normal. Simply put, in an era of increasing complexity, we can't only look backwards for answers to what might work for the coming centuries.

Fundamentally, we advocate for changes to infrastructure where the systems (institutions and technologies) respond in pace to the increasing cycle times of technologies and embrace the wicked complexity that increasingly defines the conditions under which infrastructure must deliver services. We view these institutions primarily as knowledge architects for delivering critical services, testing and employing information capabilities and technologies, i.e., Fifth Disciplines (Senge, 1990). These institutions will likely be structured very differently than those that govern our infrastructure

today. They will operate based on new principles that accept uncertainty and rapid change as normal.

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