COMMENTARY

Infrastructure as a wicked complex process

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Changing complexity in the increasingly integrated human, natural, and built systems within which our infrastructures are designed and operated make it necessary to examine how the role of engineering requires new competencies for satisficing. Several long-term trends appear to be shifting our infrastructures further away from the complicated domain where optimization and efficiency were the core approaches, to the domain of complexity, where rapidly changing environments and fragmentation of goals require fundamentally new approaches. While complexity in infrastructure has always existed in some form, making infrastructures agile and flexible for the Anthropocene will require us to acknowledge and work with the fact that infrastructure change now appears to be a wicked and complex process. Wicked complexity is the result of three competing forces that are inimical to rapid and sustained change of infrastructures in a future marked by acceleration and uncertainty: wicked problems, technical complexity including lock-in, and social complexity. The combination of these factors raises serious questions about whether rapidly changing demands, technologies, and perturbations (such as climate change, or cyber attacks) will affect our infrastructure’s capacity to provide services. What infrastructure managers need to do today is very different than in the past. Increased presence and polarization of viewpoints is becoming more common, where solutions are dictated not by technical performance measures but instead by “acceptable enough” to all parties. Adaptive management practices and associated competencies that have proven successful in managing complex socio-ecological systems may provide some guidance for how to manage infrastructure change. These competencies are i) promoting a shared understanding of what infrastructures can do, ii) managing infrastructures as systems with changing demands, iii) emphasizing experimentation over conventional approaches, and, iv) restructuring education and training for a complexity mindset that emphasizes what can be over what is, and relies on satisficing, not optimization.

Keywords: Infrastructure; Wicked complexity; Anthropocene

Introduction

Herbert Simon – a pioneer of decision-making theory – posited that given the vast information that is needed to completely understand how to maximize one’s benefit from a particular course of action, people instead satisfice; they will make a decision “which is good enough, rather than the absolute best” (Simon, 1947, 1957; Brown, 2004; Economist, 2009). Satisficing, a combination of satisfy and suffice, describes the process by which, in situations of wicked complexity where optimization techniques fail, we often settle on a course of action that is good enough and “deals with a drastically simplified model of the confusion that constitutes the real world” (Simon, 1957; Brown, 2004). We use the term optimization to describe traditional engineering decision making approaches that emphasize quantification of performance with a focus on maximizing performance or efficiency while minimizing costs and meeting some desired level of service. Simon initially developed the concept of satisficing at a time when commercial, industrial, and public sector organizations were restructuring post World War II to peacetime services. This concept had profound implications on how we view decision making, not as a process that uses complete and consistent information and preferences but instead as a “rational behavior that is compatible with the access to information and the computational capacities that are actually possessed by organisms” (Simon, 1957). With what appears to be growing complexity in the constraints imposed on how our infrastructures are designed and operated, it’s necessary to examine how the role of engineering is changing. We contend that while satisficing has always been part of the infrastructure process, the roles and responsibilities of infrastructure managers increasingly require satisficing, whereas classic optimization skills are necessary but more and more insufficient.

What our infrastructures will need to do in the coming centuries is likely very different than today. We acknowledge that the term infrastructure can have broad and evolving meanings (Carse, 2017; Clark, Seager and Chester, 2018) but in general refers to the human-made physical
and institutional elements of systems that provide services (including management, governance, finance, and regulation) (Chester and Allenby, 2018). In the Anthropocene, this could include many human systems, so to clarify the implications for the role of engineering, this paper will focus on civil infrastructure systems that, e.g., provide water and energy, facilitate transportation, and provide information and communication capabilities.

Several long-term trends appear to be creating new forms of complexity for our infrastructure systems. First, our ability to change infrastructures at a meaningful pace appears to be constrained. The infrastructures that we rely on today share many of the core design features from when they were initially conceived decades or even a century ago (Chester and Allenby, 2018). Because demand for the core services that infrastructures deliver hasn’t changed for many civil systems, the physical forms that infrastructure take and the institutions that support those forms have been organized and connected with each other over such a long history that shifting to new forms of infrastructure appears a monumental challenge — we describe this effect as lock-in. Second, as the scale and scope of human activities have grown, infrastructures have incorporated more and more of “nature” and the dichotomy between the human built and natural worlds is shrinking, thereby greatly increasing complexity, both technically and culturally (Allenby and Chester, 2018; Chester, Markolf and Allenby, 2019). Third, increasingly rapid changes in technology will more quickly drive our infrastructures to deliver services that they weren’t designed to deliver. This means that we need faster cycle times, yet as per the first trend our infrastructures appear to be increasingly locked-in, slowing down our ability to change them quickly. As the need for more rapid and complex infrastructure upgrades, redesigns, and construction accelerates, lock-in becomes a significant constraint over the long-term. Fourth, because civil infrastructures have persisted for so long there has been significant accretion — i.e. the accumulation, layering, and interconnectedness of technologies, institutions, rules, and policies. Understanding the emergent behavior of infrastructures particularly when perturbed is now challenging if not impossible. Significant change now requires action across many different sub-systems and their governing agencies. For example, modernizing the U.S. power grid requires the coordinated deployment, financing, and permitting of hardware and software across hundreds if not thousands of companies and agencies. The combination of these factors raises serious questions about whether rapidly changing demands, technologies, and perturbations (such as climate change or terrorist attacks) will affect our infrastructures’ capacity to provide services. These concurrent trends demand a shift from optimization to satisficing as the critical engineering competency.

It is now widely recognized that we are at the dawn of the Anthropocene, the era of the human, where rapid environmental, technological, social, political, and even cultural change, increasingly at regional and global scales, are likely to put new demands on our infrastructures. Yet infrastructures remain largely rigid, unable to change quickly (Chester and Allenby, 2018). Making infrastructures agile and flexible for the Anthropocene will require us to acknowledge and work with the fact that infrastructures are now wicked complex systems, and that satisficing has become the new normal for designing and managing these systems. This has profound implications for infrastructure managers who have been trained to assess bounded design problems that can be optimized, rather than wickedly complex problems that must be satisficed. In this commentary we first explore how infrastructures have become wicked complex systems. We then discuss how this wicked complexity has led to a shift in how we design and operate infrastructures, i.e., satisficing, and the challenges this approach introduces when large and fast changes are needed. Lastly, we propose that engineering (including education) needs to embrace the wicked complexity of infrastructures and the increasing satisficing that is needed to affect change.

Infrastructure Design through the Ages
Modern infrastructures are several millennia in the making. From the Neolithic period through the Classical era and the Middle Ages, infrastructure evolved relatively slowly, first with a focus on agriculture and irrigation, to much more complex systems and technologies supporting city systems and long distance transport. However, it wasn’t until the Industrial Era (mid-1700s until roughly the end of the nineteenth century) when infrastructure growth skyrocketed (Syvitski, 2012). In the past century alone, the level of social, cultural, financial, and political complexity has exploded to the point where the rules by which we deploy infrastructures have drastically changed (Rosenberg and Birdzell, 1986; Kurzweil, 2010; Marchant, Allenby and Herkert, 2011; Allenby, 2012).

Cities today are integrative technologies in that they embody the engineering, culture, and infrastructures of their various periods. Cities today reflect the changing authority granted to infrastructure designers and managers. For example, modernization of urban systems, from sanitation to public transit, marked the 18th and 19th centuries, culminating in “high modernism”. High modernism as practiced by planners such as Robert Moses in New York, and Le Corbusier in urban design, was marked by a brutal technocratic elitism which knowingly ignored local context and culture in the interest of implementing “universalist” and “scientific” principles in urban design. As Robert Moses declared, “[w]hen you operate in an overbuilt metropolis, you have to hack your way with a meat ax … I’m just going to keep right on building. You do the best you can to stop it.” (quoted in Berman, 1982). Critics such as Jane Jacobs and Charles Jencks derided high modernism as anti-human and hubristic, and favored “post-modern” city planning and architecture (Jacobs, 1961; Jencks, 1977). And indeed top-down high modernism was replaced by post-modernist bottom-up community activism, seen in such controversies as the defeat of the proposed Greenpoint-Williamsburg waste incinerator in Brooklyn, and the London Docklands proposal, both in the 1990’s (Hall, 1998; Gandy, 2003). The resulting power of activists and communities, while it accords with modern sentiment in many ways, makes many large projects such as the Boston “Big Dig” major political efforts, and
can allow small but vocal minorities to stifle projects and infrastructure that the larger public good or urban community requires. The post-modern political environment of today appears to reflect a significant shift in the roles and responsibilities of engineers, planners, and infrastructure designers. Many of the new social, political, and other roles in which the engineer must now navigate have likely been acquired from others (e.g. elected officials, voters, consumers, business managers, religious leaders, etc.) that abdicated their responsibility for one reason or another. Wicked complexity inherent in the processes associated with these new roles is integral to virtually any significant infrastructure project, a point that today’s engineers – and the professors that teach them – cannot ignore.

Modern infrastructures are thus not a technical problem, they’re a wickedly complex problem. Going forward, we explore this wicked complexity, fully acknowledging that some forms of complexity in infrastructure have existed for ages, but focusing on what is unique about it in the Anthropocene. We first examine what causes wicked complexity and second discuss how conceptualizing the process of infrastructure change as satisficing numerous stakeholders and objectives, and away from simply optimizing a technical solution, is an increasingly important engineering framework, and hence professional skill.

**Wicked Complexity**

The processes by which we design, build, operate, manage, rehabilitate, and decommission infrastructures are a wickedly complex problem. From an engineering sense, infrastructures are often thought of and taught as a physical end product, an agglomeration of specialized technological and built artifacts that provide services. However, as technologies and the demand for services change more and more rapidly, thinking of infrastructures as a physical, cultural, and institutional process providing an ever-changing function becomes important. This means that while an individual piece of physical infrastructure can be optimized for its function within an existing built system, infrastructure design and modernization necessarily becomes wickedly complex. Wicked complexity is the result of three competing forces that are, given the current approaches for designing and managing infrastructures, mimical to rapid and sustained change in a future marked by acceleration and uncertainty. These forces are 1) wicked problems, 2) technical complexity and lock-in, and 3) social complexity, which work together to fragment our capacity to manage change (see Figure 1).

There is a dearth of work characterizing engineered infrastructures as wicked complex systems, but it is becoming more widely accepted that this is the case. The complexity of infrastructures has often been defined

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**Figure 1: Wicked complexity as a product of wicked problems, technical complexity, and social complexity.**

The three forces each and together pull our ability to change infrastructure, resulting in change become a wicked complex process (adapted from Conklin 2006). DOI: https://doi.org/10.1525/elementa.360.f1
in terms of physical structure, or technical complexity (Brown, Beyeler and Barton, 2004; O’Rourke, 2007). Oughton et al., (2018) characterize infrastructure complexity by contrasting the properties of general and complex adaptive systems at the interface of supply and demand. They posit that given emergent behavior and self organization, instability and robustness, dynamics and evolution, adaptiveness, and agent diversity, infrastructures exhibit the key features of complex adaptive systems. Arbesman (2016) describes technical complexity as resulting from several dominant technological forces including accretion (the accumulation and layering of technologies and assets over long periods of time), interaction (the often indeterminate number of components are interacting in ways that we no longer fully comprehend), and edge cases (we sometimes design hardware and processes outside of standard design and operating rules). The combination of these forces, and equally complex social, financial, cultural, technological, and management forces that affect infrastructures at every scale, results in a situation where the emergent behavior, particularly when perturbed, is no longer predictable (Hall et al., 2017). While complexity has certainly been present in infrastructure management since these technologies first emerged, we contend the form of this complexity is fundamentally different. Defining infrastructure complexity in terms of physical structure is still appropriate for many purposes, of course, but rapidly becomes inadequate beyond the artifactual and short term, and especially when planning for new technologies.

There are many complexity definitions, often specific to the field and system or organization being analyzed. The Cynefin framework classifies systems as simple (the domain of best practice), complicated (the domain of experts), complex (the domain of emergence), chaotic (the domain of rapid response), and disorder (Figure 2) (Snowden and Boone, 2007). Knowing whether you’re working in the complicated or complex domain when it comes to infrastructure is critical because each domain requires fundamentally different approaches. The complex domain (the realm of unknown unknowns) is one where the inability to predict emergent behaviors means that we can only understand what happened a posteriori. Emergence (the ability of individual components of a large system to work together to give rise to dramatic and diverse behavior) is often central to characterizing a system as complex (Cilliers, 2002; Martin and Helmerson, 2014). While emergence is often front and center, complexity is determined from a number of characteristics including the number of elements, interactions that are dynamic, rich, non-linear and short range, feedback loops, system openness, non-equilibrium behavior, histories, and (related to emergence) elements which are ignorant of the behavior of the whole system (Cilliers, 2002).

The critical boundary for engineers is between complicated and complex. At this transition, optimization tools become obsolete as social, institutional, political, and economic forces come into play and together render quantitative analyses as the dominant approach for addressing the challenges insufficient. Conklin (2006) describes social complexity as a force of fragmentation that results from the number and diversity of players involved in a project (wickedness is another source of fragmentation in decision making). The more parties involved, the more different the stakeholders are, the greater the diversity of perspective they bring, and the more socially complex a decision making process becomes, thereby making collective intelligence a challenge and consensus virtually impossible to achieve (Conklin, 2006).

The somewhat ambiguous boundary between highly complicated technological artifacts or subsystems (for which optimization techniques are often appropriate) and wicked complexity (where satisficing techniques are necessary) occurs when operational requirements mean that infrastructures cannot simply be defined in terms of physical assets, but must be viewed as a process. Sometimes one

![Figure 2: Cynefin framework applied to infrastructure. For each domain, the approach differs. The Complex domain requires an approach that is capable of testing options and collecting data on how those options perform, and then repeating (framework adapted from Snowden and Boone 2007). DOI: https://doi.org/10.1525/elementa.360.f2](image)
is simply adding a component where the design is significantly constrained by existing function and assets – a tower to an existing urban mobile device network, or a new water feed to a subdivision. But especially as human, natural, and built systems integrate in new ways at virtually all scales, the fundamental goal of infrastructures – not simply to create an amalgamation of hardware, but to provide the resources and services needed to afford people the capabilities that build adaptive capacity and improve human well-being (Clark, Seager and Chester, 2018) – becomes more explicit. At this point, wicked complexity begins to dominate engineering decisions, from design to operation to maintenance to system evolution, and the lens of the engineer must broaden to consider not only the physical structures but also the institutional, cultural, financial, etc. forces that affect infrastructures, both in the immediate environment, and more broadly as the infrastructure process evolves over time.

The pioneering work of Rittel and Webber (1973) provide the foundational criteria for wicked problems that for the most part endures today. Instead of simply reiterating their 10 criteria, we’ll instead describe them in the context of infrastructures:

1) Wicked problems have no definitive problem formulation. Providing services at reasonable costs, given financial constraints, competing stakeholder views, environmental and social implications of various options, and with agility and flexibility to adapt to changing conditions means that no clear formulation can be stated containing all of the information the decision maker needs to choose a single objective solution.

2) There is no stopping rule for infrastructures, they are an evolving process that must constantly be re-examined. A chosen infrastructure solution today is typically the result of a group of decision makers saying it’s good enough, and had there been more time or resources, or different social or political constraints, a different solution may very well have been chosen.

3) Infrastructure solutions are not true-or-false, but better or worse, and each stakeholder may have a different evaluation of what these terms mean given the particular situation. It is usually not the case in these situations that a choice will be regarded as optimal by any party; rather, the best choice may be one that meets the minimal requirements of most stakeholders (in other words, the one that satisfies, rather than optimizes, from their perspective), often the result of a political process that results in compromise.

4) There is no immediate and no ultimate test of an infrastructure solution. The implementation of an infrastructure will lead to direct and indirect consequences over an extended time period.

5) Given the sheer scale and reach of infrastructures, their implementation is often a one-shot operation, particularly for rigid systems (i.e., transportation, water, power, etc.). Often there is no opportunity to learn by trial and error, and every attempt counts significantly. This does not mean, however, that engineers and engineering institutions such as universities and professional organizations should not explicitly embrace continual learning processes, because the effectiveness of a particular one-shot solution may well inform better practices elsewhere. For example, the Big Dig in Boston is a one-shot solution in that it is not significantly modifiable at this point, but the learning from what went well and didn’t, and what performed socially and environmentally in the ways anticipated, can be applied to similar activity in, say, New York City or Toronto or Brazilia. Agile and flexible infrastructures (such as ICT) on the contrary show that they can be experimented with on large scales (e.g., current 5G deployment) (Oughton et al., 2018; Gilrein et al., 2019).

6) There are no criteria by which we can say that all infrastructure solutions to a problem have been identified. As such, judgement dictates whether one should enlarge the set of solutions being considered.

7) Despite having implemented infrastructure solutions in similar forms for centuries, there is almost always a new set of distinguishing features for the next problem that makes it unique. This is especially true because, while purely technological elements of the system may be similar to predecessors, it is seldom the case that the environmental, social, political, and economic dimensions are the same. Rittel and Webber (1973) use a subway system as an example — a design that worked for one city as the template for another is likely disastrous as commuter preferences and urban form may outweigh similarities in subway network structure.

8) Change in infrastructures is often incremental, with the hope that each small step contributes to systematic improvement. However, this can be dysfunctional: tackling the need for change on such a small level can, by avoiding foundational improvement, create even more systemic inertia against fundamental, non-incremental change. Thus, for example, incremental improvement in the U.S. air traffic system has kept an obsolete infrastructure functioning (US-GAO, 2017), but the cost is continuing and growing inefficiency, and a more complex upgrade process when it is finally started.

9) The modes of reasoning for why we pick infrastructure solutions often far outweigh the choices available through scientific discourse. The problems that these solutions are attempting to address are often based on the most powerful decision makers’ world views. When engineers and decision makers are not trained in satisficing techniques, or in recognizing the impact of their own worldviews, decisions are often costly and socially damaging (this was one of the critiques of the high modernists such as Robert Moses).

10) The goal of infrastructures is typically not to find some truth, but instead to improve some characteristic of the world. The problems that infrastructure managers must deal with don’t have boundaries and their causes are often obfuscated.
The challenges associated with affecting change in infrastructures that are wicked and complex are exponentially greater and require fundamentally different approaches than what we’ve historically used. The technical and social forces of complexity combined with the wicked problems that infrastructures are more and more recognized at the center of (including e.g., access to water, affordable housing, safe, efficient, and affordable mobility, public health; see Chester 2019) result in a fragmentation of priorities driven by increasing numbers of stakeholders that render traditional approaches (i.e., approaches that emphasize quantitative analysis and optimization) obsolete. In the Anthropocene it appears that infrastructures are complex adaptive systems that engage wicked complexity on a routine basis. As such agility and flexibility are needed because of unpredictable emergent properties, and wicked complexity adds the need for satisficing.

**Infrastructure Satisficing**

In today’s post-modernist environment, where many conflicting demands must be integrated in infrastructure projects and managed by engineers, designers, and planners, satisficing is the only viable methodology. This can be seen not just in infrastructure, but in the “adaptive management” methods that are now becoming popular for managing “natural” infrastructures such as the Everglades (Berkes, Folke and Colding, 1998; Allenby, 2012; National Research Council, 2018a). The role of the infrastructure planner and designer has shifted from prescribing a professional solution to a given situation, a high modernist framing of the professional’s role, to being the expert facilitator of the emergence of a design that satisfies enough stakeholders, and the legacy systems and natural infrastructure components, to be both stable and viable (Allenby, 2012).

What the infrastructure manager needs to do today is very different than in the past. In many parts of the world, tribalism is the new norm (Chua, 2018; Hawkins et al., 2018), where solutions are dictated not by technical performance measures but instead by “acceptable enough” to all parties. While having multiple contrasting viewpoints may do a better job at bringing more voices to the table, it is inimical to flexibility and agility, the ability to change infrastructure quickly thereby creating adaptive capacity. This is not to say that having community and multi-stakeholder perspectives involved in infrastructure decision making is necessarily a bad thing (this is crucial to ensuring that no party asserts their will over others). Instead, we must recognize that the fragmentation that comes with competing and sometimes polarized viewpoints means that there are competing narratives for what infrastructures should and should not do. A wicked problem is one where you don’t understand the problem until you have a solution. This social complexity creates situations where different stakeholders think that their problem is the only and right problem (e.g., the result of where they’re from or the mission of their organization), and as such collective inquiry into what the problem is, is prevented (Conklin, 2006; Allenby, 2012, 92–97). The stronger the network of stakeholders, the less agile and flexible the system. The challenge is not to deny the involvement of stakeholders but to recognize that taken as a whole they are a significant design constraint that must be considered, and engineers must try to design for agility and flexibility in spite of it.

**Managing Infrastructure in the Anthropocene**

The processes of infrastructure design, delivery, management, and change will need to be as fast as the relevant changes in demand, technologies, demographics, and earth systems in the Anthropocene. Optimizing, the current dominant paradigm, is likely wholly insufficient for the future. The fragmentation that has resulted from the wicked complexity that has emerged in the contemporary infrastructure process produces disincentives to embrace change and plan for uncertainty. In an increasingly divided and tribal society, even something as fundamental to infrastructure design and management as problem definition becomes ambiguous and contested. Thus, rather than simply designing a solution to a given problem, the engineer will often find herself needing to satisfice both on problem definition and design solution. Wicked problems can fragment direction and mission since agreeing on the problem to develop a solution is challenging. Furthermore, social complexity fragments stakeholder unity through competing interests and identities. Given these challenges, we must seriously question whether optimizing is sufficient in terms of significant infrastructure transformation for the Anthropocene. Even if we seek a different approach, the organizational competencies needed to address complexity in infrastructure institutions are not for the most part present.

A major challenge that infrastructures face in adapting is that their managing institutions are largely configured around bureaucracies designed to address complicated (rather than complex) systems and typically single disciplines (e.g., transportation, water, power, etc.). Bureaucracies – characterized by hierarchical organizations, jurisdictional responsibilities, intentional and abstract rules, production and administration belonging to the office, appointed officials, and career employment, designed to uphold either a legal-rational or charismatic order – became largely commonplace during the industrial era (Constas, 1958; Weber, 2009; Diefenbach and By, 2012). Ancient states were largely designed to administer, expand and protect their domains from neighboring peoples. Industrialization (in addition to representative governance and nationalism) added many new tasks to bureaucracies, transforming their role in the modern era. Public services, and their associated infrastructures, became necessary for democratizing governments during the colonial era, and bureaucracies became commonplace in the management of these services, many emerging during industrialization (Riggs, 1997). While private sector infrastructure agencies are not entirely subject to the same constraints as public agencies, the policies, rules, norms, codes, etc. that govern public infrastructure likely contribute to firms also operating largely within siloes.

Modern infrastructure systems are largely managed by bureaucratic structures that are designed for the industrial era, both in terms of the problems that we were facing and the intellectual needs to address those problems. The engineering education process largely reflects this.
With the industrial era came a need to develop competencies around complicated problems. Production was becoming increasingly concentrated at factories (instead of agriculture) and the rapidly developing technologies and machinery of mass production needed workers who could understand and work with machines; creativity was not desired (Nason, 2017). Hierarchies – the staple structure of bureaucracies – were used to organize tasks vertically within organizations establishing functional and social relationships (Weber, Parsons and Tawney, 1930). Expertise was compartmentalized, access to information constrained, and resources earmarked for particular classes of workers (Diefenbach and By, 2012). These hierarchies work against creativity: they emphasize efficiency of the status quo process, they strand ideas between levels of management within the hierarchy (and each has competing priorities and doesn’t necessarily have the authority to implement new ideas), and given the separation of problems management often doesn’t understand the value of the idea. This organizational structure in many ways persists in current infrastructure management institutions, as well as in the educational structures that feed them. Compounding the traditional challenges is wicked complexity; not only are these bureaucracies expected to efficiently deliver public services but they must do so given the wicked problems, technical complexity, and social complexity that has become endemic.

Adaptive management that starts at infrastructure institutions and embraces the competencies needed to deal with complexity, emphasizes agility and flexibility of operations and physical hardware, and recognizes that infrastructure as an ever changing process will be necessary for the non-stationary norms and rapidly changing needs of the Anthropocene.

Adaptive management: Complicated to complex competencies

Infrastructure management in the Anthropocene will require new competencies that give systems the capacity to quickly adapt to deliver resources in non-stationary and ever more complex environments. The models of adaptive management and other successful strategies that have been developed for managing complexity should serve as a foundation for transforming the processes of infrastructure design, planning, operation, maintenance, and evolution. Here we don’t pretend to have a final vision of how this process is explicitly structured. On the contrary, we view the process of infrastructure as one that will need to evolve, and the forms that it takes at any given time in the future will need to reflect the complex environments and challenges of the time, most of which cannot be forecast, certainly not with any detail. However, the competencies associated with adaptive management strategies to address wicked complexity can serve as a guidebook.

Lessons can be learned for hard infrastructure systems from the practices developed by socio-ecological system (SES) practitioners. SES practitioners have been developing best practices for ecosystem resource management to coordinate resources in the face of complexity and uncertainty (Armitage et al., 2009; Chaffin, Gosnell and Cosens, 2014). Those adaptive management practices produce a “flexible system of resource management, tailored to specific places and situations, supported by, and working in conjunction with, various organizations at different scales.” The SES literature is abound with successful implementations of adaptive management for complex and rapidly changing social-ecological systems including the management of the Kristianstads Vattenrike region in Sweden (balancing development, conservation, and ecological services to address water quality and biodiversity collapse), preservation of the Great Barrier Reef Marine Park in Australia (experiencing coral bleaching, overfishing, and eutrophication), and management of fishing in the Southern Ocean surrounding Antarctica (experiencing fish stock collapse). The commonality in these examples was a looming crisis that triggered a few individuals to build trust and knowledge, connect networks, and develop a shared system vision (Schultz et al., 2015). Indeed there has been much work to frame infrastructure within socio-ecological systems (Geels, 2002; Markolf et al., 2018).

It is useful, for example, to compare recent adaptive management approaches to the Florida Everglades, challenged by environmental activism, phosphate mining, agricultural interests, and population growth and developers, with the experience of the Aral Sea since the Soviet Union diverted much of its inflow to growing cotton after World War II. Both regions are highly complex economically and culturally, but the use of adaptive management principles in the Everglades has prevented the economic, social, and ecological collapse that the Aral Sea region has suffered. A primary reason is that in the case of the Everglades, the wickedly complex nature of regional management was recognized, while in the case of the Aral Sea, the system was optimized for cotton production for export purposes (Allenby, 2012; National Research Council, 2018b). It’s critical that engineers and infrastructure managers develop competencies to be able to support and facilitate adaptive management practices.

First and foremost, infrastructure managers will need to be able to distinguish between complicated, and even chaotic problems, and those characterized by wicked complexity. Distinctions will have to be made between systems where wicked complexity is relatively low, and systems where it is high. Engineers have in recent history largely operated in and been trained for the complicated domain, that of known unknowns, where management processes largely focus on unique skills associated with diagnosing and optimizing cause and effect relationships (e.g., what types of bridges could a city build across a canyon given geologic conditions, traffic requirements, and a budget). The complex domain is unique in that it’s characterized by unpredictability and flux that lead to emergence that cannot be predicted (unknown unknowns) (Snowden and Boone, 2007). We won’t know what will work and have to accept that the best that we’ll be able to do is educated guesses and a commitment to a dynamic process where we constantly reassess what’s happened, and adjust course.

Examples of complex infrastructure challenges that face engineers are plenty. What is the right solution to a new tourism road through the Peruvian rainforest for access to Incan ruins, considering highly sensitive ecosystem impacts, preserving cultural heritage, design
for climate change and possibly more extreme rainfall events, autonomous vehicles, etc.? The likely answer is we don’t know. Sure, we could build a typical asphalt road for modern automotive technology. But this road – given the unpredictability and relationships of the factors mentioned – may be insufficient for the conditions, technologies, and needs two decades from now. Instead, infrastructure processes that embrace complexity would focus on experimental management practices and a flexibility in understanding what does and does not work, and commitment to trying something different later on once new information emerges.

Additionally, it’s reasonable to expect infrastructure managers to have to operate in the domain of chaos more frequently in the future. Catastrophic events like climate change driven natural hazards, and terrorist attacks (particularly cyber given how interconnected our physical infrastructure are becoming with information and communication technologies) are already becoming more common (Singer and Friedman, 2014; USGCRP, 2017; Roser, Nagdy and Ritchie, 2018) and showing how little training our infrastructure managers have for working through these situations. In chaotic situations, infrastructure managers will need to be trained to help establish order, sense where stability is and is not present, and then help support transitions back to the complexity domain (Snowden and Boone, 2007). This will require training and practice that is often absent from traditional university curricula.

Managing complex infrastructure systems will require fundamentally new approaches to training, education, and practice. The conventional infrastructure management organization is structured as a top-down hierarchy where experts and resources are compartmentalized. Consider a hypothetical state department of transportation that has a leader at the top (often politically appointed), division directors that oversee various domains of the system (e.g., infrastructure delivery, planning, operations), and groups within those divisions that carry out the mission. In this structure, sharing of knowledge and resources across groups to address interdisciplinary challenges is typically infeasible and solutions to challenges are often prescribed with little opportunity for deviation. This structure emphasizes compartmentalization of knowledge and efficiency in solutions. More fundamentally, if a problem requires coordination beyond the transportation domain – say, implementing a tax structure that will encourage home office work rather than commuting to an office on bad air quality days – it is essentially impossible with the stovepiped structure of today’s engineering management and education institutions. There is an obvious need to develop organizational structures that i) emphasize diversity of ideas and perspectives, and frequent opportunities for exchanging them, ii) implement infrastructures as an experiment and dynamic reassessment exercise where patterns are allowed to emerge, are studied, and new infrastructure is then implemented, and iii) emphasize the creation of new ideas over historical models. This organization, for example, allow emerging technologies to be tested in practice, pit interdisciplinary teams against each other on the same problem, and provide workers discretionary time to pursue outside-the-box ideas (Snowden and Boone, 2007).

Combining the aforementioned SES, management, and infrastructure emerging concepts on wicked complexity, several core competencies emerge.

- **Shared Understanding** – Prior to managing wicked complex problems, there needs to be shared understanding of the problems and a willingness to address the problems collectively. Shared understanding is the process by which stakeholders are made aware of each other’s goals and concerns; it is not consensus building. Shared understanding (stakeholders know about each other’s goals and concerns, they have developed trust and caring, they have created joint meaningfulness of concepts, they have established “we-ness”) can lead to shared commitments (diverse group’s commitment to a project’s directions, goals, emerging solutions, group decisions, and actions) and ultimately collective intelligence (Conklin, 2006). The processes by which infrastructure decisions are made, both internally and externally to the organization, should be radically altered towards collective intelligence. This is of course easier said than done due to the existence of a plethora of barriers that lock-in current practice and work against radical change. Nonetheless, as environmental and social forces increasingly dictate what our future infrastructures can and cannot be in the Anthropocene, current practices that attempt to balance different constraints and perspectives without building collective intelligence appear to be increasingly insufficient.

- **Manage, Not Solve** – Infrastructures too often are treated as physical assets designed and operated to solve a problem, whether that be, e.g., the facilitation of a volume of vehicle traffic or a minimum water pressure and volume. Yet in the face of increasing change, the solution will need to constantly evolve. As such, infrastructure managers will need to adopt a perspective that embraces change and that acknowledges a system is only temporary, may be the right fit for a short period of time, and is likely unacceptably for the not too distant future. Management then focuses on the changing conditions that infrastructures need to adapt to. This requires making decisions under deep uncertainty. In the past, infrastructures could be framed as artifactual (Allenby, 2012); going forward, they must be reconceptualized as a process.

- **Try, Learn, Adapt** – Complex environments are not conducive to command-and-control top-down strategies; there’s just too much distributed information, changing too rapidly, for a centralized command-and-control approach to work. Instead, an approach that emphasizes experimentation as a process of learning to better enable adaptive capacities is needed. Here infrastructure organizations, the general public, and financiers need to allow for some level of failure. For example, a region could establish that a portion of transportation infrastructure funds be routinely used for testing for new technologies, such as alternative
materials or traffic management, with the recognition that many of these technologies will not be implemented at scale but will provide valuable insights into what the agency needs to do to prepare for disruptive conditions. In addition, those responsible for infrastructure must learn to distribute management of infrastructure out to the network; decisions should be made at the most local level possible (a principle of “subsidiarity” that in politics has become familiar, particularly in the European Union).

- **Complexity Mindset** – The training that many of our infrastructure managers receive focuses on managing complicated problems, often through the use of a predefined set of options or processes, and with explicit or implicit reference to optimization techniques. A complexity mindset accepts that complexity exists, that it needs to be managed differently, and that there are limitations on what a manager can control (Nason, 2017). A complexity mindset focuses on “what can be” over “what is”, and relies on satisficing, not optimization, mental models and methods. Planning is different in each case. With complicated systems, planning is done to determine paths which are then followed. With complexity, it is the process of constantly planning that informs action; the plans themselves are seldom, if ever, implemented. As General (later President) Eisenhower observed, “In preparing for battle I have always found that plans are useless, but planning is indispensable” (Nixon, 2013). It isn’t the plan that’s important; it is the act of planning, thinking about the possibilities, the interconnectedness of problems, and the emerging properties of the system.

Every indication is that the competing forces that now define how infrastructures are implemented, and that are driving increasing complexity today, will continue if not accelerate. Unpredictable and accelerating evolution is occurring across the entire technological frontier. Social and political fragmentation and complexity is growing (Fukuyama, 2014; Kissinger, 2014). Environmental pressures, and associated perturbations in human demographics and migration patterns, as well as unpredictable shifts in natural cycles and systems, are set to accelerate. Urbanization continues to accelerate, especially in developing countries. There is thus no question that demands on technologists, managers, and engineers working on infrastructure systems are also going to grow. New approaches are needed to create coherence. For example, if water demand is increasing, then a treatment plant will need to be created based on the forecasted demand, funding may need to be secured from a new tax measure, political and social factors such as NIMBYism will need to be managed, and water rights may need to be secured. Acceptance by local communities, activist organizations (which often have different if not mutually exclusive agendas), and regional water users and managers will be required. Designs that are flexible enough to adapt to unpredictable changes in supply and demand because of, e.g., climate change, must be developed, and metrics for tracking performance of the infrastructure, and the systems context of the infrastructure, developed and institutionalized. The complicated task of designing the water treatment plant is possibly the simplest exercise in the whole process, and is perhaps the only one the infrastructure manager has been trained for.

**Conclusion**

In the Anthropocene, infrastructures are an integration of co-evolving human, built, and natural systems, and inevitably are characterized by wicked complexity. As such, engineers and infrastructure managers will need to shift their mindset away from optimizing as the dominant approach, towards satisficing. They will need to shift their thinking about infrastructures from the delivery of physical assets which meet a defined and relatively stable need, to a process by which physical systems are designed, built and operated in response to shifting priorities, new technologies and social practices, and irreducible uncertainty.

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**References**

Allenby, B. 2012. *The Theory and Practice of Sustainable Engineering*. Pearson Prentice Hall.

Allenby, B and Chester, M. 2018. ‘Reconceptualizing Infrastructure in the Anthropocene’. *Issues in Science and Technology* 34(3). Available at: http://issues.org/34-3/reconceptualizing-infrastructure-in-the-anthropocene/.

Arbesman, S. 2016. *Overcomplicated: Technology at the Limits of Comprehension*. Penguin Publishing Group. Available at: https://books.google.com/books?id=HTXRCgAAQBAJ.

Armitage, DR, Plummer, R, Berkes, F, Arthur, RI, Charles, AT, Davidson-Hunt, IJ, Diduck, AP, Doubleday, NC, Johnson, DS, Marschke, M, McConney, P, Pinkerton, EW and Wollenberg, EK. 2009. ‘Adaptive co-management for social–ecological complexity’. *Frontiers in Ecology and the Environment* 7(2): 95–102. Wiley-Blackwell. DOI: https://doi.org/10.1890/070089.

Berkes, F, Folke, C and Colding, J. 1998. *Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience*. Cambridge University Press. Available at: https://books.google.com/books?id=Q9E_ngEACAAJ.

Berman, M. 1982. *All that is solid melts into air: the experience of modernity*. New York, NY: Simon and Schuster.

Brown, R. 2004. ‘Consideration of the origin of Herbert Simon’s theory of “satisficing” (1933–1947). *Management Decision* 42(10): 1240–1256.
Chester, MV. 2017. ‘Keyword: infrastructure: How a humble French engineering term shaped the modern world’. In: Harvey, P, Bruun Jensen, C and Morita, A (eds.). *Infrastructures and Social Complexity*, 45–57. Routledge.

Chaffin, BC, Gosnell, H and Cosens, BA. 2014. ‘A decade of adaptive governance scholarship: synthesis and future directions’. *Ecology and Society* **19**(3). The Resilience Alliance. DOI: https://doi.org/10.5751/ES-06824-190336

Chester, MV. 2019. ‘Sustainability and infrastructure challenges’. *Nature Sustainability* **2**(4): 265–266. Nature Publishing Group. DOI: https://doi.org/10.1038/s41893-019-0272-8

Chester, MV and Allenby, B. 2018. ‘Towards Adaptive Infrastructure: Flexibility and Agility in a Non-Stationarity Age’. *Sustainable and Resilient Infrastructure* **3**(1): 1–19. DOI: https://doi.org/10.1080/23789689.2017.1416846

Chester, MV, Markolf, SA and Allenby, B. 2019. ‘Infrastructure and the Environment in the Anthropocene’. *Journal of Industrial Ecology*. In Press. DOI: https://doi.org/10.1111/jiec.12848

Chua, A. 2018. *Political Tribes: Group Instinct and the Fate of Nations*. Penguin Random House LLC. Available at: https://books.google.com/books?id=eYtIDwAAQBAJ

Cilliers, P. 2002. *Complexity and Postmodernism: Understanding Complex Systems*. Taylor & Francis. Available at: https://books.google.com/books?id=OeCEAgAAQBAJ

Clark, SS, Seager, TP and Chester, MV. 2018. ‘A capabilities approach to the prioritization of critical infrastructure’. *Environment Systems and Decisions*, 1–14. Springer US. DOI: https://doi.org/10.1007/s10669-018-9691-8

Conklin, J. 2006. *Dialogue Mapping: Building Shared Understanding of Wicked Problems*. Wiley. Available at: https://books.google.com/books?id=xVRnQgAACAAJ

Constas, H. 1958. ‘Weber’s Two Concepts of Bureaucracy’. *American Journal of Sociology* **63**(4): 400–409. Available at: https://www.jstor.org/stable/2774140. DOI: https://doi.org/10.1086/222263

Diefenbach, T and By, R. 2012. ‘Bureaucracy and Hierarchy – what else!?’. In: pp. 1–27. DOI: https://doi.org/10.1108/S0733-558X(2012)000035003

Economist. 2009. ‘Herbert Simon’. *The Economist*. Available at: https://www.economist.com/news/2009/03/20/herbert-simon.

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**Fukuyama, F.** 2014. *Political Order and Political Decay: From the Industrial Revolution to the Globalization of Democracy*. Farrar, Straus and Giroux. Available at: https://books.google.com/books?id=j6hAwAAQBAJ

**Gandy, M.** 2003. *Concrete and Clay: Reworking Nature in New York City*. MIT Press (Urban and industrial environments). Available at: https://books.google.com/books?id=R38TXjcG-xSC. DOI: https://doi.org/10.7551/mitpress/2083.001.0001

**Geels, FW.** 2002. ‘Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study’. *Research Policy* **31**(8–9): 1257–1274. DOI: https://doi.org/10.1016/S0048-7333(02)00062-8

**Gilrein, E, Carvalhaes, T, Markolf, SA, Chester, MV, Allenby, B and Garcia, M.** 2019. ‘Concepts and Practices for Transforming Infrastructure from Rigid to Agile’. *Sustainable and Resilient Infrastructure*, In Press. DOI: https://doi.org/10.1080/23789689.2017.1599608

**Hall, JW, Thacker, S, Ives, MC, Cao, Y, Chaudry, M, Blainey, SP and Oughton, EJ.** 2017. ‘Strategic analysis of the future of national infrastructure’. *Proceedings of the Institution of Civil Engineers – Civil Engineering* **170**(1): 39–47. Thomas Telford Ltd. DOI: https://doi.org/10.1680/jcien.16.00018

**Hall, P.** 1998. *Cities in Civilization: Culture, Innovation, and Urban Order*. Weidenfeld & Nicolson. Available at: https://books.google.com/books?id=0AmeQgAACAAJ

**Hawkins, S, Yudkin, D, Juan-Torres, M and Dixon, T.** 2018. *Hidden Tribes: A Study of America’s Polarized Landscape.*

**Jacobs, J.** 1961. *The Death and Life of Great American Cities*. Vintage Books (Vintage Books ed). Available at: https://books.google.com/books?id=deqQUJoBTnUC

**Jencks, C.** 1977. *The Language of Post-modern Architecture*. Academy Editions. Available at: https://books.google.com/books?id=NhRqQgAACAAJ

**Kissinger, H.** 2014. *World Order*. Penguin Publishing Group. Available at: https://books.google.com/books?id=NR50awAAQBAJ

**Kurzweil, R.** 2010. *The Singularity is Near*. Gerald Duckworth & Company. Available at: https://books.google.com/books?id=0d8oDwAAQBAJ

**Marchant, GE, Allenby, BR and Herkert, JR.** 2011. *The growing gap between emerging technologies and legal-ethical oversight: the pacing problem*. Springer. DOI: https://doi.org/10.1007/978-94-007-1356-7

**Markolf, SA, Chester, MV, Eisenberg, DA, Iwaniec, DM, Davidson, CI, Zimmerman, R, Miller, TR, Ruddell, BL and Chang, H.** 2018. ‘Interdependent Infrastructure as Linked Social, Ecological, and Technological Systems (SETSs) to Address Lock-in and Enhance Resilience’. *Earth’s Future* **6**(12): 1638–1659. John Wiley & Sons, Ltd. DOI: https://doi.org/10.1029/2018EF000926
Martin, A and Helmerson, K. 2014. 'Emergence: the remarkable simplicity of complexity'. The Conversation. Available at: https://theconversation.com/emergence-the-remarkable-simplicity-of-complexity-30973.

Nason, R. 2017. It's not complicated: the art and science of complexity for business. University of Toronto Press. DOI: https://doi.org/10.3138/9781487514778

National Research Council. 2018a. Progress Toward Restoring the Everglades: The Seventh Biennial Review – 2018. Washington, DC: The National Academies Press. DOI: https://doi.org/10.17226/25198

National Research Council. 2018b. Progress Toward Restoring the Everglades: The Seventh Biennial Review – 2018. Washington, DC: The National Academies Press. DOI: https://doi.org/10.17226/25198

Nixon, R. 2013. Six Crises. Simon & Schuster. Available at: https://books.google.com/books?id=93gNMZUTWCQC.

O'Rourke, TD. 2007. 'A Leader's Framework for Decision Making'. Harvard Business Review. Available at: https://books.google.com/books?id=9VDSAQAQBAJ.

Snowden, DJ and Boone, ME. 2007. 'Modernity and Bureaucracy'. Basingstoke, UK: Macmillan Company (Original from University of Minnesota).

Simon, H. 1957. Models of Man: Social and Rational. Berkeley, CA: Wiley (Original from University of California).

Singer, PW and Friedman, A. 2014. Cybersecurity: What Everyone Needs to Know. OUP USA (What Everyone Needs To Know). Available at: https://books.google.com/books?id=9VDSAQAQBAJ.

Syvitski, J. 2012. 'Anthropocene: An epoch of our making'. Global Change Magazine, March. Available at: http://www.igbp.net/news/features/features/anthropoceneanthropocenemaking.5.1081640c135c7c04eb480001082.html.

USGCRP. 2017. Climate Change Special Report: Fourth National Climate Assessment. DOI: https://doi.org/10.7930/J0J964J6

Weber, M. 2009. The Theory of Social and Economic Organization. Free Press (A Free Press paperback). Available at: https://books.google.com/books?id=G3TYBu6-4GC0.

Weber, M, Parsons, T and Tawney, RH. 1930. The Protestant ethic and the spirit of capitalism. G. Allen & Unwin, ltd. (Unwin university books). Available at: https://books.google.com/books?id=_jwYZNNrWqMC.