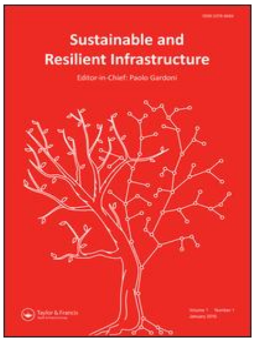

Taylor & Francis
Taylor & Francis Group

Sustainable and Resilient Infrastructure

ISSN: 2378-9689 (Print) 2378-9697 (Online) Journal homepage: http://www.tandfonline.com/loi/tsri20

Toward adaptive infrastructure: flexibility and agility in a non-stationarity age

Mikhail V. Chester & Braden Allenby

SUSTAINABLE AND RESILIENT INFRASTRUCTURE, 2018
https://doi.org/10.1080/23789689.2017.1416846

Taylor & Francis
Taylor & Francis Group

Toward adaptive infrastructure: flexibility and agility in a non-stationarity age

Mikhail V. Chester and Braden Allenby

Civil, Environmental, and Sustainable Engineering, School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ, USA

ABSTRACT
As technologies rapidly progress, there is growing evidence that our civil infrastructure do not have the capacity to adaptively and reliably deliver services in the face of rapid changes in demand, conditions of service, and environmental conditions. Infrastructure are facing multiple challenges including inflexible physical assets, unstable and insufficient funding, maturation, utilization, increasing interdependencies, climate change, social and environmental awareness, changes in coupled technology systems, lack of transdisciplinary expertise, geopolitical security, and wicked complexity. These challenges are interrelated and several produce non-stationary effects. Successful infrastructure in the twenty-first century will need to be flexible and agile. Drawing from other industries, we provide recommendations for competencies to realize flexibility and agility: roadmapping, focus on software over hardware, resilience-based thinking, compatibility, connectivity, and modularity of components, organic and change-oriented management, and transdisciplinary education. First, we will need to understand how non-technical and technical forces interact to lock in infrastructure, and create path dependencies.

ARTICLE HISTORY
Received 2 June 2017
Accepted 20 November 2017

KEYWORDS
Infrastructure; flexibility; agility; adaptation; resilience; non-stationarity

Introduction

A quotation written in 1963 by Leon Megginson that is often misattributed to Sir Charles Darwin states that

> it is not the most intellectual of the species that survives; it is not the strongest that survives; but the species that survives is the one that is able best to adapt and adjust to the changing environment in which it finds itself. (Megginson, 1963)

The concept of adaptation and the complex principles that support it have largely been the focus of researchers in the fields of biology, but with significant application in other fields including business (Brennan, Turnbull, & Wilson, 2003), management (Chakravarthy, 1982; Hrebiniak & Joyce, 1985), and computer science (Garlan, Cheng, Huang, Schmerl, & Steenkiste, 2004). Adaptation is perhaps one of the most fundamental and powerful explanatory concepts for the changes in complex systems, in that it provides an explanation for the persistence of successful systems in the face of significant changes in internal and external environments. In biology, adaptation is a trait maintained by natural selection that enhances fitness and survival. More broadly across fields, the concept characterizes the capability of organisms, complex systems, businesses, or institutions to change their organizing principles, structure, and behaviors to succeed in unpredictably changing environments. How success is measured changes across disciplines, with biology focused on reproduction and business focused on maintaining growth and ultimately profitability (Chakravarthy, 1982; Grisogono, 2006). Yet when it comes to infrastructure, the systems that we've deployed and continue to maintain – the backbones of our cities, economies, and overall well-being – there appears to be limited capabilities to adapt, raising serious questions about their ability to provide services in a future with changing demands, population, climate, security challenges, and environmental conditions.

The infrastructure that support our societies provide untold benefits. Infrastructure are socio-technical systems composed of physical assets and the institutions that manage, govern, finance, and regulate them. The services they provide deliver resources such as energy, water, and information, and move and process waste. These services are not purely physical. While our focus on infrastructure is primarily on hard (or gray) systems in this manuscript – roads, buildings, power, water, etc. – we will also examine the role of soft (i.e. institutions) infrastructure and its relationships with hard systems. Transportation infrastructure provides mobility and ultimately access to people, goods,

CONTACT Mikhail V. Chester mchester@asu.edu

and services. Buildings provide shelter for people, businesses, and services. Hard infrastructure can be characterized as services that either produce or deliver resources directly (energy, water, waste, information and communication technologies (ICT)), or provide mechanisms for resource consumption (buildings). In the U.S., critical infrastructure are defined as chemical, commercial facilities, communications, critical manufacturing, dams, defense, emergency services, energy, financial, food and agriculture, government facilities, health care and public health, information technology, nuclear, transportation, water, and wastewater (DHS, 2017). People's daily needs are typically met by municipal infrastructure and in many cases private energy companies. Supply chains for food, fuel, and materials are generally supported by institutions at larger scales, regional, state, and federal. As such, the funding and planning for adaptive infrastructure must recognize the client. More broadly, infrastructure facilitates derived demands; we don't usually demand the resource or service that infrastructure provides, but instead what that resource or service enables, in other words, the utility that it provides. While the extent of infrastructure, what it delivers, and how it is used is somewhat quantifiable, the benefits of infrastructure ultimately are in its functioning as an engine of social well-being, which can be characterized through economic growth, health, quality of life, etc. To communicate the value of infrastructure, efforts have been made to monetize this well-being, both for gray infrastructure (ASCE, 2016) and even ecological infrastructure (Costanza et al., 2017).

In the developed world, the core physical structures that define our infrastructure have often not changed in decades, sometimes centuries, from roads to water delivery to power generation and transmission. These infrastructure have certainly seen the implementation of new technologies (e.g. sensors and computing, automation, more efficient components) in support of the services delivered, but the core structures that have been used for decades if not longer – from roadways to centralized fossil-based electricity generation to water distribution networks – are the cornerstones of the systems that we critically rely on today. Some are old and in need of may rehabilitation or replacement. Some are new and likely to last into the long-term making change difficult. And some are yet to be built, with more opportunities for affecting their design. Furthermore, infrastructure have often been built in support of the dominant technologies at the time they were conceived, not just in physical manifestations, but also in the rules, financing, and governing of the institutions that manage the infrastructure. This becomes a problem when the demands that we ask infrastructure to satisfy change and infrastructure cannot change quickly enough to meet these demands. In the past century, we've seen the design of many technological and institutional forces that lock-in infrastructure structure. Prioritization of funds to roadways post World War II and minimum off-street parking standards are perhaps the most dominating forces for automobile-centric transportation development in the U.S. (Pollard, 2003; Shoup, 2011). The commitment of manufacturers through the investment of resources, labor, and manufacturing plants supported several waves of technological innovation that used polyphase electric supply (Hughes, 1993). The rapid growth of water utilities and distribution systems in the late 1800s was largely driven by concerns for public health (through the emergence of bacteriology) and safety, to protect growing populations against disease and fires. Centralized water distribution systems grew exponentially between 1880 and 1895 (from roughly 600 to 3000 in the U.S.) while at the same time regulatory agencies emerged to ensure provision of services and affordability (NRC, 2002). As new technologies come online or as demand for services changes, our infrastructure (both hard and soft) may be unable to adapt, raising questions about how quickly they can change given new societal needs or threats. Given that our infrastructure tend to persist for long time periods, are they agile? Can they adapt to changing conditions? Why do our infrastructure need to be adaptable? How do we and why should we design our infrastructure to be adaptable?

There are fundamental reasons why these questions arise at this time. There is a critical category distinction between physical infrastructure designed to be part of an overall infrastructure that is intended to last many decades, and the shorter and more abrupt changes in economic, technological, social, and institutional systems that are coupled to infrastructure. If the rate of change of these latter systems is relatively slow, as it has been for most of our history, infrastructure with half-lives of decades is not a problem. If, however, the rate of change of the system accelerates, we reach a point where the cycle time of infrastructure change simply decouples from the increasingly rapid social systems which they serve. We have seen this happen in other long lived institutions such as law (Marchant, Allenby, & Herkert, 2011). For example, the shift to autonomous local vehicle service from owned automobiles is happening much faster than in historical periods, yet we have just begun to think about the implications for urban and transport infrastructure design.

Here we attempt to answer the aforementioned questions. We start by identifying several major challenges that have created a crisis for current infrastructure. We then attempt to unpack the design principles for infrastructure in the past century and how these principles constrain our ability to adapt infrastructure to challenges. We then characterize – based on evidence from industries that have successfully deployed adaptable infrastructure – the novel design and operation principles for infrastructure for a future in which demands on our systems are changing rapidly and there is heightened unpredictability across a number of domains.

Infrastructure challenges in the non-stationarity age

Infrastructure systems are facing several major challenges that threaten their performance, the services they deliver, and ultimately the well-being of the societies that rely on them. The confluence of these challenges can be described as a *crisis*. This is especially true in the U.S., where significant attention is now focused on the state of disrepair of many major infrastructure systems (ASCE, 2017), but is also true in many other developed regions of the world. We posit that these challenges are (i) inflexibility, (ii) funding, (iii) maturation, (iv) utilization, (v) interdependencies, (vi) earth systems changes, most immediately climate change, (vii) designing for social and environmental well-being, (viii) transdisciplinary practices and processes, and (ix) geopolitical security. These challenges are interrelated and several produce non-stationary effects. We define non-stationarity loosely on statistical definitions as the unpredictability of future conditions based on past trends. There is a rich discourse around how climate change produces non-stationarity, that, e.g. precipitation and rates of discharges of rivers are becoming increasingly difficult to predict (Milly et al., 2008). We argue that funding for public infrastructure (namely transportation and water) also now exhibits non-stationarity as a result of policies (at federal, state, regional, and municipal levels and financial planning that now inconsistently allocates funding (partly the result of escalating rehabilitation and maintenance costs) and creates significant uncertainty as to how much funding will be available for upkeep. This non-stationarity combined with the other challenges creates a crisis that must be imminently addressed to ensure that we are able to adapt infrastructure for the future. More specifically, these challenges are:

(1) *Inflexibility* – A unique characteristic of hard infrastructure and the soft infrastructure that support them is that they provide services for demands that are difficult to change except incrementally, even in the long-term. Some exceptions exist, notably ICT services having changed radically over short time periods. Inflexibility, which we'll explore in more detail later, emerges partly because physical infrastructure don't need to significantly change form as the services they've delivered have remained fairly consistent for long periods of time. Unlike microchip fabrication, automobile manufacturing, and ICT, the demands that infrastructure facilitate are relatively consistent on decadal scales. Electricity consumption, mobility (particularly by automobile), water use, and waste management demands are similar to demands 10, 30, 50, even 80 years ago. There have of course been efficiencies and technological improvements implemented in these infrastructure systems, and some such as ICT may change more rapidly than others, but their core physical structure has not changed dramatically in the long-term.

(2) *Funding* – While there has been much attention focused on the state of disrepair of infrastructure in the U.S., we argue that a major challenge is the sustainability of funds, particularly for long-term rehabilitation and technological improvement. Funding sustainability challenges result from two major forces: (i) many infrastructures were deployed in the middle of the last century and are now in need of major rehabilitation and (ii) there remains significant uncertainty about the availability of funds for this rehabilitation. The explosive growth of hard infrastructure in the U.S. with the New Deal but more substantially post World War II continued through the latter parts of the twentieth century. The Silent Generation – born between the 1920s and 1940s – experienced heavy capital investment (as a percentage of GDP) in new infrastructure which continued through the 1970s (Davis, 2017). As infrastructure built in the middle of the twentieth century began to reach the end of its service life new pressures emerged to rehabilitate these systems. As these rehabilitation demands have grown, many public agencies find themselves with insufficient funds to cover maintenance activities (ASCE, 2017). Municipalities are forced to triage their limited rehabilitation funds, deciding which components of infrastructure get rehabilitated while delaying others (Menendez, Siabil, Narciso, & Gharaibeh, 2013). In the U.S., a compounding challenge is the uncertainty of federal funds. The Highway Trust Fund for example is supported by federal fuel taxes which have not been increased since 1993 and is not indexed to inflation (Shirley, 2015). Furthermore, many states use their tax for purposes other than transportation (Paletta, 2014). There have been instances where the fund

was projected to become insolvent. Major challenges also exist for water, electricity, aviation, waste management, rail, and other infrastructure (ASCE, 2016; AWWA, 2012).

(3) *Maturation* – Some infrastructure in developed regions of the world have grown to a point where substantial expansion no longer takes place. This infrastructure is mature in the sense that cumulative increases in physical infrastructure and its capacity have leveled off over time, and funding priorities are shifting from capital investment in new infrastructure to increased investment in maintenance and rehabilitation of existing infrastructure (Fraser & Chester, 2016). This maturation can occur for several reasons. First, there are limits to the outward extent that infrastructure can grow, not necessarily physically, but more so practically. Resource, demand, and budget constraints including travel time budgets, natural boundaries (such as oceans, bays, mountains, and protected land), growth boundaries can limit how far outward people and services will be, and ultimately infrastructure are deployed (Garreau, 2011; Kornai, 1979). There are certainly many places where infrastructure is still being deployed outward, however, infrastructure grows where people demand services and if demographics, costs or other barriers reduce or constrain that demand then growth will slow or stop.

Related to maturation is geographic scale. In many countries (and particularly the U.S.) infrastructure exists on such large scales that meaningful and timely changes may require herculean efforts. Take for example the U.S. roadway, railway, power, and pipeline networks (Figure 1) which when visualized show the boundaries and urban centers of the country. Replacing or enhancing infrastructure at large scale means a big change in physical assets and across many geographies. Even if unlimited funds were available, physical resource, time, and manpower constraints likely exist and non-technical barriers so large that the rate of change may be severely limited.

(4) *Utilization* – Long-term infrastructure capacity planning remains a major challenge for financing and upkeep given the centralized nature of systems, lack of modularity, and resulting inflexibility. Infrastructure capacity is often planned on decadal scales, with forecasting of traffic demands, water consumption, and power consumption, for example, developed with increasingly sophisticated models. Yet accurate forecasting for roughly 30 or more years out remains elusive given the increasing uncertainty associated with the multitude of variables that drive infrastructure use including population, socio-economics, climate,

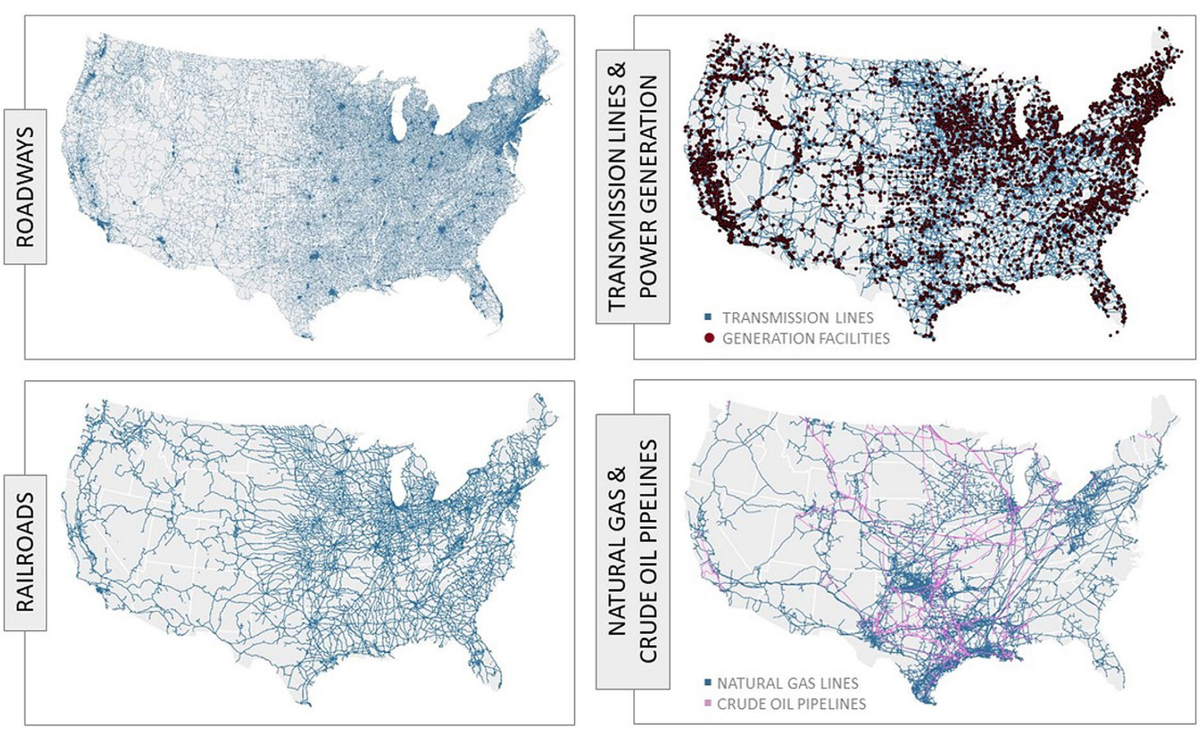

Figure 1. Geographic extent of U.S. infrastructure.

technologies, economics, and activities. With largely centralized and inflexible infrastructure, managers will ultimately be confronted with the challenge of infrastructure that is either under- or oversized, sometimes grossly. This is evident in the oversizing of infrastructure after the population collapses of Detroit and New Orleans, or sports stadiums that lose their teams, or the undersizing in the cases of cities that have experienced rapid population growth, like Phoenix or Las Vegas. While oversizing is apparent through cries for more funding to maintain underutilized systems or derelict structures, undersizing is not usually as obvious as short term policies to meet say rapid changes in population growth are quickly established to deploy tried and true technologies.

(5) *Interdependencies* – Infrastructure are becoming increasingly interdependent, with other hard infrastructure, with managing institutions, and with information (more and more delivered digitally). Imagine early instances of shared public hard infrastructure, systems that were deployed on small scales that in no significant way relied on other infrastructure. Roads didn't have electronic traffic control nor did they have power lines above them or water lines beneath them. By the late 1800s the Edison Illuminating Company had deployed a number of electricity generating facilities in the Northeast U.S. and connected them to nearby neighborhoods, each disconnected from the other. Early water conveyance and distribution systems exclusively relied on gravity. Electrical pumps didn't appear until the early 1900s (Walski, 2006). Today, vast and largely centralized infrastructure systems are deeply connected with each other. Infrastructure can be interdependent in several ways: geographic (co-location or in close proximity); physical (output of one system is an input into another); cyber (data or information from one system is input in another); and logical (the social, financial, political, etc., relationships between infrastructure) (Rinaldi, Peerenboom, & Kelly, 2001). Power, water, and ICT share space with roadways, pipelines sometimes follow rail rights-of-way, and critical systems are often found at the same spatial location, also known as a geographic interdependency. Because investments in hard infrastructure are fixed, sunk, and irreversible, they are a large risk. Sharing (in terms of co-location or hardware) physical infrastructure can reduce the costs of entry making it easier for new players or technologies to compete in a market (Chanab, El-Darwich, Hasbani, & Mourad, 2007). Infrastructure that deliver resources (such as energy or water, and also ICT) serve as the backbone of other infrastructure (i.e. physical interdependencies). Traffic control, train propulsion, water pumping and treatment, and communications rely on electricity. Wet-cooled thermoelectric facilities rely on water systems. Virtually all infrastructure need transportation services to move people and goods. And the digital age has shifted mechanical controls to digital, and introduced remarkable opportunities for generating, transmitting, and processing digital information, processes that are now deeply embedded in many infrastructure processes (cyber interdependencies). The degree to which this embrace of ICT has introduced new vulnerabilities and unpredictabilities into infrastructure systems, from, for example, geopolitical adversaries of the United States, is underappreciated and poorly addressed in most infrastructure systems (Amoroso & Vacca, 2013). The interface of hard infrastructure with the institutions that manage them produces logical interdependencies that define the rules, policies, and norms for how they are designed and operated, and how quickly they can change (more on this later).

These tightly coupled interdependencies are a challenge because they introduce complexity at scales and with outcomes that we poorly understand. A perturbation – or even worse, a failure – in one infrastructure can cascade to other infrastructure leading to service interruptions. The complexity of these interconnected systems, the emergent behaviors of infrastructure when one is shocked, is largely unknown, and represents a critically important area of study when financial, security, or climate change disturbances are introduced.

(6) *Earth Systems Changes Including Climate Change* – there is increasing evidence that critical earth systems are becoming destabilized due to human activity. While climate change is receiving more and more attention, it is likely that we will need to manage other systems including nitrogen, phosphorous, and water going forward (Childers, Corman, Edwards, & Elser, 2011; Vitousek et al., 1997; Vörösmarty & Sahagian, 2000). Infrastructure in part creates a man-made world in place of a naturally evolving one, and at the decadal level the dynamics of changing earth systems becomes important

for engineers. Climate change is likely the most immediate and direct earth systems change hazard that we're confronting and as such is the most developed in terms of infrastructure impacts. As such we focus on climate change as a case study that illustrates more fundamental challenge of infrastructure design and management for changing earth systems.

Some weather-related extreme events are occurring with greater frequency and intensity (NCA, 2014), and infrastructure, typically designed based on historical conditions, are vulnerable to both extreme and gradual perturbations. Infrastructure are the front line of defense against climate change. The services that they provide are critical during storms, heat, flooding, wildfires, and cold, in terms of the resources they deliver and their direct protection against exposure. Infrastructure are typically designed against return periods, the frequency that the infrastructure will experience a particular intensity. For example, a bridge over a wash might be designed to maintain structural integrity for a 100 year return period, i.e. a flow rate of water through the wash that is experienced on average every 100 years. Two major challenges exist. First, much of our existing infrastructure has been designed for return periods that under climate change forecasts are likely to change. A storm that has historically occurred at a particular intensity every 100 years may now occur every 20 years (Gilroy & McCuen, 2012; Tramblay, Neppel, Carreau, & Najib, 2013). Second, codes require that designs be based on historical weather conditions that are no longer valid. Those who design infrastructure have not used climate forecasts and even if they were to they would need different design processes that embrace the uncertainty associated with climate forecasts. We can expect indirect effects on infrastructure from climate change as well, including new conflicts, mass migration, and disease. How these effects will impact infrastructure remain largely unexplored but nonetheless present serious risk to the reliability of infrastructure services and challenges for delivering services in a future marked by these events.

(7) *Social and Environmental Awareness* – Gone are the days when infrastructure can be designed without serious considerations for social well-being and adverse environmental effects. The last half century has produced a mountain of knowledge about how the design, construction, and use of infrastructure affect people and the environment. Some of this knowledge has affected regulatory processes that require environmental assessments. In addition to the NEPA process requiring more and more disclosures through special purpose laws, research on social equity and the rapid incorporation of sustainability principles has created novel thinking about how infrastructure should be deployed. That's not to say that the deployment and use of infrastructure do not produce social and environmental impacts, but that we are more aware of these impacts and some measures have been put in place to reduce them. When deploying new infrastructure, the knowledge that has been generated from this past half century of study is much more likely to be known by engineers, designers, and managers, as well as the general public who is able to participate by voting, providing public comments, and protesting. While we are much more aware of social and environmental impacts, infrastructure designers and managers do not necessarily have the flexibility and resources to avoid them, and more broadly balance social, environmental, economic, and technical costs and benefits in a holistic but rigorous manner. Policies, financing, and codes may perpetuate existing practices despite evidence of negative outcomes.

(8) *Transdisciplinary Practices and Processes* – Integration of disciplinary and institutional practices and processes is needed to reflect the interdependencies in not just physical infrastructure, but in the institutions and cultures within which they are embedded. As infrastructure has become increasingly interconnected and as our knowledge of the complex systems in which these infrastructure function, provide services and result in unintended tradeoffs grows, our traditional disciplinary boundaries are no longer sufficient. Infrastructure are designed, funded, and managed by typically by a multitude of players, sometimes private and sometime public. They are governed and owned by different asset management systems, standards, businesses, and funding mechanisms. To effectively acknowledge and work within these complex arrangements, transdisciplinariness will be required.

(9) *Geopolitical Security* – Several fundamental trends in geopolitical and military doctrine and strategy have come together to make security challenges a critical challenge to infrastructure. The first is a rise in non-state actor violence, often in the guise of terrorism, against communities and societies. Because infrastructure systems are increasingly reliant on cyber for connectivity, and software which can be hacked for

operational capacity, deliberate attacks against infrastructure are ever more tempting for those seeking soft targets. The second is a shift in military strategy by major adversaries of the U.S. and Europe, especially Russia and China, towards 'hybrid warfare' and 'unrestricted warfare,' which reframe military confrontation as a conflict across all social and cultural systems, including infrastructure (Galeotti, 2014; Liang & Xiangsui, 1999). Along these lines, it is notable that at a particularly fraught moment in the Ukrainian–Russian conflict, Ukraine's electric system was hacked and taken down, substation by substation, on 23 December 2013 (Zetter, 2016). Finally, the extent of the Russian attack on American and European social and structural systems is just becoming apparent, and is far more significant than most professionals, embedded in their daily routine, realize: indeed, a leading NATO analyst has voiced what many have concluded, 'Recent Russian activities in the information domain would indicate that Russia already considers itself to be in a state of war.' (Giles, 2016). No infrastructure design which isn't hardened against deliberate information attack can be considered resilient; failure to design security into infrastructure from the beginning is a major source of fragility and vulnerability. And given that cities may have decade or century-old infrastructure, there may need to be prioritization of assets when hardening (FEMA, 2017).

(10) *Wicked Complexity* – interdependent and even independent infrastructure are dominated by nonlinear interactions, emergent and self-organizing behavior, and distributed control, key properties of complex systems (Oughton & Tyler, 2013). These properties are defined by physical and non-physical factors and result in limitations on our ability to understand the emergent behavior of infrastructure systems, where the interactions at one level produce unanticipated phenomena at another (Arbesman, 2016). And interdependencies explode this complexity. Consider the 2003 North America blackout. What started as a single downed power line resulted in a cascading failure throughout the Northeast U.S. and Canada that left 55 million people without electricity, some for up to two weeks (NERC, 2004). Beyond the power system, outages were experienced in the water, transportation, communications, and industrial systems. Technical complexity results from several forces: accretion, interaction, and edge cases (Arbesman, 2016). Accretion describes how infrastructure has accumulated and layered technologies over long time periods to the point where it is no longer apparent how controls work (consider the use of the 1980s IBM mainframes by the U.S. Federal Aviation Administration). The ease of interconnections coupled with accretion leads to interactions that over time and scale become so numerous that testing and understanding their behavior becomes challenging. Lastly, edge cases – exceptions to standard design and operating rules – introduce additional layers that obfuscate our ability to understand system behaviors. Given the obdurate nature of infrastructure, their scale, and ubiquitous use, it can be argued that the systems that we so critically rely on naturally tend toward complexity. Complexity is not strictly the result of technical variables. The increased fragmentation of organizations that have some say in infrastructure, and the processes associated with accommodating different perspectives on how infrastructure is designed or managed has contributed to wicked complexity (Conklin, 2006; Willetts, 2015). How to build and operate infrastructure is a wicked problem. Wicked problems are characterized as (i) you don't understand the problem until a solution is developed (implementation of infrastructure provides new insights into the problem), (ii) have no stopping rule (once infrastructure are deployed you often continue to modify them based on changing needs), (iii) having solutions that are not right or wrong (there are generally multiple ways to deploy infrastructure, e.g. route alternatives), (iv) having novel problems (the multitude of technical and social considerations means that how infrastructure are deployed and operated for a particular circumstance are unique), (v) solutions are a one-shot operation (Rittel: 'one cannot build a freeway to see how it works') (v) having no alternative solutions (there may be no way to meet the need, or many potential solutions, but there is no single solution) (Conklin, 2006; Rittel & Webber, 1973). The combination of these factors means that infrastructure is a wicked complex system. This means that it has become extremely difficult, if not impossible, to predict how systems will behave across space and time when

perturbations occur and to change systems towards future goals.

As we've transitioned into the twenty-first century, we will likely find our infrastructure increasingly defined by these challenges. Several of these challenges manifested during the latter part of the last century and combined with emerging challenges – specifically the non-stationarity introduced by climate change and financing – mean that new models of infrastructure design, construction, operation, and use will be needed. As services and technologies change, the demands that we place on infrastructure will also change. To meet these changing demands infrastructure will need to be *agile* (in the face of both predictable and unpredictable challenges) and *flexible,* preconditions for *adaptability*. Yet when it comes to hard infrastructure we have not seen a system that has these characteristics. In the following sections, we explore systems that have successfully implemented these characteristics to meet rapidly changing demands and environmental conditions. We identify the designing principles and operating conditions that enable these systems to behave with these characteristics and discuss the changes that are needed in hard infrastructure systems so that they too can meet rapidly changing demands in the twenty-first century.

Designing and planning principles

Successful infrastructure in the twenty-first century will need radically different design principles. Engineers will need to be part of a process that reconceptualizes infrastructure from the purely physical, to a system that includes institutional components and knowledge as integral parts. Infrastructure will need to change their structure, behavior, or resource use as demands change. In doing so they will need to support the rapid deployment and growth of nascent technologies (such as renewable electricity generation, microgrids, gray water systems, material reuse, and autonomous and electric vehicles) as well as technologies that we haven't yet begun to envision. These technologies are liable to change not just the physical operation, but the mathematics of the underlying systems, in unpredictable ways. A deeper challenge is that we're not just operating on the level of infrastructure itself, but at the implicit models of operation that we sometimes haven't revisited in decades, requiring us to expand how we think about the institutional and disciplinary ways that we think about infrastructure. They will need to create opportunities for embedding sensing, data processing, and data analysis digital (so-called 'smart') technologies that improve our understanding of how interdependent and complex infrastructure behave, provide us with protective measures against vulnerabilities and added security, and enable new understanding of how our built environment functions to improve well-being. These infrastructures will need to be able to meet these characteristics with unpredictability around financing and in the face of both extreme events and gradual changes in climate and the challenges that result from climate instability, in itself a proxy for the challenge of designing and building infrastructure in a world where human activities increasingly impact all environmental systems. And they will usher in new metrics of infrastructure success that measure the ability to meet rapidly changing needs and respond to perturbations. This will require a fundamentally new paradigm in how we design, build, and operate our infrastructure. *Flexibility* and *agility* will need to be at the core of this new paradigm. In the context of hard infrastructure, we distinguish between flexibility and agility based on changing demands and non-stationarity. With rapid changes in technology and ultimately the services that our systems provide, infrastructure will need to be flexible to changing demands. Infrastructure will also need to be agile in that its physical structure and the rules, policies, norms, and actors who manage and operate it, will need to be able to maintain function in a non-stationary future. This includes planning and responding to unpredictable events such as extreme weather or budget shortfalls, disease events, security challenges such as cyber attacks and physical terrorism, population migrations, and other phenomena. Infrastructure managers can expect that at some point in the future these events will occur but cannot easily or accurately predict when or to what extent, or for that matter how perturbations in underlying human and natural systems will manifest themselves. The combination of flexible and agile design and operation characteristics are the preconditions for *adaptability*. These challenges are monumental but they are not without precedent. Successes in implementing flexible and adaptable infrastructure for rapidly changing demands in other industries can offer invaluable insight into the processes that need to shift the design paradigm of civil systems.

How do we design our infrastructure to be adaptable? We don't purport to know the ultimate forms of infrastructure that enable flexibility and agility, as it is likely that these forms have not yet been identified, developed, tested, or implemented. Also, we're not likely training engineers and planners to function in the integrated infrastructure systems of the future (Allenby, 2012). However, what we can do is identify the characteristics of flexibility and agility that have been successfully implemented in other infrastructure and their processes, and describe how they may translate to civil systems. These characteristics do not strictly belong to the physical world; they must also

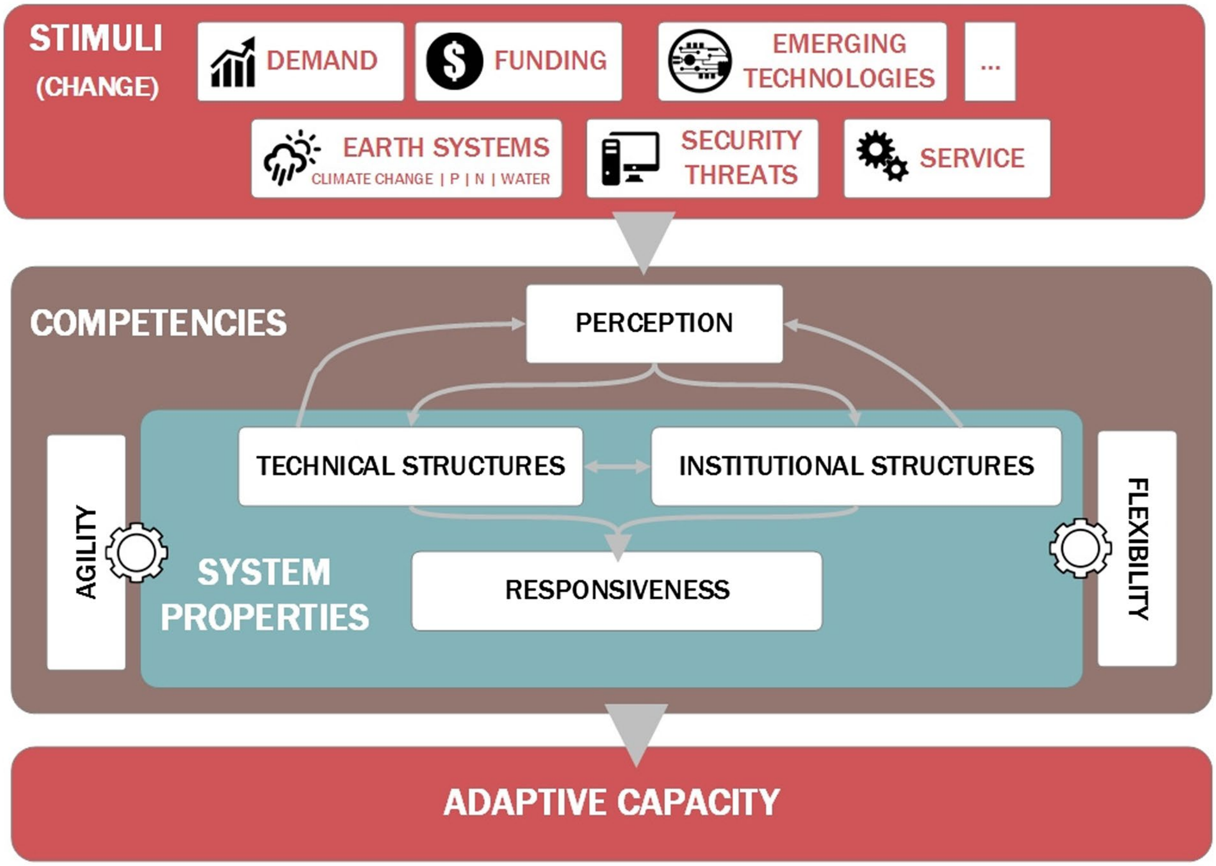

Figure 2. Stimuli, properties, and competencies for adaptive capacity.

exist in the organizations and institutions that manage and govern physical systems. We synthesize characteristics of flexibility and agility from several industries that have successfully changed their organizations and physical processes to meet rapidly changing demands and respond to unpredictability. We focus largely on ICT and manufacturing. We also explore the shifting of technological functions within automobiles and automobile travel to characterize the substitution of functionality from physical to digital and efficiency gains within technological and infrastructural constraints. These industries have infrastructure that have evolved in response to economic and competitive pressures that are not usually felt strongly by either the professionals that design infrastructure, or the public planners and mangers that operate it. Through this review we identify several characteristics that enable flexibility and agility. Given the rapidly changing demands for services that commercial sectors must often meet and the structure of public institutions that typically manage civil infrastructure, we question where best practices are most likely to arise. Finally, we attempt to organize these characteristics into a structured framework, identifying drivers and characteristics that produce competencies for flexibility and adaptability. This framework is shown in Figure 2.

An adaptive infrastructure is one that has the capacity to perceive and respond to perturbations in such a way as to maintain fitness over time. Adaptive infrastructure have the capacity to recognize that stimuli or changes in demand are occurring or will occur including the effects of these stimuli, and have the socio-technical structures in place to change quickly enough to meet future demands. *Stimuli* can take many forms and we focus on those related to the aforementioned challenges. They describe a direct stress (e.g. climate change extreme event or inadequate funding for maintenance), change in demand (e.g. a rapid change in population resulting in more or less need for infrastructure services), or change in service (e.g. a technology or behavioral shift that brings about less to no need for an infrastructure). Other stimuli also exist including emerging technologies and physical and cyber threats. *Competencies* for adaptive capacity include agility and flexibility, but are preceded by the ability to perceive stimuli and how they will affect the system and ultimately the infrastructure. There is a rich body of study on how individuals and organizations perceive risk (Mitchell, 1995; Slovic, 2016). Infrastructure managers must be able to recognize that stimuli are or will occur and understand how they will affect the system. Beyond SCADA systems, they must have physical and informational sensing capabilities that provide insight into the behaviors of increasingly complex and interconnected systems (both in terms of the infrastructure and its use). This is related to sensing and anticipating in resilience frameworks (Hollnagel, 2011; Park, Seager, Rao, Convertino, & Linkov, 2013). Knowledge is a critical aspect of perception which we argue is currently in several ways insufficient to deal with the aforementioned challenges facing infrastructure. As such the capacity for infrastructure managers to anticipate the effects of stimuli is lacking. The capacity to perceive is a function of the technical and institutional structures supporting infrastructure (Hommels, 2005), and frequently fails when rates of change, or system complexity, exceed normal bounds. Institutions tasked with designing, managing, building and maintaining infrastructure do so based on standard practices, codes, and methodologies reinforced by disciplinary expertise, training and organizational culture (Bijker, Hughes, & Pinch, 1987; Carse & Lewis, 2017). In periods of rapid, non-incremental change, this disciplinary training produces barriers to the knowledge needed to understand and respond to stimuli, to perceive, to maintain fitness.

While infrastructure can take on many forms defined by network typology, public to private management, and national to local scale, the *system properties* that define physical configuration combined with the rules and objectives of the managing institutions ultimately affect its ability to respond. Responsiveness is defined as the propensity for purposeful and timely behavior change in the presence of stimuli (Bernardes & Hanna, 2009). The definitions of responsiveness, flexibility, and agility are often conflated, and there have been few efforts to differentiate. Following Bernardes and Hanna, we differentiate in the context of infrastructure adaptation as responsiveness being the propensity for timely behavior change and agility and flexibility being associated with reconfiguration of the system.

Competencies and appropriate system properties enable *adaptive capacity*, the ability of infrastructure to respond to inevitable and unexpected stimuli. Adaptive capacity has largely been defined by sociological–ecological systems researchers (Meerow, Newell, & Stults, 2016). The dominant approach for designing infrastructure systems is that of risk management, i.e. sizing infrastructure to be able to withstand an event of a particular magnitude and frequency (the 100 year return period is often chosen). This approach leads to large gray infrastructure that favor designs that keep hazards away (e.g. levees) or can continue operating during the hazard. Yet as infrastructure become larger and more permanent, the consequences of failure increase (Park, Seager, & Rao, 2011). Furthermore, the less adaptive it is because it has more legacy components that impede efficient system evolution in response to unanticipated stresses. This approach, while robust in protecting against particular shocks, ultimately is highly inflexible for changes in demand beyond what was forecast, can result in major consequences when failure occurs, and is generally unable to cope with unforeseen stimuli. Adaptive capacity approaches are inimical to risk based in that they focus on maintaining capacity in the face of stimuli, minimize the consequences of stimuli instead of minimizing the probability of the damages, privilege the use of solutions that maintain and enhance services, design autonomous management schemes instead of hierarchical, and encourage interdisciplinary collaboration and communication (Ahern, 2011; Möller & Hansson, 2008; Park et al., 2013). We contend that the competencies and system properties needed to achieve adaptive capacity will require transformational shifts in the way that we build, operate, and perceive system purpose and function, and the educational and organizational institutions that we have historically relied on to design and manage infrastructure systems.

Adaptive infrastructure

The competencies and system properties that can help enable adaptive capacities require novel planning techniques, technical and institutional structures, and integration of education and interdisciplinary practices across the life cycle of infrastructure. Drawing on past successes from other industries, recommendations can be made for civil infrastructure systems. Following from Figure 2, the competencies and system properties associated with current infrastructure are contrasted with those of successful adaptive systems, based on the following discussion. These are summarized in Table 1 and discussed in detail as follows.

Table 1. Competencies and system properties for adaptive systems.

Competency	Current	Adaptive
Perception & Responsiveness	Prioritizes perpetuation of existing designs	Roadmapping
Perception, Responsiveness, & Technical Structure	Obdurate design	Design for obsolescence
Technical Structure	Hardware focused	Software focused
Technical & Institutional Structures	Risk based	Resilience based
Technical Structure	Incompatibility	Compatibility
Technical Structure	Disconnected	Connectivity
Technical Structure	Non-modular design	Modularity
Institutional Structure	Mechanistic	Organic
Institutional Structure	Culture of Status Quo	Culture of Change
Perception & Responsiveness	Discipline-focused Education	Trans-disciplinary Education

Note:
For each of the four driving competencies identified in Figure 2, the current approaches and exploration of adaptive approaches are shown.

Roadmapping and planned obsolescence

Industry roadmaps have proven to be valuable for enabling radical innovation and evolution by aligning common goals across a number of different domains. We use the term *roadmap* to describe the development of a model or structure that allows multiple organizations with competing goals operating at many different levels of a technology system to plan together to enable the rapid evolution of systems and manage uncertainty. In the 1990s, during the early stages of development of much of today's ICT backbone and associated computational technologies and tools, roadmapping emerged as a valuable process for prioritizing technologies and identifying infrastructure gaps, suggesting robust interconnections between modules within which powerful innovation was occurring, and creating standards and business practices to meet these challenges across many (often competing) organizations (iNEMI, 2017; Pedersen, Wilson, Pitts, & Stotesbery, 1996). For example, electronic industry roadmaps enabled constant improvement in computer performance at the user level even as disruptive innovation characterized component subsystems (e.g. portable storage devices evolved from large floppy disks to hard disks to thumb drives). At the institutional level, Roadmapping includes creating industry committees and associations, which subsequently use conferences, workshops, less formal collaborative practices, and other activities effectively create institutional structures that supported constant innovation and communication in often highly competitive environments with significant antitrust and other legal constraints. Given that right now funding is often spent on expensive failures instead of preventative maintenance (given limited budgets), roadmapping, when using measures such as return-on-investment, could help identify lower cost pathways in addition to necessary technological change. Without roadmapping, the combination of unpredictable and disruptive innovation, and smooth system level evolution that characterized the growth of electronics and communications technologies across the entire spectrum of the ICT sector would have been impossible.

These roadmapping techniques suggest several general principles supporting agile and adaptive design. Most importantly, at an institutional level they suggest that a complex combination of competition, innovation, and collaboration can be managed through sophisticated use of modular design. They also suggest that rapid cycles of innovation and obsolescence within modules cannot just be tolerated, but encouraged, even as the overall system remains stable. In ICT, they helped to enable rapid and unpredictable development in ICT sub-systems while maintaining a framework that ensured the overall technologies remained operational (Pedersen et al., 1996). They managed unpredictable and important innovation within the module, yet interconnection at the systems level. Applying a roadmap model to infrastructure becomes a way to enable radical innovation within systems, while at the same time supporting a high level of inter-domain communication and constantly improving product providing continuous and uninterrupted functionality to users. Consortia including cities and firms can generate such a roadmap that not only crosses engineering domains (e.g. includes, energy, water, ICT, and transport at a minimum), but policy domains (e.g. tax policy and transportation management), and institutional domains (e.g. the city government with all its silos, and the critical private firms in each sector) to facilitate the planning and operation of next generation infrastructure in non-stationarity conditions, and to encourage continuing innovation and efficiency in provision of services without disruption and at low life cycle cost.

Roadmapping can be valuable for shifting design considerations from obdurate paradigms to planned obsolescence. For many components of infrastructure we favor designs and assets that can last a long time. This paradigm is problematic in that it locks us in to technologies into the long-term, constraining our ability to modernize systems for changes in demand. *Obduracy* in infrastructure persists because managing institutions are constrained in their ways of thinking and changing one component requires multiple changes and it is therefore easier to maintain old configurations than introduce innovation (Bulkeley, Castán Broto, & Edwards, 2014; Hommels, 2005). Alternatively, *planned obsolescence* – planning for changes regarding function, profitability, and other dimensions of performance – can result in greater capacity to substitute infrastructure components and technologies to more efficiently meet changes in demands (Lemer, 1996). Access to infrastructure is important when replacing hardware. Much of our infrastructure is buried underground where access is costly and conditions are often unknown. This inaccessibility encourages waiting for failure. Accessibility will be critical for ensuring quick and frequent replacement or upgrades. While infrastructure obsolescence has largely been studied from a physical asset perspective, the integration of computing and substitution of software for hardware function creates new opportunities for shifting functions.

Software for hardware substitution

With the increasing availability of sensors, processors, and data analytical tools, at decreasing costs, there is a growing *substitution of software for hardware*, transitioning physical to digital processes that increase the flexibility and adaptive capacity of technologies while improving their efficiencies. These technologies are sometimes collectively referred to as 'smart' technologies or systems. They are increasingly replacing or being used to augment the capabilities of physical processes. With their use, industries are finding that core business practices can be shifted (Lohr, 2016). Sensors can predict the structural health of hardware notifying operators of needed maintenance (Lynch & Loh, 2006), measure fluctuations in manufacturing processes and adjust inputs to improve production and reduce costs (Frankowiak, Grosvenor, & Prickett, 2005), and provide real-time information to users or software to adjust operations, likely avoiding the need for manual labor and associated resources. Fuel sensors in automobiles can adjust the air-to-fuel ratio optimizing combustion and emissions. Digital technologies now allow industrial manufacturers to configure processes virtually before changing or upgrading equipment to proactively identify potential incompatibilities in parts or processes (Resnik, 2016). Variable frequency drives that use electronics to monitor motor performance and load requirements to optimize work by pumps eliminating the need for smaller pumps and control valves in applications such as water distribution (Neuberger & Weston, 2012; Roethemeyer & Yankaskas, 1995). Traffic camera software is now smart enough to identify cars, pedestrians, and bicycles, reducing the need for in-pavement loop detectors and the associated asphalt impacts (Kenny, 2004). Implementing wireless communications instead of landlines reduces the need for wiring. In addition to the efficiencies that are gained in substitution, there is likely less waste when you upgrade via software instead of hardware. Additionally, software-driven functions are more agile when faced with unpredictable and rapid change than hardware-driven functions that require physical alterations for upgrades. As software has progressed, the prior practice of upgrading via physical media – sending a disk with the upgrade through snail mail, for example – has become largely obsolete and has been replaced by the use of online software fixes which are more efficient and produce less waste. This is an important evolution improving the agility of embedded software systems. Real-time fixes are necessary in an environment, where malware and viruses are instantaneous; the next step is to have artificial intelligence responding to challenges and changes as they occur on a network-wide basis.

The implementation of smart technologies within existing infrastructure and technologies can create efficiencies within the constraints of inflexible systems. They can also help improve our understanding of the increasing complexities of infrastructure. Take for example the use of GPS, smart phones, and navigation software in personal automobile travel. Initially the automobile consisted of mechanical components with little to no interaction with the environment except through the driver's decisions. With the advent of electronics automobile systems began working together, communicating information to each subsystem so that subsystem-specific adjustments could be made thereby increasing the efficiency of the overall vehicle. Currently smart technologies are introducing new efficiencies. Within the confines and rules of the roadway system, sensing technologies and software are now able to communicate to drivers' shortest paths including routes that avoid traffic, thereby possibly saving fuel and time (Gonder, Earleywine, & Sparks, 2012). These technologies are introducing agility within the constraints of the current infrastructure that is now up to a century old. There are of course limitations to the benefits that these technologies. The inefficiencies or poor condition of old infrastructure may prove to be a limiting factor in how much improvement smart technologies can provide. In the future it is conceivable that smart technologies will know the condition of infrastructure and reroute flows or traffic away from vulnerable links, or prevent component failures from cascading through or across infrastructure. They may provide us with insight into the increasing complexities of infrastructure.

Another benefit of hardware to software substitution is the integration of modules into a larger system or with the environment, effectively changing the *scale and scope* of the system that can then be optimized. With a mechanical system efficiency improvements are largely confined to particular modules. Prior to the integration of software and smart technologies into automobiles, it wasn't possible to optimize the performance of the vehicle in real time, much less reach beyond it. But with sensors and ICT, you cannot only optimize the automobile in real time, but make it part of a much larger system that includes other vehicles, infrastructure conditions, and traffic controls. This hardware to software substitution shifts not only the underlying technologies, but also the larger governing rules of travel where today, navigation software can provide improvements across the entire transportation system and onboard software can optimize how your vehicle is performing in real time.

Risk to resilience thinking

Infrastructure will need to operate in natural environments defined by non-stationarity. For example, infrastructure are already experiencing more frequent extreme weather events, raising questions of whether traditional risk-based approaches to design are adequate. Many infrastructures (or their components) are designed for return periods, for example, a 100 year precipitation event that characterizes in this case an event with a particular intensity that has a

1% chance of occurring annually. However, there is growing evidence that these events will become more frequent and unpredictable, raising questions of which return periods to design to, the affordability of larger designs, and whether we want to live near bigger structures. This risk-based approach which focuses on the risk triplet – threats × threat probability × consequences (Kaplan & Garrick, 1981) is often based on historical data and results in large gray infrastructure with low probabilities of failure, long lifetimes, and oversizing (e.g. levees or retention basins). The problem is that the risk management approach does not incorporate an understanding of what may happen when the infrastructure itself fails. Larger and more permanent infrastructure tend to be associated with greater damages when they fail (Jeryang Park et al., 2011). Climate change necessitates new approaches to infrastructure design that recognize risks but are adaptable in that they do not compromise the entire system upon failure. More broadly infrastructure will need to be design with new rules that recognize the non-stationarity in earth systems, created by human activities.

Compatibility, connectivity, and modularity

ICT, particularly those developed in the Internet age, are designed to meet rapid changes in demand and types of services offered. Early work in ICT recognized the necessity of flexibility as both a system attribute and core competency (Chung, Rainer, & Lewis, 2003). The characteristics of flexibility are defined as compatibility, connectivity, and modularity (Duncan, 1995). *Compatibility* is the ability to share information across different technological components, involving integration rules and access standards which affect shareability and reusability. *Connectivity* is the ability of any technology to communicate with components inside and outside of the system. It is a measure of the number of processes that are able to interact. Connectivity enables shareability which is central to flexibility in that it allows resources to be used for new functions (Duncan, 1995).

Modularization in the manufacturing and computing industries has helped manage complexity, enabled parallel work, and accommodated future uncertainty (Baldwin & Clark, 2006). *Modularity* is the ability to add, modify, or remove components easily, without needing to change other modules and subsystems, achieved through standardization (Duncan, 1995). Integrated systems that lack modularity have fixed processes embedded within the structure that interact, but cannot be easily removed or reconfigured. Likewise, the system is not capable of easily adding new processes. Systems become more manageable when processes are modularized, i.e. processes are designed with standards for information and hardware interactions, and the core routines are compartmentalized. They can be designed independently and used in a variety of situations or systems. Modern computing uses modular design in both software and hardware to enable rapid responses to changing customer demand and manufacturing processes more adaptive (Baldwin & Clark, 2006). The explosive reach of the Internet both in terms of information and hardware embodies these three characteristics. Standards for information transfer such as web languages (e.g. HTML and FTP), transmission and information control protocols (i.e. TCP/IP), and the heavily modularized use of hardware and software have enabled the internet to grow at a pace never before seen (Freeman, Louç, & Oxford University Press, 2001).

Flexible management

Successful organizations reflect the complexity of the environment in which they operate (Hatch, 1997; Vecchio, 2006). Contingency theories state that organizations must be analyzed as open systems that directly interact with their environment, and as such, in order to be effective, must be able to adapt to changing contingencies (Donaldson, 2001; Sherehiy, Karwowski, & Layer, 2007). Organizations that can successfully operate in unstable, changing, and unpredictable environments have organic design characterized by less precise division of labor, wider span of control, more decentralized authority, fewer rules and procedures, and more personal means of coordination (Sherehiy et al., 2007). This is in contrast with the typical mechanistic design of organizations that manage infrastructure which is characterized by highly hierarchical structures, formal management with a centralized authority, a large number of rules and procedures, precise division of labor, narrow span of control, and formal means of coordination. Table 2 contrasts these characteristics in the context of infrastructure. The mechanistic form persists because of historically relatively stable and predictable demands and

Table 2. Characteristics of mechanistic and organic infrastructure management structures.

	Current (Mechanistic)	Adaptive (Organic)
Authority	Hierarchy	Less adherence to authority and control
Communication	Hierarchical	Networked
Knowledge	Centralized	Decentralized
Loyalty	Organization	Project
	High degree of formality	High degree of flexibility and discretion
Coordination	Formal and impersonal	Informal and personal
Rules and Procedures	Many	Few
Tasks	Specialized	Contribution to common tasks

Note: Adapted from Sherehiy et al. (2007).

environments. The ways in which water, electricity, and mobility are demanded have not changed significantly in the past century. The mechanistic approach has been shown to be most effective in environments that require routine operation and little change. In these environments high-level management possesses the appropriate amount of knowledge to make decisions and organize work. However, when the environment becomes unstable, high-level management cannot acquire all of the knowledge associated with the changing environment, and distributing the knowledge and decision-making at the bottom of the hierarchy becomes more effective (Sherehiy et al., 2007). This is because in order for one system to be able to understand and manage another, it needs to be of the same or greater complexity (Ashby, 1960). Organic structures allow for more internal specialization to respond to changing environments, thereby increasing responsiveness (Lawrence & Lorsch, 1967). Sherehiy citing a large body of literature goes on to argue that flexible and adaptable organizations have low fewer regulations of job description, work schedules, organization policies, and power differentials (e.g. titles). They have fewer levels of hierarchy, informal and changing lines of authority, open and informal communication, loose boundaries among function and units, distributed decision-making, and fluid role definitions. Furthermore, authority is tied to tasks instead of positions, and shifts as task shifts (Weick & Quinn, 1999).

Significant questions remain as to whether the public institutions that manage infrastructure have the flexibility to change from mechanistic to organic cultures – do laws and policies constrain their organizational form? Given that public institutions are directly beholden to taxpayers, can they take on new organizational forms or change how infrastructure performance are measured? This should not be taken as an argument that infrastructure should be privatized, but instead as a challenge to conceptualize new management structures that embrace organic characteristics. Taxonomies of organizational flexibility tend to focus on a few key factors to meet changing demands which may be helpful when developing new organizational structures for managing infrastructure (Dastmalchian, 1993). They alter the number of employees and hours through employing part time, temporary or short-term contracts or by changing working times. They create opportunities for changing workforce skills to accomplish a wider range of tasks. And they recommend financial flexibility through pay for performance and profit sharing plans (Dastmalchian & Blyton, 1998; Kalleberg, 2001; Sherehiy et al., 2007). Whether these factors are feasible for public institutions in the context of infrastructure management remains an open question.

Culture of change

Related to flexibility in management is a culture of change, an organization supportive of experimentation, learning, and innovation, and that is aware of changes in the environment (Sherehiy et al., 2007). Whether infrastructure organizations are capable of achieving these remains an open question as a lack of incentives (related to what has historically been consistent market demand), legal and regulatory requirements (such as adherence to codes and regulations), safety requirements, reliability requirements, and constraints (e.g. missions that are tied to public goods, or earmarked funding) exist. Given that infrastructure is typically associated with the provision of public goods, many constraints exist to ensure that resources are delivered reliably, fairly, and at lowest cost, and these constraints may be inimical to rapid experimentation, innovation, and change. We can even question whether it makes any sense to reimagine public institutions that manage infrastructure as reflections of private enterprises that must persist in very different environments. However, there remains pressing need for infrastructure organizations to be able to change to ensure reliability and foster new activities and technologies into the future. Change-oriented cultures are partly the result of education which can take on several forms. Organizations can directly support research activities, and structurally integrate research into decision-making at all levels. They can budget for experimentation, the testing of new and emerging infrastructure designs and management strategies. They can consider changing organizational and individual responsibilities towards the anticipated stressors (and ultimately solutions) and away from structures that are purely disciplinary and focused on process or challenges within those disciplines, toward competencies that span multiple disciplines. Part of this responsibility falls to those educating the next generation workforces.

Education

Institutional design is partially an artifact of training, and infrastructure education (largely engineering) continues to emphasize knowledge and problem solving within single domains. Related, infrastructure continues to be planned, designed, and operated as rigid silos with little to no understanding of the complexity that emerges from the inherent interdependencies of systems. The result is that each system, to the extent it does try to optimize, does so within subsystems. Integrated education at the university level, and integrated planning in practice, is almost the opposite of what we do today, but is a necessity for understanding the impacts of stressors and opportunities for developing strategies to handle stressors going forward.

The true complexity of mitigating the infrastructure crisis includes challenges not only in physical infrastructure and the institutions that manage them but at all levels of knowledge production, starting with education and training. Engineers must be able to think about institutional design in these complex environments, as well as technical design. And engineers don't necessarily need all of the expertise themselves, but could be part of teams that design, deploy, and operate systems.

Lock-in and path dependency

Transitions toward agile and flexible infrastructure will require the identification of, and strategies to overcome, barriers that perpetuate infrastructure forms despite a need to change. These barriers will need to be cataloged and associated with the actors and forces (rules, policies, norms, financing, etc.) that support them. There is a long history of describing how major changes are needed for infrastructure as well as the technologies that use these infrastructure, often expressed as scenario analyses, showing how things can be given some monumental aligning of forces (Delucchi & Jacobson, 2011; Jacobson & Delucchi, 2011; McCollum & Yang, 2009). While some infrastructure have changed quickly (e.g. the shift from landlines to wireless technologies in ICT), when it comes to many core civil systems (i.e. water, electricity, transport) large scale transitions have not happened. This is because many barriers exist that prevent these transitions including financial (lack of funding for capital investments or earmarking of funds for particular purposes), political (limited political will and 'not in my term of office' mentality), codes (minimum parking requirements), social (communities may not see the value of redirecting resources from an established technology to an alternative), cultural (for example, consumers' unwillingness to consume treated wastewater), and technological forces. We describe *lock-in* as the inability to change infrastructure due to these barriers and their often synergistic interactions with other infrastructure (i.e. interdependencies where we cannot radically change the structure or function of one infrastructure because another relies on that structure or function). Many infrastructure have persisted for so long that other infrastructure and institutions have become interdependent, leading to additional barriers and complications for making transitions, and inflexibility. Furthermore, given that demand for infrastructure services doesn't change quickly, we end up prioritizing low cost rehabilitation and supporting of established technologies. Despite the dire state of infrastructure (ASCE, 2016), as long as people get basic services cheaply, the impetus for major reform will not exist. New funds tend to go to these infrastructure and technologies because we know how to do them inexpensively and we've codified so much for them. Also, regulated infrastructure is often permitted to expend capital for variable costs, but not for fixed costs or capital improvements, for example, in the case of American railroads (Wolmar, 2012). While ASCE has done a good job of communicating the state of infrastructure to policy-makers and engineers, they do not engage directly with the general public, the group that will need to pay to avoid aging and failing infrastructure.

The persistence of forces that maintain lock-in into the long term creates *path dependency*, a characteristic of all complex adaptive systems, whereby past conditions significantly impact possible future trajectories. In the case of long lived infrastructure in a period of rapid change, path dependency can lead to the perpetuation of infrastructure and the technologies, activities, and behaviors that rely upon them despite alternative futures being preferable. These alternative paths may describe futures with lower user and public agency costs, reduced energy use and greenhouse gas emissions, or better social equity outcomes. As infrastructure and the technologies they support continue into the long-term, and interdependencies are established with other systems, there exists the possibility that the achievement of benefits become limited. Learning how to design infrastructure in such a way as to enable more desirable future states given the reality and complexity of path dependency thus becomes a necessary future competency.

We characterize the confluence of constraints (barriers) that prevent us from achieving more desirable state as a *limit*. In mathematics, limits are values that functions approach as the inputs approach some value. In the case of infrastructure, limits can be thought of as the practical achievable futures given technical and non-technical barriers. The concept of a limit is important because it recognizes the reality that the infrastructure that we've integrated into all facets of society may not allow us to reach a desirable future, that there's only so much better we can make it or the activities that use it. For example, given the preference and incentivizes for automobile technology focused roadway infrastructure there may not be a pathway where greenhouse gas emissions can be reduced fast enough to avoid some significant climate change threshold. Or consider that the design and deployment of housing stock (specifically the materials, building technologies, and form) may limit our ability to reduce building energy use beyond a certain threshold (Nahlik & Chester, 2015). As such, our current infrastructure and the forces that maintain their persistence are limiting our ability to achieve desired goals. More subtly, so is our educational system. Educating engineers to think of systems only in terms of traditional technological frameworks, such as energy, transportation, or information, makes it difficult to achieve integrated design and management of infrastructure, and thus impedes ability to reduce the deleterious effects of lock-in. And yet engineering education has its own path dependency, reflecting such constraints as professional and school accreditation (e.g. meeting accreditation requirements).

Understanding how lock-in with various coupled systems is acting in a particular design space can help identify the barriers that need be overcome to create opportunities for agile and flexible infrastructure. There is a long history of scenario analysis that shows that it is technologically feasible to reach more preferable future states. Research is needed that identifies the barriers (financial, political, social, technological, institutional, educational, etc.) to achieving these states and competencies needed for overcoming these barriers. These competencies will likely center on changing social and cultural norms, and current educational practices and institutions that drive the formalization of codes and financial structures, and institutional practices that drive infrastructure growth and management.

A century of change

A century from now we may look back and ask ourselves what the costs were of not transitioning our antiquated infrastructure fast enough. These costs would have taken many different forms from economic benefits to environmental losses to possibly even loss of life (consider infrastructure not sufficiently protecting us from climate change). Or maybe we will look back at the monumental success that was the rapid transition of physical infrastructure and their managing institutions, and the accumulating benefits that it afforded. In this future, pipes may still deliver water, lines may still deliver power, and roads may still move people and goods, but infrastructure (as socio-technical systems) will need the competencies and structure to be able to meet changes in service demand in environments of unpredictability. Today, as we debate what the next infrastructure component should be, we should fundamentally question whether new infrastructure should be more of what we already have or something that doesn't exist yet. Until we get to that point, we will maintain lock-in and perpetuate systems that we know may already be obsolete.

Acknowledgments

The authors would like to thank Andrew Fraser, Samuel Markolf, and Thad Miller for their input.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was in part supported by the National Science Foundation's Urban Resilience to Extremes Sustainability Research Network [grant number 1444750].

Notes on contributors

Mikhail V. Chester is an associate professor of Civil, Environmental, and Sustainable Engineering at Arizona State University. His research laboratory studies the resilience to climate change and sustainability of urban infrastructure systems. He and his team identify infrastructure vulnerabilities to climate hazards and work with cities and infrastructure agencies to identify and deploy adaptation strategies. More broadly he is interested in transitioning and designing infrastructure for the Anthropocene. He is co-leader of the National Science Foundation Urban Resilience to Extremes Sustainability Research Network, a consortium of roughly 120 researchers across 17 institutions in North and South America focused on developing novel strategies for preparing urban infrastructure for climate change.

Braden Allenby J.D. is the Lincoln Professor of Engineering Ethics and Professor of Civil, Environmental, and Sustainable Engineering, and Law, at Arizona State University. His areas of interest are design for environment, earth systems engineering and management, industrial ecology, technological evolution, and the convergence of nanotechnology, biotechnology, information and communication technology, and cognitive sciences. He is a AAAS Fellow, a Batten Fellow in Residence at the University of Virginias Darden Graduate School of Business Administration, and a fellow of the Royal Society for the Arts, Manufactures & Commerce. He was the U.S. Naval Academy Stockdale Fellow in 2009-2010, a Templeton Fellow in 2008–2010, and the J. Herbert Hollowman Fellow at the National Academy of Engineering in 1991-1992. During 1995 and 1996, he served as the director of Energy and Environmental Systems at Lawrence Livermore National Laboratory.

ORCID

Mikhail V. Chester http://orcid.org/0000-0002-9354-2102

References

Ahern, J. (2011). From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world. *Landscape and Urban Planning, 100*(4), 341–343. doi:10.1016/j.landurbplan.2011.02.021

Allenby, B. (2012). *The theory and practice of sustainable engineering*. Upper Saddle River, NJ: Pearson Prentice Hall.

Amoroso, E. G., & Vacca, J. R. (2013). *Cyber attacks : Protecting national infrastructure*. OxfordButterworth-Heinemann.
Arbesman, S. (2016). *Overcomplicated: Technology at the limits of comprehension*. Penguin Publishing Group. Retrieved from https://books.google.com/books?id=HTXRCgAAQBAJ.
ASCE. (2016). *Failure to act*. Washington, DC: Author.
ASCE. (2017). *2017 Infrastructure report card – A comprehensive assessment of America's infrastructure*. Washington, DC: Author.
Ashby, W. (1960). *Design for a brain: The origin of adaptive behaviour*. Berlin, Germany: Chapman & Hall and Science Paperbacks.
AWWA. (2012). *Buried no longer*. Denver, CO: Author.
Baldwin, C. Y., & Clark, K. B. (2006). Modularity in the design of complex engineering systems. In D. Braha, A. A. Minai, & Y. Bar-Yam (Eds.), *Complex engineered systems: Science meets technology* (pp. 175–205). Berlin: Springer Berlin Heidelberg. doi:10.1007/3-540-32834-3_9
Bernardes, E. S., & Hanna, M. D. (2009). A theoretical review of flexibility, agility and responsiveness in the operations management literature: Toward a conceptual definition of customer responsiveness. *International Journal of Operations & Production Management, 29*(1), 30–53 doi:10.1108/01443570910925352
Bijker, W. E., Hughes, T. P., & Pinch, T. (1987). *The Social construction of technological systems: New directions in the sociology and history of technology*. Cambridge, MA: MIT Press.
Brennan, D. R., Turnbull, P. W., & Wilson, D. T. (2003). Dyadic adaptation in business-to-business markets. *European Journal of Marketing, 37*(11/12), 1636–1665. doi:10.1108/03090560310495393
Bulkeley, H., Castán Broto, V., & Edwards, G. A. S. (2014). *An urban politics of climate change: Experimentation and the governing of socio-technical transitions*.London: Routledge.
Carse, A., & Lewis, J. A. (2017). Toward a political ecology of infrastructure standards: Or, how to think about ships, waterways, sediment, and communities together. *Environment and Planning A, 49*(1), 9–28. doi:10.1177/0308518X16663015
Chakravarthy, B. S. (1982). Adaptation: A promising metaphor for strategic management. *Academy of Management Review, 7*(1), 35–44.
Chanab, L., El-Darwich, B., Hasbani, G., & Mourad, M. (2007). *Telecom infrastructure sharing: Regulatory enablers and economic benefits*. Retrieved from http://www.boozallen.com/media/file/Telecom_Infrastructure_Sharing.pdf
Childers, D. L., Corman, J., Edwards, M., & Elser, J. J. (2011). Sustainability challenges of phosphorus and food: Solutions from closing the human phosphorus cycle. *BioScience, 61*(2), 117–124. doi:10.1525/bio.2011.61.2.6
Chung, S., Rainer, R. K., & Lewis, B. (2003). The impact of information technology infrastructure flexibility on strategic alignment and application implementations. *The Communications of the Association for Information Systems, 11*(1), 191–206. Retrieved from http://aisel.aisnet.org/cais/vol11/iss1/44/
Conklin, J. (2006). *Dialogue mapping: Building shared understanding of wicked problems*. Wiley. Retrieved from https://books.google.com/books?id=xVRnQgAACAAJ
Costanza, R., de Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., … Grasso, M. (2017). Twenty years of ecosystem services: How far have we come and how far do we still need to go? *Ecosystem Services, 28*(Part A), 1–16. doi:10.1016/j.ecoser.2017.09.008
Dastmalchian, A. (1993). The concept of organizational flexibility: Exploring new direction. In *Organizational flexibility, proceedings of a Colloquium* (pp. 15–25). Victoria, British Columbia: University of Victoria.
Dastmalchian, A., & Blyton, P. (1998). Organizational flexibility in cross-national perspective: An introduction. *The International Journal of Human Resource Management, 9*(3), 437–444. doi:10.1080/095851998340991
Davis, J. (2017, May). Federal Infrastructure Grants: How to Get Back to "Average?" *Eno Transportation Weekly*. Retrieved from https://www.enotrans.org/article/infrastructure-week-preview-federal-infrastructure-grants-get-back-average/
Delucchi, M. A., & Jacobson, M. Z. (2011). Providing all global energy with wind, water, and solar power, Part II: Reliability, system and transmission costs, and policies. *Energy Policy, 39*(3), 1170–1190. doi:10.1016/j.enpol.2010.11.045
DHS. (2017). Critical infrastructure sectors. Retrieved from https://www.dhs.gov/critical-infrastructure-sectors
Donaldson, L. (2001). *The contingency theory of organizations*. Thousand Oaks, CA: SAGE.
Duncan, N. B. (1995). Capturing flexibility of information technology infrastructure: A study of resource characteristics and their measure. *Journal of Management Information Systems, 12*(2), 37–57. doi:10.1080/07421222.1995.11518080
FEMA. (2017). Hazard mitigation planning. Retrieved from https://www.fema.gov/hazard-mitigation-planning
Frankowiak, M., Grosvenor, R., & Prickett, P. (2005). A review of the evolution of microcontroller-based machine and process monitoring. *International Journal of Machine Tools and Manufacture, 45*(4–5), 573–582. doi:10.1016/j.ijmachtools.2004.08.018
Fraser, A., & Chester, M. V. (2016). Environmental and economic consequences of permanent roadway infrastructure commitment: City road network lifecycle assessment and los angeles county. *Journal of Infrastructure Systems, 22*(1), 4015018. doi:10.1061/(ASCE)IS.1943-555X.0000271
Freeman, C., & Louç ã, F., & Oxford University Press. (2001). *As time goes by: From the industrial revolutions to the information revolution*. Oxford: Oxford University Press.
Galeotti, M. (2014). The "Gerasimov Doctrine" and Russian non-linear war. Retrieved from https://inmoscowsshadows.wordpress.com/2014/07/06/the-gerasimov-doctrine-and-russian-non-linear-war/
Garlan, D., Cheng, S. W., Huang, A. C., Schmerl, B., & Steenkiste, P. (2004). Rainbow: Architecture-based self-adaptation with reusable infrastructure. *Computer, 37*(10), 46–54. doi:10.1109/MC.2004.175
Garreau, J. (2011). *Edge city: Life on the New Frontier*. New York: Knopf Doubleday Publishing Group.
Giles, K. (2016). *Handbook of Russian information warfare*. Retrieved from http://www.ndc.nato.int/news/news.php?icode=995.
Gilroy, K. L., & McCuen, R. H. (2012). A nonstationary flood frequency analysis method to adjust for future climate change and urbanization. *Journal of Hydrology, 414–415*, 40–48. doi:10.1016/j.jhydrol.2011.10.009
Gonder, J., Earleywine, M., & Sparks, W. (2012). Analyzing vehicle fuel saving opportunities through intelligent driver

feedback. *SAE International Journal of Passenger Cars, 5*(2), 450–461. doi:10.4271/2012-01-0494
Grisogono, A.-M. (2006). Success and failure in adaptation. In *International Conference on Complex Systems*, Boston, MA.
Hatch, M. J. (1997). *Organization theory: Modern, symbolic, and postmodern perspectives*. Oxford: Oxford University Press.
Hollnagel, E. (2011). *Resilience engineering in practice : A guidebook*. Farnham: Ashgate.
Hommels, A. (2005). Studying obduracy in the city: Toward a productive fusion between technology studies and urban studies. *Science, Technology & Human Values, 30*(3), 323–351. doi:10.1177/0162243904271759
Hrebiniak, L. G., & Joyce, W. F. (1985). Organizational adaptation: Strategic choice and environmental determinism. *Administrative Science Quarterly, 30*(3), 336–349. doi:10.2307/2392666
Hughes, T. P. (1993). *Networks of power: Electrification in western society, 1880–1930*. Baltimore, MD: Johns Hopkins University Press.
Jacobson, M. Z., & Delucchi, M. A. (2011). Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials. *Energy Policy, 39*(3), 1154–1169. doi:10.1016/j.enpol.2010.11.040
Kalleberg, A. L. (2001). Organizing flexibility: The flexible firm in a new century. *British Journal of Industrial Relations, 39*(4), 479–504. doi:10.1111/1467-8543.00211
Kaplan, S., & Garrick, B. J. (1981). On The quantitative definition of risk. *Risk Analysis, 1*(1), 11–27. doi:10.1111/j.1539-6924.1981.tb01350.x
Kenny, R. (2004, May/June). *Replacing in-pavement loops with video detection International Municipal Signal Association*, 32–35.
Kornai, J. (1979). Resource-constrained versus demand-constrained systems. *Econometrica, 47*(4), 801. doi:10.2307/1914132
Lawrence, P. R., & Lorsch, J. W. (1967). *Organization and environment: Managing differentiation and integration*. Boston, MA: Harvard Business School Press.
Lemer, A. C. (1996). Infrastructure obsolescence and design service life. *Journal of Infrastructure Systems, 2*(4), 153–161. doi:10.1061/(ASCE)1076-0342(1996)2:4(153)
Liang, Q., & Xiangsui, W. (1999). *Unrestricted warfare*. Beijing, China. Retrieved from http://www.c4i.org/unrestricted.pdf
Lohr, S. (2016). G.E., the 124-Year-Old Software Start-Up. *New York Times*. New York, New York: New York Times. Retrieved from http://www.nytimes.com/2016/08/28/technology/ge-the-124-year-old-software-start-up.html
Lynch, J., & Loh, K. (2006). A summary review of wireless sensors and sensor networks for structural health monitoring. *The Shock and Vibration Digest, 38*, 91–128.
Marchant, G. E., Allenby, B. R., & Herkert, J. R. (2011). *The growing gap between emerging technologies and legal-ethical oversight: The pacing problem*. New York, NY: Springer.
McCollum, D., & Yang, C. (2009). Achieving deep reductions in US transport greenhouse gas emissions: Scenario analysis and policy implications. *Energy Policy, 37*(12), 5580–5596. doi:10.1016/j.enpol.2009.08.038
Meerow, S., Newell, J. P., & Stults, M. (2016). Defining urban resilience: A review. *Landscape and Urban Planning, 147*, 38–49. doi:10.1016/j.landurbplan.2015.11.011
Megginson, L. (1963). Lessons from Europe for American Business. *Southwestern Social Science Quarterly, 44*(1), 3–13. Retrieved from http://www.jstor.org/stable/42866937
Menendez, J., Siabil, S., Narciso, P., & Gharaibeh, N. (2013). Prioritizing infrastructure maintenance and rehabilitation activities under various budgetary scenarios. *Transportation Research Record: Journal of the Transportation Research Board, 2361*, 56–62. doi:10.3141/2361-07
Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., & Stouffer, R. J. (2008). Stationarity Is dead: Whither water management? *Science, 319*(5863), 573–574. doi:10.1126/science.1151915
Mitchell, V.-W. (1995). Organizational risk perception and reduction: A literature review. *British Journal of Management, 6*(2), 115–133. doi:10.1111/j.1467-8551.1995.tb00089.x
Möller, N., & Hansson, S. O. (2008). Principles of engineering safety: Risk and uncertainty reduction. *Reliability Engineering & System Safety, 93*(6), 798–805. doi:10.1016/j.ress.2007.03.031
Nahlik, M. J., & Chester, M. V. (2015). Policy making should consider time-dependent greenhouse gas benefits of transit-oriented smart growth. *Transportation Research Record: Journal of the Transportation Research Board, 2502*, 53–61. doi:10.3141/2502-07
NCA (2014). *Climate change impacts in the United States*. Washington, DC: U.S. Global Change Research Program.
iNEMI. (2017). iNEMI Roadmap. Retrieved from http://www.inemi.org/
NERC (2004). *Technical analysis of the august 14, 2003, blackout*. Retrieved from http://www.nerc.com/docs/docs/blackout/NERC_Final_Blackout_Report_07_13_04.pdf
Neuberger, T., & Weston, S. (2012). *Variable frequency drives: Energy savings for pumping applications*. Cleveland, OH: Eaton Corporation.
NRC. (2002). *Privatization of water services in the United States*. Washington, DC: National Research Council Committee on Privatization of Water Services in the United States, National Academies Press. doi:10.17226/10135
Oughton, E., & Tyler, P. (2013). *Infrastructure as a complex adaptive system*. Oxford: Infrastructure Transitions Research Consortium.
Paletta, D. (2014, July 16). States siphon gas tax for other uses. *The Wall Street Journal*. Retrieved from https://www.wsj.com/articles/states-siphon-gas-tax-for-other-uses-1405558382
Park, J., Seager, T. P., & Rao, P. S. C. (2011). Lessons in risk-versus resilience-based design and management. *Integrated Environmental Assessment and Management, 7*(3), 396–399. doi:10.1002/ieam.228
Park, J., Seager, T. P., Rao, P. S. C., Convertino, M., & Linkov, I. (2013). Integrating risk and resilience approaches to catastrophe management in engineering systems. *Risk Analysis, 33*(3), 356–367. doi:10.1111/j.1539-6924.2012.01885.x
Pedersen, S., Wilson, C., Pitts, G., & Stotesbery, B. (1996). *Electronics industry environmental roadmap*. Pittsburgh, PA. Retrieved from http://www.cmu.edu/gdi/comprec/eier96roadmap.pdf
Pollard, T. (2003). Follow the money: Transportation investments for smarter growth. *Temple Environmental Law & Technology Journal, 22*, 155.

Resnik, J. (2016). *Virtual assembly lines are making the auto industry more flexible*. *Ars Technica*. Ars Technica. Retrieved from http://arstechnica.com/cars/2016/09/virtual-assembly-lines-are-making-the-auto-industry-more-flexible/

Rinaldi, S. M., Peerenboom, J. P., & Kelly, T. K. (2001). Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Control Systems Magazine, 21*(6), 11–25. doi:10.1109/37.969131

Rittel, H., & Webber, M. (1973). Dilemmas in a general theory of planning. *Policy Sciences, 4*(2), 155–169. doi:10.1007/BF01405730

Roethemeyer, D., & Yankaskas, D. (1995). Evolution of motor and variable frequency drive technology. In *Summer study on energy efficiency in industry conference proceedings* (pp. 541–552). American Council for an Energy-Efficient Economy. Retrieved from http://aceee.org/files/proceedings/1995/data/papers/SS95_Panel2_Paper53.pdf

Sherehiy, B., Karwowski, W., & Layer, J. K. (2007). A review of enterprise agility: Concepts, frameworks, and attributes. *International Journal of Industrial Ergonomics, 37*(5), 445–460. doi:10.1016/j.ergon.2007.01.007

Shirley, C. (2015). *The status of the highway trust fund and options for paying highway spending*. Testimony to the Congressional Budget Office.

Shoup, D. (2011). *The high cost of free parking*. Chicago, IL: Planners Press, American Planning Association.

Slovic, P. (2016). *The perception of risk*. Abingdon: Taylor & Francis.

Tramblay, Y., Neppel, L., Carreau, J., & Najib, K. (2013). Non-stationary frequency analysis of heavy rainfall events in southern France. *Hydrological Sciences Journal, 58*(2), 280–294. doi:10.1080/02626667.2012.754988

Vecchio, R. P. (2006). *Organizational behavior: Core concepts*. Thomson/South-Western. Retrieved from https://books.google.com/books?id=c4dOPwAACAAJ

Vitousek, P. M., Aber, J. D., Howarth, R. W., Likens, G. E., Matson, P. A., Schindler, D. W., … Tilman, D. G. (1997). Human alteration of the global nitrogen cycle: Sources and consequences. *Ecological Applications, 7*(3), 737–750. doi:10.1890/1051-0761(1997)007[0737:HAOTGN]2.0.CO;2

Vörösmarty, C. J., & Sahagian, D. (2000). Anthropogenic disturbance of the terrestrial water cycle. *BioScience, 50*(9), 753. doi:10.1641/0006-3568(2000)050[0753:ADOTTW]2.0.CO;2

Walski, T. (2006). A history of water distribution. *Journal of the American Water Works Association, 98*(3), 110–121. Retrieved from http://www.awwa.org/publications/journal-awwa/abstract/articleid/15413.aspx

Weick, K. E., & Quinn, R. E. (1999). Organizational change and development. *Annual Review of Psychology, 50*(1), 361–386. doi:10.1146/annurev.psych.50.1.361

Willetts, P. (2015). The growth in the number of NGOs in consultative status with the economic and social council of the United Nations. Retrieved from http://www.staff.city.ac.uk/p.willetts/NGOS/NGO-GRPH.HTM

Wolmar, C. (2012). *The great railroad revolution: The history of trains in America*. New York, NY: PublicAffairs.

Zetter, K. (2016). *Inside the cunning, unprecedented hack of Ukraine's power grid*. *Wired Magazine*. Retrieved from https://www.wired.com/2016/03/inside-cunning-unprecedented-hack-ukraines-power-grid/