SUSTAINABLE AND RESILIENT INFRASTRUCTURE
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Reconciling complexity and deep uncertainty in infrastructure design for climate adaptation

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ABSTRACT

As climate change is emerging as a major challenge for man-made systems in the coming century, there has been significant effort to understand how to position infrastructure to adapt and deliver services reliably. Particularly, the climate is changing faster than the expected lifetime of critical infrastructure, resulting in situations well beyond the intended design conditions of a stationary climate. This study assesses how well existing infrastructure design approaches – traditional fail-safe, armoring, low regret, safe-to-fail, and adaptive management – account for climate-related complexity and uncertainty through an application of the Cynefin and Deep Uncertainty Frameworks. The results indicate that existing infrastructure design approaches have varying levels of validity for addressing climate change across spatial and temporal scales. The most common infrastructure design approaches undertake lower levels of complexity and uncertainty than climate change demands, indicating the potential of approaches that address complexity and deep uncertainty have not been fully realized.

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1. Introduction

While wide-scale infrastructure has been largely built only in the past century, the environment in which engineers design infrastructure is drastically changing (Chester et al., 2019). The United States began to heavily invest materials, labor, and money in water, power, and transportation infrastructure in the early 1900s, marking the shift from an agricultural to industrial era (Matos & Wagner, 1998). Since the early twentieth century, there have been many drivers of global climate change, including natural forces such as solar irradiance and volcanoes, anthropogenic sources including greenhouse gas emissions and land-use changes, and ecosystem and climate feedbacks (Fahey et al., 2017). Climate change is of increasing importance given that infrastructure and the environment are intricately linked (Miller et al., 2018) since the phenomena introduces an array of hazards. Managers must be able to adapt infrastructure to the emerging climate patterns that are changing more rapidly than the design life of infrastructure systems. In particular, the rigidity and long design lives of infrastructure may result in systems where the rate of change in climatic conditions that they must be robust against is exceeded.

Infrastructure managers often encounter lock-in from financial, political, technical, social, cultural, and technological barriers, preventing transformative reimagining of infrastructure (Chester & Allenby, 2018). This can be perpetuated since the individual consumer demand of services such as electricity and water have not changed drastically (i.e. individuals continue to expect instantaneous access); however, pressures of urbanization, population growth, and climate change are expected to increase demand and induce stress on existing systems (Ayyub, 2018). Infrastructure services are expected to become less reliable (beyond natural deterioration) due to gradually changing climate patterns while also becoming increasingly vulnerable to extreme weather events (e.g. tropic storms, winter storms) – even when considering modern design standards. This change introduces an emerging challenge to how managers design infrastructure. Typically, engineers design infrastructure parameters to historical climate patterns and extremes. Extreme storm and heat events can impact the integrity of asphalt roads and bridges, causing chronic degradation, acute damage, and higher demand and failure risk (Nasr et al., 2019). For instance, in order to determine the thermal design conditions for roadways, managers refer to standards that encourage the use of 1964 to 1995 climate data to determine temperature extremes (Underwood et al., 2017). These historic extreme temperatures are now being surpassed on a regular occurrence, meaning roadway surfaces will fail more

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frequently (i.e. roadways will have a shorter design life than intended). Extreme temperatures also impact water and power infrastructure (Bondank et al., 2018; Burillo et al., 2017).

Designing infrastructure to historical climate conditions poses a large risk. Investigating stormwater infrastructure design, storm events are integrated by utilizing historical intensity-duration-frequency (IDF) curves to calculate a design storm standard. Typically, for large hydraulic infrastructure, a 100-year design storm standard is chosen (Bauer, 2011). A 100-year design storm is a precipitation event that has a 1 in 100 (or 1%) chance of occurring in a given year based on the historically-derived IDF curves. The use of design storms has come under scrutiny given the reliance on historical data (Adams & Howard, 1986; Ayyub, 2018; Harvey & Connor, 2017; Hirabayashi et al., 2013; Koerth-Baker, 2017; Packman & Kidd, 1980; Watt & Marsalek, 2013). Recent catastrophic floods, such as in Houston, TX (three 500-year floods in 3 years; Ingraham, 2017) and Ellicott City, MD (two 1,000-year floods in 2 years; Bacon, 2018), have resulted in review of employing the 100-year design storm standard by elevating the issue to mainstream media, motivating city officials to update flood mitigation plans, and encouraging further research (Swartz, 2018).

Climate change is also expected to increase extreme cold (Francis & Vavrus, 2012), droughts (Strzepek et al., 2010), sea-level rise (Hansen et al., 2016), and wildfires (Westerling, 2016). These events may be amplified in regions that already experience these hazards, or they may migrate to regions with no past experience of dealing with these threats, increasing risk. Additionally, climate change is expected to increase the magnitude and frequency of extreme weather events (Cheng & AghaKouchak, 2015). Recent catastrophic events such as Hurricanes Katrina (2005), Sandy (2012), Harvey (2017), and Maria (2017) devastated aged and new infrastructure alike. This devastation is not a consequence of neglect by any single (or several) infrastructure manager(s), but partly a consequence of the fundamental decision-making and design approaches utilized in infrastructure that perpetuate lock-in, enforce planning based on historical conditions, and restrict transformative change (Chester et al., 2019). Infrastructure managers heavily rely upon economic analysis, such as cost-benefit analysis, when appraising alternative solutions. These approaches look to quantify the tradeoffs in monetary terms for evaluation, but not all tradeoffs are easily quantifiable – specifically, those related to environmental and social outcomes (Atkinson et al., 2012), which can unintentionally simplify the problem when excluded. As infrastructure managers construct in a world with undefined environmental design parameters due to a rapidly changing climate that undermines the expected lifetime of infrastructure, they must understand the associated complexity and uncertainty (Chester & Allenby, 2019). Climate change is an issue of complexity because there is not a singular solution to address the elaborate interactions between economic, environmental, and social drivers that are causing emergent climatic behaviors. It is also a problem of deep uncertainty, partially related to modelling parameters and assumptions, but primarily driven by the inability to know how socioeconomic systems will respond. This uncertainty may be alleviated or further complexed by new scientific discoveries (Walker et al., 2013b). A variety of decision-making methods have been created to account for these attributes (Table 1 highlights a few of these strategies); however, infrastructure design is still most commonly approached with conventional decision-making methods which do not inherently account for complexity and uncertainty (Sánchez-Silva, 2018; Walker et al., 2013a).

Infrastructure managers must integrate these attributes – complexity and uncertainty – into their design approaches so that infrastructure may continue to provide the services the public has come to expect despite the pressures of climatic shifts and extreme events. For this study, the term ‘infrastructure design approaches’ is referring to various strategies of designing, operating, and maintaining infrastructure for climate change – whether designing new or retrofitting old infrastructure. Infrastructure managers implementing new infrastructure will have increased flexibility, not needing to work around legacy components; however, they will still need to address lock-in such as institutional constraints. The impact of climate change on infrastructure is complex due to the interdependence of infrastructure systems, multiple technologies, competing stakeholders, and other factors that result in their emergent behaviors being systemically unpredictable (Chester & Allenby, 2019). These complex system dynamics with positive and negative feedback loops between numerous infrastructure systems (and individual components) that are not necessarily working in cohesion can cause cascading failures and social consequences beyond what is initially predicted (Rinaldi et al., 2001), emphasizing that infrastructure managers cannot only consider how climate change will impact infrastructure design but how failure may have cascading effects to other infrastructure sectors and services.

Adaptive infrastructure systems should be approached with flexible and agile designs in order to address future challenges such as climate change (Chester & Allenby, 2018). To achieve adaptive systems, Chester and Allenby

Table 1. Infrastructure decision-making methods.

Decision-Making Methods	Description	Source
Conventional		
Cost-Benefit Analysis (CBA)*	CBA is based upon the comparison of costs and benefits (monetized) across potential designs.	(Dittrich et al., 2016)
Cost Effectiveness Analysis (CEA)*	CEA is a comparison of infrastructure alternatives effectiveness evaluated by a single, non-monetized parameter.	(Dittrich et al., 2016)
Risk Assessment*	A risk assessment is a component of risk analysis, which seeks to quantify the probability and magnitude of a risk associated with an infrastructure project.	(Yoe, 2011)
Environmental		
Life Cycle Assessment	This approach considers the emissions and wastes of the infrastructure throughout its entire lifespan (raw material extraction to disposal).	(Baumann & Tillman, 2004)
Environmental Impact Assessment*	An environmental impact assessment considers the impact of development on the environment and further looks to assess avoidance or minimization of those impacts.	(Banhalmi-Zakar, 2012)
Social		
Social Impact Assessment	This qualitative approach assesses the social and cultural consequences of development.	(Burdge & Vanclay, 2012)
Deep Uncertainty		
Real Option Analysis	This method expands upon CBA by adding an adaptable learning component for uncertainty of a singular parameter.	(Swart et al., 2004)
Robust Decision Making	In this approach, a wide variety of scenarios are assessed to determine design parameters. This increases robustness but decreases optimization.	(Lempert et al., 2003)
Info-Gap Analysis	Info-gap analysis focuses on quantifying the information the decision maker knows and does not know by considering uncertainty, risk, and robustness.	(Ben-Haim, 2006)
Adaptation Pathways	The primary focus of this method is to determine which decisions can be made now and which decisions can be made later at identified tipping points.	(Haasnoot et al., 2012)

*Legally/typically required.

(2018) propose 10 competencies: roadmapping, designing for obsolescence, hardware-to-software focus, risk-to-resilience based, compatibility, connectivity, modularity, organic structures, a culture of change, and transdisciplinary education. While achieving completely flexible and agile infrastructure will likely take a transformative alteration of hard and soft infrastructures, where hard infrastructure consists of physical systems such as water, power, and transportation networks and soft infrastructure entails institutions such as politics and finance, emerging hard infrastructure design approaches, including safe-to-fail infrastructure and adaptive management, are being discussed as pathways forward (Dittrich et al., 2016; Kim et al., 2019).

Infrastructure managers need a methodology to navigate climate-related complexity and uncertainty when approaching infrastructure design. In Section 2, the paper will address this gap by mapping existing frameworks for complexity and deep uncertainty together. In Section 3, there is exploration of how existing infrastructure design approaches manage these topics as related to climate change. The Cynefin Framework and levels of deep uncertainty (hereafter referred to as the Deep Uncertainty Framework) address complexity and uncertainty faced by decision-makers and help provide recommendations for making decisions in varying degrees of these attributes as shown in Section 4. In summary, this study applies these frameworks to infrastructure design and seeks to analyze how well existing hard infrastructure design approaches account for the concepts of climate-related complexity and uncertainty in which infrastructure managers operate. By implementing infrastructure design approaches that are increasingly flexible and agile, future infrastructure managers will be further prepared to adapt existing infrastructure to emerging climate patterns and brace for unknowable events as discussed in the final section.

2. Frameworks for complexity and deep uncertainty

Two existing frameworks that focus on complexity and deep uncertainty present opportunities for advancing infrastructure design and management. The Cynefin Framework has been proposed by Chester and Allenby (2019) as a way to conceptualize complexity in infrastructure design and highlights climate change as one of the contributing factors of this complexity. The Deep Uncertainty Framework is also applied since it is frequently identified in climate literature when exploring the uncertainty of climate change (Dittrich et al., 2016; Döll & Romero-Lankao, 2016; Helgeson, 2018; Kandlikar et al., 2005; Manocha & Babovic, 2018; Olsen, 2015; US Army Corps of Engineers, 2015; Walker et al., 2013a). The Cynefin and Deep Uncertainty Frameworks presented in the following subsections will 1) introduce frameworks for managers to evaluate and respond to complexity and uncertainty, 2) provide explicit examples of infrastructure and climate change within each context, and 3) build a tool to evaluate existing infrastructure design approaches' capacity to handle climate-related complexity and uncertainty. It is increasingly important to understand how existing infrastructure design approaches respond to climate change as public demand pushes for climate change to be addressed with new passing policy (Gustafson et al., 2019).

2.1. Cynefin framework

The Cynefin Framework (Figure 1) is a leading management strategy for understanding and making decisions in domains of increasing complexity (Snowden & Boone, 2007). The framework describes four primary domains: obvious, complicated, complex, and chaotic. The first domain, obvious (previously known as simple), is the domain of known knowns, where there is a clear cause-and-effect relationship that reveals a solution. In this domain, all the information is known to make a decision; and, therefore, decision-makers need only to understand the situation, evaluate their options, and take action. The second domain is complicated, where there are known unknowns and cause-and-effect relationships are not clearly apparent. Projects classified as complicated are not straight forward and might have multiple solutions but can be solved with expertise. In this domain, a decision-maker will still sense and respond to a problem; but instead of categorizing the options, they will need to analyze them. This is the realm that infrastructure managers have been operating under by assuming a calculated environmental parameter exists (e.g. design storms for precipitation events). The third domain, complexity, is the domain of unknown unknowns, which emphasizes unpredictability and emerging behaviors. Decision-makers now need to research the problem and associated feedback loops through probing before sensing and responding; however, there will not be a 'right' solution since not all the information can be known. The fourth domain is chaos, where there is no ability to distinguish cause-and-effect relationships. In this domain, a decision-maker should act first to create order, and then sense and respond to the problem. Each of these four primary domains are represented within infrastructure design approaches and their ability to integrate climate complexity as seen in Table 2. There is a fifth domain, disorder, which occurs when decision-makers cannot identify which of the four primary domains they are operating in. In this situation, decision-makers must step back and evaluate the situation to determine which of the four primary domains they are operating.

Infrastructure systems are now operating under the domain of complexity while infrastructure managers continue to design within the complicated domain (Chester & Allenby, 2019). This complexity is derived from the variety of dynamic interactions infrastructure systems have with the natural, built, and social environment. Climate non-stationarity innately moves infrastructure systems from the complicated to complex domain. Infrastructure managers should no longer calculate design parameters from stationary climate datasets but

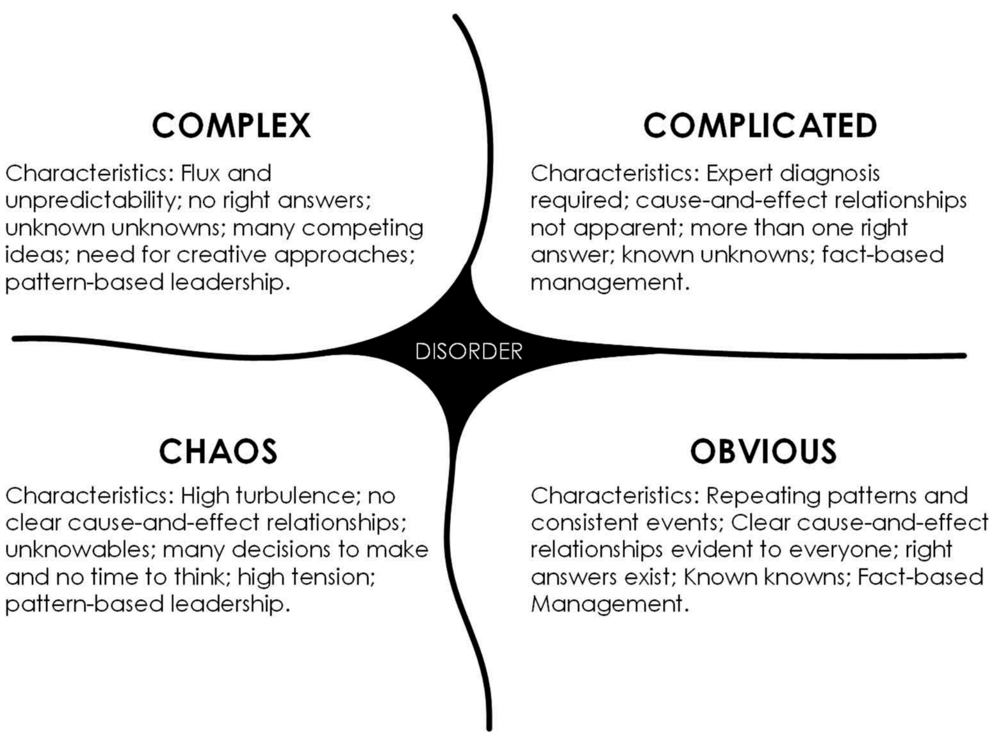

Figure 1. Cynefin Framework as it relates to infrastructure, adapted from (Chester & Allenby, 2019) and (Snowden & Boone, 2007).

Table 2. Cynefin framework domains in infrastructure design approaches relative to climate.

Domain	Climate Scenario	Infrastructure Application
Obvious	Recognizing current weather	Managing day-to-day operations, e.g. not operating airplanes in extreme heat
Complicated	Extrapolating historical climate patterns	Determining environmental design parameters, e.g. design storm standards for water infrastructure
Complex	Analyzing a range of predicted climate scenarios	Implementing infrastructure that expects unpredictability, e.g. planning for failures
Chaos	Experiencing an extreme weather event	Responding to an event without all the information, e.g. immediate response to a level 5 hurricane

instead incorporate climate forecasts (Underwood et al., 2017). Furthermore, the built environment itself is becoming more complex as new technologies are implemented on top of legacy components (Arbesman, 2017), reducing the need for massive infrastructure overhauls, but relying upon infrastructure managers passing down knowledge and production continuing to manufacture parts. Additionally, complexity has increased within the built environment from the interactions between infrastructure systems as seen with cascading failures (Rinaldi et al., 2001). Infrastructure managers must work under the assumption of complexity to manage these factors; however, it is largely unknown how infrastructure should be managed in this capacity – particularly regarding climate change.

2.2. Deep uncertainty framework

The Deep Uncertainty Framework (Figure 2) was created to understand the uncertainty decision-makers face when making decisions. By recognizing uncertainty, a decision-maker can make more confident decisions – and avoid paralysis – by understanding the risk involved (Courtney et al., 1997). There are four levels of deep uncertainty that fall between the extremes of complete certainty and total ignorance. The first level is a *clear enough future* (Level 1) where the decision-maker understands the outcome with small tolerances for uncertainty. In this stage, uncertainty is nearly negligible, and decision-makers do not need to consider the uncertainty-related risk involved. If a stationary climate is assumed, there is little concern regarding how the infrastructure will perform because the environmental design parameters are considered known. In this level, decision-makers may use conventional, environmental, or social decision-making methods as were seen in Table 1 to obtain an optimal solution. The second level, *alternate futures* or *discrete scenarios* (Level 2), describes situations where there are multiple potential outcomes with quantifiable probabilities of occurrence. Climate science has not yet reached this level of certainty due to the complexity of technological, climate, social, and environmental interactions. In this level, decision-makers can only make the best decision based on what occurs, which they can only know retrospectively. In order to make decisions in level two, decision-makers should evaluate each plausible scenario for tradeoffs and consider the probability of that event occurring to make an appropriate decision; therefore, at this point, decision-makers may continue to use conventional, environmental, or social decision-making methods or deep uncertainty decision-making methods listed in Table 1. These trade-offs between probability, risk, and consequence happen frequently in infrastructure management as it is expensive (money, time, resources, etc.) to build infrastructure to withstand the largest risk – especially if it is unlikely to occur. It has been acknowledged that making progress in applicability and understanding risk of deep uncertainty decision-making for infrastructure managers can greatly help address climate change in infrastructure design (Shortridge & Camp, 2019). The next two levels represent deep uncertainty, which climate change has long been attributed to, and these levels often provide the alleged basis for inaction (Kandlikar et al., 2005). Level 3, *range of futures*, describes where numerous outcomes are possible within a range predicted by key variables. The decision-making process for Level 3 is similar to that of Level 2, but the decision-maker must create their own unique scenarios within the range of predicted occurrences that have the highest likelihood of happening for evaluation. A direct

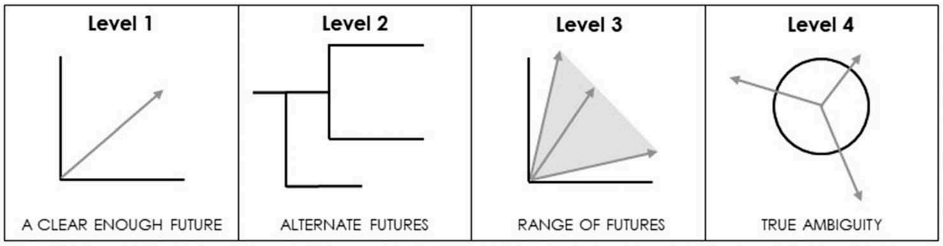

Figure 2. Deep uncertainty framework adapted from (Courtney et al., 1997).

solution cannot be computed, but a decision-maker can test for robustness within this level. Infrastructure managers can implement robust infrastructure, which is designed to handle a wide range of scenarios instead of optimizing for one potential outcome. Since there is not a clear, direct solution within a *range of futures*, infrastructure managers may also implement incremental design until there is a more distinct alternative. Modern climate change models fall into this category. They can predict temperature fluctuations for internally consistent, future scenarios that assign socioeconomic, land use, emission, and climate data; however, it is uncertain how any of these technological, political, and social factors will play out, embedding climate models with a range of uncertainty (van Vuuren et al., 2011). The fourth level of uncertainty, *true ambiguity* (Level 4), is a future that cannot be predicted. In this level, decision-makers should break down what they know, what they can learn, and what they cannot learn. Decision-makers may then track the variables they do know to make incremental changes to their plans as the knowledge becomes available (Courtney et al., 1997). As with the Cynefin Framework, each of level of uncertainty is represented within infrastructure design approaches and their ability to integrate climate uncertainty into design as seen in Table 3. Courtney et al., (1997) assert that most decision-makers will treat problems as Level 1 or 4 uncertainty and apply the same decision-making methods regardless; however, most problems are Level 2 or 3 uncertainty and should not be analyzed in the same manner.

2.3. Understanding complexity, uncertainty, and infrastructure design within climate change

By operating within complexity and deep uncertainty, an infrastructure manager will have established the underlying assumption necessary to achieve flexible and agile infrastructure and, ultimately, adaptive infrastructure systems. Chester and Allenby (2019) connect flexible and agile infrastructure to the Cynefin Framework to understand how managers should make decisions under different domains of complexity. This is necessary as infrastructure must continue to deliver services reliably in an unpredictable environment. Climate science faces uncertainty due to the lack of confidence surrounding the location, timing, and magnitude of climatic change (Ayyub, 2018) and has been asserted a problem of deep uncertainty (Easterling & Fahey, 2018), operationalizing the Deep Uncertainty Framework principles will likely be necessary to make decisions in the future as confirmed by emerging decision-making methods such as real option analysis, robust decision-making, info-gap analysis, and adaptation pathways. Complexity and deep uncertainty are a unified problem, where one cannot be addressed without addressing the other. Complexity is defined by unpredictability and emerging behaviors, which lend to uncertainty of how a system may evolve. Meanwhile, uncertainty is driven by the inability to determine an outcome with confidence, which is heightened by complexity. These concepts are intricately linked and can be visualized when mapping the Cynefin and Deep Uncertainty Frameworks. By navigating these frameworks, infrastructure managers may analyze their designs with a transdisciplinary perspective to create adaptive infrastructure systems. The mapping of these frameworks does not seek to provide an assessment for infrastructure managers to achieve a quantifiable goal, but, instead, looks to provide guidance so that managers may understand how complexity and deep uncertainty is embedded in the design parameters and react accordingly to the presence of these attributes.

By navigating the Cynefin and Deep Uncertainty Frameworks (Figure 3), infrastructure managers can assess the reality of underlying complexity and uncertainty within their design choices. A *clear enough future* (Level 1) from the Deep Uncertainty Framework maps to both the obvious and complicated domains from the Cynefin Framework, depending on the circumstance. When infrastructure design is approached with a fixed set of climatic parameters for the design condition that are either known (obvious) or can be easily calculated (complicated), it is assuming a Level 1 uncertainty as the

Table 3. Deep uncertainty framework levels in infrastructure design approaches relative to climate.

Level	Climate Scenario	Infrastructure Application
Level 1	Utilizing a single extrapolation of climate behavior	Designing infrastructure to manage a fixed environmental design parameter, e.g. a threshold for extreme heat
Level 2	Applying probabilities of climate behavior extrapolations	Constructing infrastructure that designs to the most probable climate scenario, e.g. raising substations to likely flood-safe heights
Level 3	Testing a range of potential climate behaviors	Building infrastructure that may manage minimum and maximum environmental parameters, e.g. phase-change materials in pavements
Level 4	Realizing not all climate behaviors can be known in advance	Creating infrastructure that may be adapted to new information, e.g. adding diverse perspectives to a design team to encourage new ideas

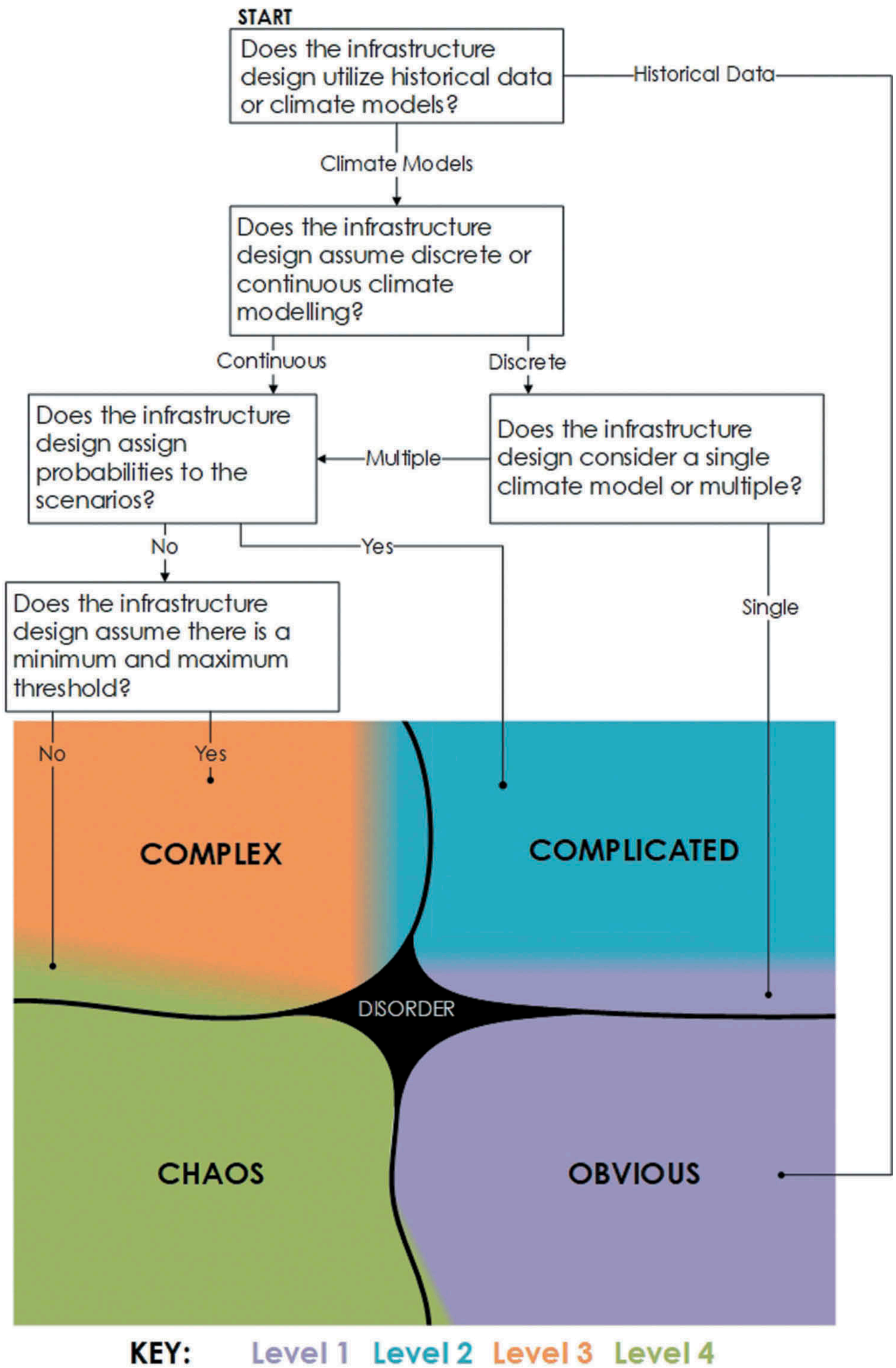

Figure 3. Navigation for infrastructure managers between the Cynefin and Deep Uncertainty Frameworks to understand how climate-related complexity and uncertainty influence design.

climate pattern is not expected to change. This approach is commonly seen in avoidance and anticipatory pathways to climate change. Avoidance pathways ignore climate change and operate with the assumption of a stationary climate. Anticipatory pathways recognize climate change and seek to climate-proof development upon implementation (Asian Development Bank, 2013); however, this still assumes known parameters by accepting an extent of climate change for the environmental design parameter. There are instances where this assumption is valid in infrastructure design, most obviously when the design life is short or within a few months to a couple years, where the weather and climate, respectively, can be reasonably predicted or if the design is a smaller component of a larger system that may be easier to replace or has lower failure consequences. By assuming *alternate futures* (Level 2) uncertainty into an infrastructure design approach, a decision-maker has increased complexity by accepting that there is not a single optimal future but predictable, discrete scenarios. Now, infrastructure managers may need to introduce decision-making methods such as real options analysis or robust decision-making to best understand the knowable risks associated with a particular infrastructure design. An assumption of Level 2 uncertainty related to climate is best applied for infrastructure with a decadal design life such as road surfaces or public buses. This application is ideal for two reasons: 1) climate predictions are more precise due to the shorter time span, and 2) the short design life allows for reevaluation to address long-term uncertainty incrementally.

By *a range of futures* (Level 3), infrastructure managers are operating under complexity through evaluation of a continuous climate model. The representative concentration pathways (RCPs) adopted by the Intergovernmental Panel on Climate Change highlight select pathways from a range of climate futures that can be utilized in infrastructure design, which can be recalled as a decision strategy for Level 3 uncertainty. Here, infrastructure design must be able to account for the deep uncertainty of climate change and the complexity of interactions that further drives the uncertainty. There is often no singular solution to reasonably accommodate all RCPs, but infrastructure design may be approached in a manner where it is flexible and agile enough to adapt to new information. The inclusion of RCPs within an infrastructure design approach may be seen as an adaptation strategy to climate change, where infrastructure managers plan to adapt to future complexities and deep uncertainties; and, therefore, they approach decision-making and infrastructure design with intentions of adjusting or reiterating upon the first design implementation. This approach is optimal for infrastructure with a design life of decades to centuries as it allows planning for change throughout the design life. For instance, integrating green infrastructure into a stormwater management system helps reduce volume throughout the man-made pipe system. As rainfall intensity increases, infrastructure managers may choose to implement more green infrastructure to maintain the integrity of the pipes. Finally, *true ambiguity* (Level 4) of the Deep Uncertainty Framework can be approached with the same incremental design changes as Level 3 uncertainty but with recognition that it also associates with the chaotic domain in the Cynefin Framework since chaotic events cannot be predicted. While infrastructure cannot be designed specifically to handle unforeseeable events, infrastructure that is designed to manage increasing complexity and uncertainty will have an increased likelihood of withstanding these abnormalities.

3. Capacity of infrastructure design approaches to manage climate complexity and uncertainty

Infrastructure managers utilize a variety of design approaches across the water, power, and transportation sectors, but there are no universal methodologies established for infrastructure design, management, and transformation (Hansman et al., 2006; Shortridge & Camp, 2019). Typically, traditional fail-safe approaches are utilized, designing infrastructure to legal safety standards and the customer's satisfaction in the most efficient manner available (Ayyub, 2018). However, there have been proposed approaches for climate adaptation to address complexity and uncertainty (Olsen, 2015) such as armoring, low regret, safe-to-fail, and adaptive management (Table 4). Each of these infrastructure design approaches have varying capacities to manage climate-related complexity and deep uncertainty, and these capacities can be explored by navigating the Cynefin and Deep Uncertainty Frameworks to evaluate the flexibility and agility of existing infrastructure design approaches. Each infrastructure design approach is analyzed independently throughout this section to understand their origins and fundamental assumptions; however, it is important to realize that these practices may be used in conjunction throughout a system, which is encouraged in the discussion. For example, adaptive management can be applied to fail-safe approaches to increase infrastructure flexibility: the infrastructure may be strengthened after implementation or even rebuilt at pre-determined intervals. However, the infrastructure managers would no longer be operating with the fundamental assumptions of fail-safe design but those of adaptive management even though it may initially appear to be a fail-safe approach.

3.1. Traditional fail-safe infrastructure

Traditional fail-safe methods use historical climate patterns to determine these parameters. This is a risky, avoidance approach to infrastructure design due to non-stationarity; therefore, fail-safe infrastructure may be stretched beyond its designed capacity, resulting in cascading, and potentially catastrophic, failures. When considering the complexity and

Table 4. Infrastructure design approaches.

Infrastructure Design Approaches	Description	Examples
Traditional Fail-Safe	Infrastructure designed to withstand stress up to a pre-determined design parameter, and when these parameters are breached, the design fails in uncontrolled ways (Kim et al., 2019).	Formulating material for a roadway based upon historical maximum temperatures.
Armoring Fail-Safe	Infrastructure that utilizes a fail-safe approach but uses more stringent environmental conditions for parameters.	Increasing a levee height based upon future climate predictions.
Low Regret	Infrastructure that will perform well across a range of futures without changing the function of the system and having co-benefits (Olsen, 2015).	Employing transmissions lines with capacity to handle low and high predicted peak demands.
Safe-to-Fail	Infrastructure designed to lose function in controlled ways, thus different types of failure consequence are experienced as expected based on prioritized decisions (Kim et al., 2019).	Implementing a green space that retains water during storm events but otherwise serves as recreational space.
Adaptive Management	Infrastructure designed to for risk-adverse incremental adjustments, where this changeability increases the ability of infrastructure to react to known and unknown uncertainties (Allenby, 2011; Sánchez-Silva, 2019).	Constructing a building along a coastline that has an easily modifiable first floor to prepare for sea level rise.

uncertainty frameworks, it is evident that the underlying assumption of traditional fail-safe design approaches align with Level 1 uncertainty and the complicated domain. By operating under these assumptions, traditional fail-safe infrastructure design is inflexible and perpetuating lock-in because the design process does not consider any deviations from the expected climate pattern. The challenge of lock-in with traditional fail-safe design is further fortified by social norms, which perpetuate the application of this infrastructure design approach. For instance, within the stormwater field, infrastructure managers (e.g. developers, regulators, engineers, practitioners, etc.) are accustomed to the traditional fail-safe design approach and the risks associated with it (Roy et al., 2008); consequently, their institutions are optimized to handle these expectations.

3.2. Armoring infrastructure

Armoring (also referred to as hardening or strengthening) infrastructure utilizes the same approach as traditional fail-safe infrastructure; however, climate forecasts are used to determine design parameters. Typically, this increase of robustness occurs after a failure. For instance, if winds during an extreme event wreck power lines, standards may be adjusted to protect infrastructure from this higher wind speed. This approach remains risky as infrastructure managers deliberate between the probabilities of alternative scenarios and trade-offs to determine the design parameters. There is no confirmation that building to a particular climate scenario – or even the worst-case climate scenario – will protect the infrastructure in the future since there is uncertainty in climate modelling. Therefore, if the new environmental parameters are exceeded, the infrastructure will fail even more catastrophically than traditional fail-safe due to designing to a stronger magnitude of event. This can be seen in the levee effect and safe development paradox where hazardous areas are made safer by the government such as levees designed to withstand a larger flooding event, and developers feel more protected and continue to build within the flood zone (Burby, 2006).

Armoring infrastructure design continues to operate under the complicated domain because the approach does not consider the emerging behaviors of climate and remains an inflexible approach that identifies a singular climate outcome as a design parameter for the infrastructure. The armoring approach may assume Level 2 uncertainty if infrastructure managers compare alternative futures to determine the parameters, or it may assume Level 1 uncertainty if managers simply design to the worst-case event that has occurred. Notably, if Level 2 uncertainty it involved, the infrastructure will be simplified to Level 1 uncertainty upon implementation since the design will target a single scenario. This infrastructure design approach still perpetuates lock-in, ignoring climate-related complexity and deep uncertainty. It is important to recognize that this anticipatory approach is not adaptive toward climate change and exhibits the same concerns as traditional fail-safe infrastructure despite being utilized in practice as a response to climate change.

3.3. Low regret infrastructure

Low regret infrastructure differs from armoring in that the infrastructure is designed to manage more than one climate scenario. This strategy is oftentimes inflexible; however, the approach steps away from optimization and moves toward robustness. A robust approach minimizes risk over the lifetime of the system as long as the infrastructure's design life is shorter than the occurrence of climate patterns altering beyond the minimum and maximum design parameters. The robust strategy of low regret infrastructure inherently assumes complexity and Level 3 uncertainty. First, the design approach considers the complex domain by acknowledging there are unknowable environmental design parameters due to emergent behaviors in climate patterns. Second, the approach accommodates a range of potential futures (Level 3) uncertainty; it does not yet accept true ambiguity (Level 4) since it is an inflexible approach to design. If adaptive management approaches were combined with the low regret strategy as explored by Olsen (2015), the system would have the potential to address Level 4 uncertainty. The integration of iteration has not been universally adopted into low regret infrastructure literature (Dittrich et al., 2016; Preston et al., 2013). By the definition adopted here, low regret infrastructure still perpetuates lock-in due to the inflexibility to adapt the infrastructure over time, but it does take an anticipatory approach to climate change recognizing deep uncertainty.

3.4. Safe-to-fail infrastructure

Safe-to-fail design methodology embraces the happenstance of extreme events by expecting and containing such occasions (Park et al., 2013). Desired outcomes of safe-to-fail infrastructure include maintaining services; minimizing consequences; promoting social and ecosystem services; designing decentralized, autonomous infrastructure; and encouraging transdisciplinary perspectives (Kim et al., 2017) through the use of design strategies that follow the competencies of flexible and agile infrastructure (Ahern, 2011; Chester & Allenby, 2018; Park et al., 2013). Safe-to-fail infrastructure ultimately assumes complexity and Level 4 uncertainty by recognizing that the interactions between infrastructure and the natural environment are not predictable. Therefore, safe-to-fail designs infrastructure to handle this unpredictability (i.e. uncertainty) by controlling failure and managing both the working and failing operational states of the system. This infrastructure design approach embodies an adaptable strategy that embraces modularity and learning so that the design may be adjusted to emergent climate patterns. If complexity and deep uncertainty simplifies, safe-to-fail infrastructure would still be operational, allowing this infrastructure design approach to also operate within the other domains. Safe-to-fail infrastructure has the capacity to manage complexity and uncertainty of climate change and provides a valuable adaptive strategy for infrastructure managers.

3.5. Adaptive management

Adaptive management assumes complexity and Level 4 uncertainty, but has the capacity to address complicatedness and all levels of uncertainty although that would potentially be an overexertion of resources. Adaptive management must consider financial, political, environmental, technical, social, cultural, and technological inputs to determine a best course of action forward. These inputs are web of dependencies and interdependencies, which results in emergent behaviors and exemplify complexity. At this time, it is difficult for infrastructure managers to assess the benefits of flexible infrastructure, but researchers are working toward developing long-term evaluation methods (Špačková & Straub, 2017). Adaptive management should be approached as a transdisciplinary problem due to the complexities involved, and infrastructure managers should look to integrate multiple perspectives into the design process (Chester & Allenby, 2019).

Concerning uncertainty, adaptive management addresses Level 4, or *true ambiguity*, as there is no determination of the design conditions expected near the end of lifetime of the infrastructure. Instead, the approach looks to make incremental and experimental adaptations as new information is available. This means that the infrastructure managers can address climatic deep uncertainty while making less risky decisions. In order for this to work properly, infrastructure managers cannot indefinitely resign from the next incremental design change but must accept a threshold of uncertainty or a frequency of adaptation. Recent literature by the Committee on Adaptation to a Changing Climate (Ayyub, 2018) promotes the observational method, a form of adaptive risk management to address climate change but also recognizes limitations of available knowledge exploring deep uncertainty in practice. Altogether, this approach embraces the concept of flexible and agile infrastructure, alleviating lock-in and providing an adaptation strategy to climate change.

4. Discussion

Climate change is a wickedly complex problem surrounded by deep uncertainty, and infrastructure managers are in the nascent stages of integrating measures within their designs to protect against known and unknown hazards. Existing infrastructure design approaches are positioned to address a range of

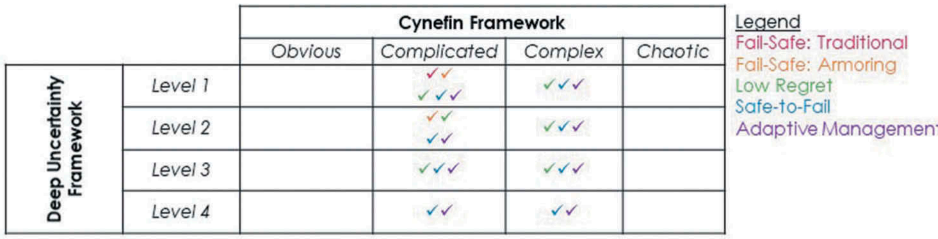

Figure 4. Capacity of infrastructure design approaches to handle climate-related complexity and uncertainty.

complexity and uncertainty challenges (Figure 4). However, these approaches are not necessarily designed to directly address these attributes, but provide promising qualities that can be employed to support resilient infrastructure in a future marked by these challenges.

Current state-of-practice remains largely focused on fail-safe approaches (Kim et al., 2019), which operate in the complicated domain. This simplification of complex problems as complicated problems are likely to perpetuate lock-in. As this paper has shown, by only considering the effects of climate non-stationarity, infrastructure design can be considered a problem of complexity and deep uncertainty. Yet, there are numerous other factors – interactions and interdependencies between natural, built, and social environments, accretion, cascading failures – that increase the complexity and uncertainty of infrastructure design. The reconciliation of the Cynefin and Deep Uncertainty Frameworks is not exclusive to climate non-stationarity but may be extended to consider these other factors.

Furthermore, as seen in Figure 4, none of the infrastructure design approaches were mapped to the obvious or chaotic domains of the Cynefin Framework. There are no obvious approaches because infrastructure design fundamentally requires expertise and are not problems of categorization as seen in the obvious domain. Additionally, no approaches are explicitly classified as chaotic since this is the domain of unknowables that cannot be foreshadowed and, therefore, cannot be planned for; however, as designs become more flexible and agile, they reduce the potential magnitude of impact of chaotic situations. In the examination of the Deep Uncertainty Framework, all levels of uncertainty are accounted for across the six identified design approaches. This indicates that a specific infrastructure design approach is neither a valid or invalid approach for designing infrastructure to address climate change, but it may be better adept to addressing a particular scale of complexity and uncertainty. Infrastructure systems assuming complexity and deep uncertainty will be more equipped to handle chaotic and truly ambiguous scenarios by implementing systems that are capable of adaptation (and proactively investing in that competence).

4.1. How to approach infrastructure design for climate-related complexity and uncertainty?

Not every component of an infrastructure system will need to be designed exclusively for complexity and deep uncertainty to improve resilience. Resilience is the ability of a system to rebound from a disruption to intended functionality, increase robustness to maintain a state of functionality in increasing complexity, an ability to dampen the impacts of a disruption, and produce sustained adaptability (Woods, 2015). This indicates that infrastructure managers must be able to determine when an inflexible strategy (traditional fail-safe, armoring, and low regret) should be chosen in lieu of a flexible strategy (safe-to-fail and adaptive management) to address the varying degrees of climate-related complexity and uncertainty within an infrastructure system. One way to place the appropriateness of an approach is to consider scale. Overall, an infrastructure system (e.g. stormwater management of a watershed) should be flexible and agile, but not every individual component (e.g. a pump) must be designed in this mindset to achieve a resilient system. Therefore, infrastructure managers should consider the goals and characteristics of their design to determine an appropriate approach.

Figure 5 shows the characteristics of infrastructure design approaches with their capacity to address climate-related complexity and uncertainty and when they are best applied. The key difference in the characteristics of infrastructure addressing complicatedness and low uncertainty compared to complexity and deep uncertainty is fundamentally the focus on optimizing versus satisficing. Optimization is traditionally defined in engineering as maximizing the performance or efficiency of the primary function while minimizing costs. Satisficing (an agglomeration of the words satisfy and suffice) is settling on a course of action that may not be

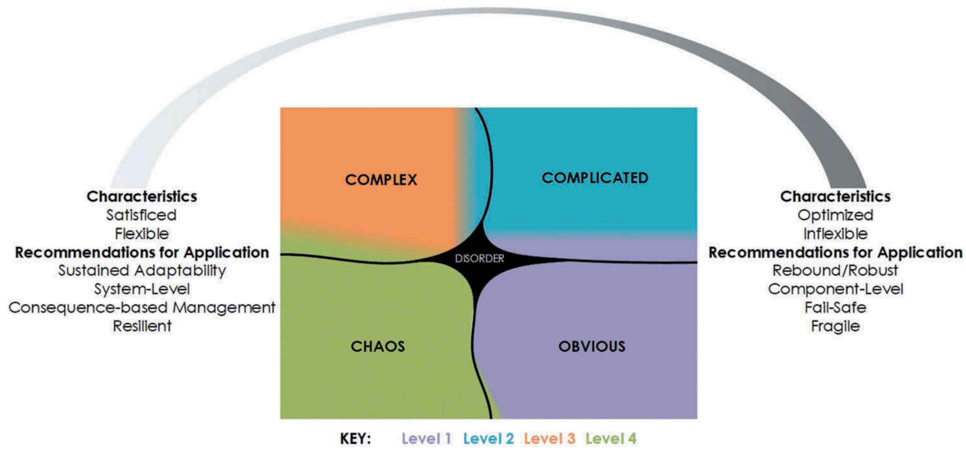

Figure 5. Characteristics and recommendations for application of infrastructure design approaches considering capacity to address climate-related complexity and uncertainty.

optimal, but is good enough (Chester et al., 2019). Therefore, there are times when one side of the spectrum may be more appropriate for designing than the other. There are instances in infrastructure design where there is reduced complexity and uncertainty. This can arise when an infrastructure has a planned obsolesce within a short time frame. It can also occur when a component or sub-system has minor failure consequences (spatially and temporally) within a system. Lastly, some components are fragile to environmental parameters and must operate in a fail-safe manner. Components and subsystems with short design lives and few failure consequences will benefit most from a fail-safe design choice since it will not be a question of 'if' the infrastructure will fail but 'when' as the environmental design conditions are exceeded by gradual climate change or extreme events and a short design life forces adaptation.

Climate science is not yet definitive enough to make accurate long-term assessments of the environmental conditions in which infrastructure will need to operate due to uncertainty of socioeconomic responses, meaning projects with longer design lives or larger failure consequences should be approached in a way that considers complexity and deep uncertainty (Easterling & Fahey, 2018). This finding aligns with the recommendations of the Committee on Adaptation to a Changing Climate, which states that higher levels of uncertainty analysis should be utilized for critical infrastructure with design lives greater than 30 years (Ayyub, 2018). In order to make the tradeoff between fail-safe and safe-to-fail infrastructure, infrastructure managers must consider their project as part of a larger system that interacts with the given infrastructure sector, other infrastructure sectors, society (including their institutions and governances), and the environment so that they may understand the potential failure consequences and/or cascading effects when assessing the design. Furthermore, infrastructure managers cannot assume a previous system is adaptive or resilient purely because it has exhibited these competencies in the past, since the lack of failure does not necessarily indicate resilience (Hollnagel et al., 2006). Infrastructure managers must continue to question their design processes and evaluate them to emerging behaviors and information. It is important to recognize that the ability of an infrastructure manager to make decisions is constrained by their institution and resources. Some of these constraints are obvious such as funding and time, but others may be deeply embedded in the system and not yet recognized. To effectively address complexity and deep uncertainty in infrastructure design, there needs to be a change in culture within the establishment as well as increased education across disciplines – two competencies identified by Chester and Allenby (2018) for flexible and agile infrastructure. Institutions that design infrastructure are large hierarchies with many subdivisions that must all be educated on the long-term goals of address complexity and uncertainty to achieve resilience because a system must be considered holistically to achieve resilience. Arteaga-Bastidas and Stewart (2019) recommend for institutions to have high engagement with stakeholders, identify decision-relevant information, integrate from national to local levels, employ decision-making tools based in science, and secure funding to achieve resilient infrastructure. To achieve the goals outlined in this discussion, institutions should promote multidisciplinary teams to expand perspective. This challenges the current institutional structure, which struggles to integrate multidisciplinary perspectives due to constraints such as funding and time. However, by reforming institutions and investing in diverse perspectives and acknowledging opportunities for flexibility, infrastructure managers will have the capacity to expand the design life of infrastructure in today's changing climate.

At present, infrastructure managers generally seek immediate solutions (i.e. fail-safe infrastructure) rather than proposing systems that will need to be continuously maintained and managed (Park et al., 2013), which leaves the majority of infrastructure incapable of addressing deep uncertainty. This requires a significant change in mindset from current engineering practice from one of optimization to one of satisficing – and ultimately flexibility – as advocated in deep uncertainty decision-making literature to 'monitor and adapt' rather than 'predict and act' (Chester & Allenby, 2019; Walker et al., 2013a). A low regret strategy operates within complexity and Level 3 deep uncertainty, and this approach is best applied to projects that have a design life within a couple of generations or integrated into systems that need to increase flexibility. Low regret can address water, power, and transportation infrastructure, and this leaves low regret infrastructure being the most common infrastructure design approach promoted to address Level 3 uncertainty in the power and transportation sector since safe-to-fail and adaptive management has not penetrated these sectors as it has in the water sector. Low regret infrastructure can be a costly way forward if everything is designed and implemented to operate for all climate scenarios; therefore, it needs to be determine in what situations this infrastructure design approach would be preferred in a system. Infrastructure managers can implement safe-to-fail and adaptive management strategies, which address upwards of Level 4 uncertainty, to fill this void of flexible infrastructure. Safe-to-fail and adaptive management infrastructure are best equipped to manage climate-related complexity and deep uncertainty due to their flexible and agile nature. Therefore, these design approaches should be utilized for large-scale infrastructure systems that have long design lives, larger consequences upon failure, and flexibility toward environmental design parameters (refer to Figure 5). However, adaptive management, while seen as an inherent component of socio-ecological systems (SES) (Cote & Nightingale, 2012), is infrequently applied beyond conceptual theory to water, power, and transportation infrastructure design (Chester & Allenby, 2019) although promoted by the new manual of practice, *Climate-Resilient Infrastructure* (Ayyub, 2018). Adaptive management accounts for deep uncertainty by enabling infrastructure managers to evaluate their options over time, which parallels the engineering design process where engineers are taught to reiterate – or improve – their design as more information becomes available. Infrastructure managers should explore how to conduct a reiterative adaptive management approach within large systems, which has significant barriers of lock-in previously explored. In order to be successful, infrastructure managers must clearly define and communicate objectives; work collaboratively; and monitor, learn, and adjust strategies to adapt to emerging climate science. As new information becomes available, infrastructure managers can either decide between maintaining current practices and implementing new strategies. Both of these approaches – safe-to-fail and adaptive management – need further exploration to become influential within design, particularly, regarding adaptive management.

The examination of adaptive capacity for infrastructure to manage deep uncertainty reveals two important paths forward. First, infrastructure design addressing Level 3 deep uncertainty needs to be flexible and agile. As aforementioned, Chester and Allenby (2018) identified 10 competencies for flexible and agile infrastructure: roadmapping, designing for obsolescence, hardware-to-software focus, risk-to-resilience based, compatibility, connectivity, modularity, organic structures, a culture of change, and transdisciplinary education. Infrastructure managers should not design an inflexible structure when there are not clear or likely environmental design conditions because that infrastructure is subjected to become antiquated and risk failure. With no learning or management in place, the infrastructure will need to be rebuilt to meet new design conditions (if it is under-designed), which is costly and time-consuming. Gilrein et al. (2019) identify 50 infrastructure practices that demonstrate adaptability. For example, one way to increase the flexibility of infrastructure by utilizing the hardware-to-software, compatibility, connectivity, and modularity competencies is to incorporate information and communication technology (ICT), making smart infrastructure with a feedback loop between design, operation, and maintenance (Stephens et al., 2013; Trindade et al., 2017). While ICT innately increases complexity and uncertainty through the integration of an additional technological layer to infrastructure, infrastructure managers can leverage monitored changes between the built infrastructure and surrounding environment with emerging climate science to adapt the system to specific feedback. Another pathway, utilizing competencies such as risk-to-resilience thinking, is to strategically integrate green infrastructure into system designs. Green infrastructure (GI) is broadly defined as 'environmental or sustainability goals that cities are trying to achieve through a mix of natural approaches' (Foster et al., 2011). GI may be fail-safe or safe-to-fail depending upon implementation, but a clear benefit of green infrastructure (versus grey infrastructure) is the ability to provide ecosystem services in addition to the intended services.

5. Conclusion

The climate is changing faster than the design life of infrastructure, leaving infrastructure vulnerable as it must operate in conditions it was not designed to withstand. This is primarily credited to infrastructure lock-in – structural and institutional – which is associated with standards and incentives that encourage infrastructure managers to continue implementing inflexible fail-safe infrastructure. These standards and incentives have been implemented where 'traditional risk analysis is used to determine the acceptable likelihood and magnitude of an event to which infrastructure is expected to withstand' (Markolf et al., 2018), leaving infrastructure vulnerable to changing conditions. Climate change can be an overwhelming concept to evaluate in infrastructure design, but it is important to not let emergent behaviors paralyze efforts to create resilient infrastructure. By embracing the Cynefin and Deep Uncertainty Frameworks, infrastructure managers have tools to assess the contexts of complexity and deep uncertainty and may respond accordingly to address those contexts within design. The preceding review of existing infrastructure design approaches shows that those being employed today are capable of addressing varying contexts of climate-related complexity and deep uncertainty, and even increasing a buffer for truly ambiguous events. However, the majority of infrastructure approaches applied in practice operate in the context of complicatedness and uncertainty. Infrastructure managers should pursue approaches that assume complexity and deep uncertainty in system design while also looking to expand the capacity of less adaptive approaches to become more resilient by integrating opportunities for flexibility and agility. This navigation of the Cynefin and Deep Uncertainty Frameworks improves comprehensibility of integrating conceptual attributes of complexity and deep uncertainty into design practice so that infrastructure managers may understand the contexts in which they are operating and implement appropriate design for the situation.

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