Abstract

Anthropogenic climate change poses risks to transport infrastructure that include disrupted operations, reduced lifespan and increased reconstruction and maintenance costs. Efforts to decrease the vulnerability of transport networks have been largely limited to understanding projected risks through governance and administrative efforts. Where physical adaptation measures have been implemented, these have typically aligned with a traditional 'engineering resilience' approach of increasing the strength and rigidity of assets to withstand the impacts of climate change and maintain a stable operating state. Such systems have limited agility and are susceptible to failure from 'surprise events'. Addressing these limitations, this paper considers an alternate approach to resilience, inspired by natural ecosystems that sense conditions in real-time, embrace multi-functionality and evolve in response to changing environmental conditions. Such systems embrace and thrive on unpredictability and instability. This paper synthesises key literature in climate adaptation and socio-ecological resilience theory to propose a shift in paradigm for transport infrastructure design, construction and operation, towards engineered systems that can transform, evolve and internally manage vulnerability. The authors discuss the opportunity for biomimicry (innovation inspired by nature) as an enabling discipline for supporting resilient and regenerative infrastructure, introducing three potential tools and frameworks. The authors conclude the importance of leveraging socio-ecological resilience theory, building on the achievements in engineering resilience over the past century. These findings have immediate practical applications in redefining resilience approaches for new transport infrastructure projects and transport infrastructure renewal.

Keywords: Transport and society, socio-ecological resilience, engineering, infrastructure, climate change

Introduction

While international efforts to mitigate anthropogenic climate change continue, it is recognised that cities and communities must adapt to unavoidable changes in climate conditions. With over half of the global population residing in cities, and with the frequency and intensity of extreme weather events projected to increase, the resilience of transport infrastructure systems is a priority (Fiksel, 2003, Wan et al., 2018). Globally, the interconnectedness of social, built environment and natural systems is generating highly complex, dynamic challenges that require new design and engineering approaches (Allenby and Chester, 2018). Built environment professionals must now seek to design, construct and operate transport infrastructure in a way that optimises operability and resilience in dynamic and unpredictable environments (Fiksel, 2003, Allenby and Fink, 2005, FEI, 2012, Woods and Hollnagel, 2017).

Projected impacts on transport infrastructure from climate change are significant. Consideration of such impacts requires recognition of both the changing nature of natural hazards, and the vulnerability of the communities and built environment affected (IPCC, 2014a). Natural hazards include increases in the frequency and intensity of extreme heat days, extreme wind events, severe storms and heavy rainfall, among other anticipated changes (IPCC, 2014b, The Royal Academy of Engineering, 2011). More gradual climatic changes will also have an impact, with long-term shifts in weather patterns and operating conditions leading to acceleration of materials degradation and a potential longer-term reduction in operational efficiencies (i.e. extreme heat impacts on tunnel ventilation), and performance (i.e. more regular exceedance of drainage system capacity and flood tolerances). Given the integral role of transport infrastructure in maintaining the supply and transfer of goods, services and expertise, as well as free movement of citizens, such impacts trigger extensive cumulative and flow-on effects across the transport industry, government and society. The Intergovernmental Panel on Climate Change (IPCC) concludes that transport systems must seek to concurrently enhance mobility, reduce greenhouse gas emissions, and build resilience to climate change (IPCC, 2015).

A growing body of literature articulates the benefits of enhancing critical infrastructure resilience to climate change (Fiksel, 2003, Huq et al., 2007, Moensch et al., 2011, IPCC, 2014a, UNISDR, 2015). Yet despite recognition of the important role of critical infrastructure, there is still much to be done to improve resilience in transport networks worldwide (Regmi and Hanaoka, 2011, IPCC, 2014a, Wan et al., 2018). Where pursued at all, efforts to enhance infrastructure resilience typically involve single-point-in-time design adaptations to make the asset more rigid and impermeable to impact. These approaches largely seek to fend off the dynamic and unpredictable impacts of a changing climate, as opposed to building ongoing adaptive capacity and system resilience to changing conditions. Recognising limitations of rigid asset-level engineering responses when responding to dynamic system-wide challenges, a growing cohort of researchers and practitioners are calling for alternative approaches to transport infrastructure design and construction, including those that seek to leverage strategies found in resilient socio-ecological systems to enhance resilience in engineered systems (Albertson, 2010, Moensch et al., 2011, Kenny et al., 2012, Wilkinson, 2012, Woods, 2015, Taylor Buck, 2017, Chester and Allenby, 2018).

Building on this discourse, this paper explores opportunities to enhance the resilience of infrastructure systems by drawing on resilience concepts more commonly found in socio-ecological resilience theory. Understanding resilience as a process and an emergent characteristic, as opposed to a single metric, it supports the pursuit of resilience as a capacity to respond to 'surprise events' and disruptions that are beyond predicted variations (Woods and Branlat, 2012). Recognising that natural systems have developed proven strategies for enduring and even benefitting from dynamic and unpredictable conditions, it is proposed that it is possible to design and engineer transport systems that similarly thrive under such conditions. We posit that attempts to engineer infrastructure that can *withstand* a changing climate could tangibly be recalibrated towards infrastructure that can *accommodate, adapt to* and even *benefit from* such changes.

This work builds on strong theoretical foundations – Gunderson and Holling (2002) and others have explored the numerous lessons that can be learnt from socio-ecological resilience when looking to build resilience in human systems, however they have often stopped short of applying these lessons to non-living systems. Important work has nonetheless been undertaken to explore the potential for ecological resilience theory to inform cities and urban development at a policy and planning level (Ahern, 2011, Wilkinson, 2012, Wu and Wu, 2013, Pickett et al., 2014, Meerow, 2016). Infrastructure designers, constructors and managers have made strong advances in hard engineering responses to climate risk, however, these tend to focus on stability and permanence, as opposed to ongoing adaptive capacity and flexibility (Allenby and Fink, 2005, FEI, 2012, Sage et al., 2015). More recently, numerous authors have highlighted the opportunity to move towards an 'evolutionary' or 'sustained adaptation' interpretation of resilience in engineering, though largely at a theoretical level (Woods, 2015). This paper seeks to unite and build upon these research agendas in support of an emerging climate resilience strategy that embraces a socio-ecological resilience approach to reducing vulnerability in transport infrastructure assets.

We begin by considering the variety of climate change risks to transport infrastructure, and emerging international efforts to enhance infrastructure resilience to climate change. Current strict engineering interpretations of resilience are based largely in infrastructure vulnerability assessments and conventional, fixed, adaptation responses. Inspired by resilience possibilities put forward by researchers including Lovins et al. (1999) and Fiksel (2003), and by comparisons to nature made by resilience researchers such as Woods and Hollnagel (2017), we turn to ecology for inspiration. 'Resilience' is presented as a dynamic and evolving characteristic of transport infrastructure, with key features of sustained adaptability, multi-functionality and real-time feedback loops. Opportunities are identified for research enquiry into transport infrastructure design, construction and operation, wherein design and engineering approaches are informed by resilience strategies and characteristics found in living systems.

Methods

Our approach is a narrative review, with narrative synthesis including reviewing source text to summarise findings, explore current status and identify key themes for explanation. The focus is on investigating existing theoretical foundations and current practice across multiple fields and unifying these in a proposed theoretical framework for future consideration. Most of the 92 papers that comprised the literature review documented in this paper are sourced from academic databases including SCOPUS, Google Scholar and Web of Science (June to October 2017) with search terms including "Resilience", "Socio-ecological resilience", "Engineering Resilience", "Adaptation", "Climate AND infrastructure", "Resilience AND infrastructure". The papers include peer-reviewed journal articles, as well as key conference papers, paradigmatic books, industry reports and dissertations. An additional 11 papers are included as a result of the journal peer-review process. These papers are located primarily in ecology and environmental journals, with some transport, infrastructure, building, engineering and planning journals also present. Most sources have been published after 2004, with only 16 sources (primarily seminal papers for their disciplines), published prior to 2005. The results and analysis are provided in the following sections, including reference to key literature published while this paper was under review.

Results

In reviewing the literature, two key areas of theory and applied practice are explored – climate adaptation approaches in transport infrastructure, and various conceptions of resilience in engineered and natural (including regenerative) systems. While the papers reviewed here focus primarily on physical infrastructure assets, there is also some consideration of social infrastructure, such as institutional and organisational structures, social and community infrastructure, and other key socio-ecological elements that are increasingly understood to be inextricably tied to vulnerability and resilience of physical infrastructure networks.

Addressing climate risk and adaptation in transport infrastructure

Where transport infrastructure networks are not equipped for a changing climate, the increased frequency and intensity of these events may impact durability of materials, structural integrity, maintenance regimes and operability of transport assets and networks (Holper et al., 2007, Austroads, 2010). Given the long life-span of transport infrastructure, it is important to both understand the potential risks to assets and networks, and to actively reduce that risk. By integrating climate risk assessment, adaptation and resilience efforts into infrastructure design and construction, there is an opportunity to reduce hazard exposure and the vulnerability of cities and communities to infrastructure failure and associated reconstruction costs (IPCC, 2014a).

These reconstruction costs should not be underestimated. Assessment of climate risk to infrastructure in Europe alone now indicates that cost impacts are likely to reach €37 billion per annum by 2080, of which €11.9 billion per annum is a result of transport infrastructure damage (Forzieri et al., 2018). This magnitude of risk to infrastructure justifies a concerted approach to addressing climate-related risk, as recognised in a growing number of emergent frameworks, with numerous national and international programs developed in support of enhanced resilience and reduced disaster risk (UNISDR, 2015, Djalante and Thomalla, 2010, Manyena, 2009, UNISDR, 2005, OECD, 2016). These frameworks encourage a greater understanding of the projected risks to infrastructure assets and enhanced effort to manage these risks and reduce vulnerability through adapted design and engineering, yet current climate risk management efforts are struggling to deliver resilient transport infrastructure that facilitates mobility, access and connectivity in the face of changing climate conditions.

Acknowledging current adaptation approaches

Asset owners, operators, investors and insurers (among others) are increasingly conducting climate change risk assessments to better understand the vulnerability of infrastructure assets and networks (Rissik and Smith, 2015, Jones and Boer, 2003). These assessments typically assess the type and magnitude of potential climate change-related risk, and evaluate current vulnerability at the asset, network and portfolio levels as well as identifying potential adaptation options (Rissik and Smith, 2015, Füssel and Klein, 2006, Downing et al., 2005). While focussing largely on the vulnerability of physical assets to predicted changes in climate and weather patterns (including for example, impacts associated with increased rainfall and storm events, extreme wind, sea-level rise and extreme heat), these assessments also include some consideration of social vulnerabilities to asset failure. Investor groups are increasingly incorporating vulnerability assessments into investment decisions, and asset owners are mapping climate change-related risk across their portfolios (Ang and Copeland, 2018, QIC, 2017, Smith, 2013). At the same time, the emergence of a sustainability discipline within built environment design and engineering is supporting a growing focus on climate-related risks and opportunities facing infrastructure.

Research into adaptation efforts in developed countries is showing, however, that while significant efforts have been made to understand exposure (with a host of governance frameworks, assessment toolkits and reports developed), actions to reduce vulnerability and improve resilience remain *ad hoc*, champion-based and highly variable (Wise, 2014, IPCC, 2014a, Ford et al., 2011, Regmi and Hanaoka, 2011, Wilby and Dessai, 2010). Adaptation actions, understood as deliberate changes made in anticipation of or reaction to stimuli and stress, also tend to be largely institutional (i.e. guidelines and policies), or focus on the provision of financial support, rather than tangible adjustments to design and construction methodologies (Nelson, 2007). Many examples of engineering efforts to improve resilience do exist, however, the application of physical adaptation approaches in transport infrastructure remains relatively limited within the overall asset stock.

Given the relative infancy of such efforts in infrastructure design, it is not surprising that actions are typically grounded in conventional engineering practice, where engineers prioritise professional commitments including safety and risk reduction as priorities (Regmi and Hanaoka, 2011, Moensch et al., 2011). This includes for example increasing the height and rigidity of structures; selecting more robust materials; altering maintenance regimes and building protection walls and other engineered defences (Moensch et al., 2011, Klein et al., 2007, Davoudi, 2012). Such adaptation approaches focus on achieving engineered resilience (or short-term, stable systems) through increased strength, scale, rigidity and ability to defend the asset from projected climate change impacts (Sage et al., 2015). While these approaches may reduce vulnerability to selected climate events, they offer limited capacity to adapt to unpredictability or variance beyond this. Further, attempts to enhance robustness and rigidity to address one selected hazard, may also increase vulnerability to other hazards. There is now growing recognition that this form of 'rigid' targeted resilience effort could be complemented by more agile and flexible resilience strategies (Chester and Allenby, 2018, Woods, 2015, Ahern, 2011).

Evolving climate adaptation approaches in infrastructure

Changing perspectives can be seen in the incremental evolution of approaches to climate adaptation in infrastructure design and engineering, as approaches move from single-point-in-time design changes at the asset level, through to a more systemic view which recognises complexity and unpredictability across networks and over time. Traditionally, many examples of climate adaptation in infrastructure have involved one-off design changes at the asset level. Often designers, constructors and operators conduct vulnerability assessments in the design phase for new assets on a case-by-case basis – an approach fostered by the application of sustainability rating schemes for infrastructure – applied at the individual asset level and with ratings awarded at completion of design and construction phases (ISCA, 2016, ISI and Zofnass, 2012). Similarly, government policies introduced to assess climate vulnerability are often implemented as requirements for new-build assets, supporting single-point-in-time project-level vulnerability assessment and adaptation. Such assessments and adaptation efforts can deliver tangible benefits, however these design changes are often limited in appraising broader network and system interrelationships and, by virtue of their rigidity and permanence, limited in their ability to increase ongoing adaptive capacity.

This single-point-in-time design change approach is nonetheless perceived to be the only avenue available to many designers, constructors and operators who lack control over broader infrastructure networks, or the ability to influence decision making over long-term lifecycles of assets. As such, there exist many examples of design-phase adjustments for climate adaptation in transport infrastructure assets. In the design and construction of the New Parallel Runway at Brisbane Airport in Australia, for example, designers incorporated climate and sea-level rise projections into design modelling and selected a 'strongly precautionary' design height, as well as including tidal channels and a new sea wall to minimise potential impacts from projected climate change (Colonial First State, 2012).

Such efforts are often informed by analysis of a subset of available climate risk data and managed within a traditional risk management framework (Standards Australia, 2013, Jones and Boer, 2003). It is recognised, however, that attempts to reduce exposure and vulnerability assessments to individual projected data points (for example flood frequency, number of extreme heat days), may not adequately reflect climate variability, and that uncertainties associated with climate projections, policy directions and broader global trends create challenges for near-term adaptation decisions for long-term assets and networks (Wise, 2014, Wilby and Dessai, 2010). As such, it has been proposed that an 'adaptation pathways' approach may provide a more suitable strategy for climate adaptation in infrastructure (Haasnoot et al., 2013).

Adaptation pathways seek to find balance between engineering certainty and climate uncertainty by developing adaptation plans that extend over the life of assets –a subtle shift towards enhancing *adaptive capacity* of systems over time, as opposed to only implementing selected adaptation actions in the initial design phase (Nelson, 2007).

Given the long life-span of infrastructure assets and inherent uncertainty in climate modelling at the local scale, engineered adaptation measures implemented during construction run tangible risks of being maladaptive, insufficient or perhaps even overengineered. Rather than locking in potentially maladaptive design and engineering solutions at the project design phase, it is instead possible to develop a 'pathway' for adaptation over time, allowing for avoided upfront expenditure and increased certainty prior to major investments in adaptation actions..

This pathway may begin with no-loss or 'low-regret' adaptation measures that can be implemented in the design and construction phase at minimal cost and with low risk (Wise, 2014). Adaptation actions may be implemented up-front where certainty around a projected risk is very high or deemed worthy of addressing regardless of future climate and policy outcomes. After this, key milestones will be decided for assets wherein relevant personnel assess vulnerability, reassess projections and decide on adaptation actions (or lack thereof) at a future date (Wise, 2014). In the example above, for instance, this could mean that the runway design height was increased in the initial design and construction, however the decision on whether to install the new sea wall was delayed until 2030 when projections and asset performance would be reassessed. The decision would then be made as to whether the wall should be added, delayed or removed from the adaptation plan.

The Thames Estuary 2100 (TE2100) project in London provides an example of an adaptation pathway for infrastructure that supports transport and mobility. Modelling of potential climate impacts showed the Thames Estuary area, home to 1.25 million residents and 40,000 commercial and industrial buildings, has the greatest probable future flood risk in Britain (Ranger et al., 2013). In developing a plan of action to 2100, it was recognised that a range of climate, policy and social outcomes could influence the likelihood and scale of flood risk in the area. As such, an evolving adaptation pathway was created to allow for decisions to be made and refined over time based on available data. The TE2100 plan outlined key milestone points throughout the asset lifecycle where relevant personnel would reassess and decide on appropriate adaptation action. Such decision points could be triggered by climate thresholds, time, or other criteria (Ranger et al., 2013).

The team adopted three methods to support ongoing flexibility in decision-making. Firstly, low-regret measures (cost effective and immediately reduced risk) were implemented in the near term, including raising existing defences around the estuary, with the capacity to build on this later. Secondly, they sought to engineer-in flexibility, designing infrastructure in a way which supported future additional adaptation action with reduced additional cost or redesign. Finally, recognising the uncertainty of predictive modelling and the complexity of Earth system processes, they developed an adaptive planning approach based on iterative risk management and adaptive management theories, which allowed for ongoing adjustment over time as additional information became available (Ranger et al., 2013).

There are advantages and disadvantages to this approach. Adding a longitudinal component allows for ongoing adaptation and evolution, enabling assets to be adjusted to suit changing conditions and demands as required. On the other hand, trigger points for such adaptation decisions are often decades apart and require external input and resources. They rely on organisational knowledge that can be susceptible to changes such as staff turnover, organisational restructure, changing management systems and strategic priorities. This creates a risk that factors such as lack of political or leadership interest, lack of resources, and loss of knowledge regarding the plan may reduce the effectiveness of the adaptation pathways approach over time.

Multi-functional assets provide a different type of flexibility, having the capacity to operate in different states and modes dependant on environmental conditions. An example of a multi-functional transport asset is Kuala Lumpur's SMARTunnel, which switches from a roadway to a storm water tunnel in the event of flooding (Abdullah, 2004). While this provides greater flexibility, the asset is engineered to respond to modelled changes in (typically) one climate variable and within forecast ranges. Such designs are well suited to targeted adaptation efforts designed to manage well modelled and predictable disturbances yet may not deliver infrastructure able to manage unpredictable changes and conditions over time.

These approaches to transport infrastructure adaptation are designed to achieve 'specified' or 'targeted' resilience, where specific system components are adapted in response to known variables (Pickett et al., 2014). Such actions enhance adaptedness to selected climate impacts, however there exists a risk that 'generalised' resilience can be undermined by locking in rigid adaptation approaches that reduce diversity, flexibility and responsiveness to events and circumstances outside of predicted changes (Woods, 2015, Walker and Salt, 2012). It is this capacity to accommodate unexpected and unpredictable change and disturbance that is highlighted in the major streams of resilience theory, to which we now turn.

Understanding the differences in socio-ecological and engineering approaches

In the literature surrounding resilience theory, numerous definitions and categorisations exist (Gunderson and Holling, 2002, Haimes, 2009, Meerow, 2016). These interpretations of resilience, what it means and how it may be achieved, reflect their respective roots in diverse fields and their development through distinct disciplinary lenses. Resilience theory now has applications and interpretations in psychology, social sciences, organisational management and supply chain theory, among many others (Bhamra et al., 2011). However it is the work of Holling (1973) in ecological resilience and later socio-ecological resilience (Gunderson and Holling, 2002), that is often credited with launching widespread investigation and application of resilience theory to the built environment.

In a comprehensive review of resilience literature across a wide range of disciplines, Davoudi (2012) identified three broad conceptualisations of resilience: engineering, ecological and evolutionary (socio-ecological) resilience. Grounded in the engineering discipline, traditional approaches to infrastructure resilience typically seek constancy, predictability and a single equilibrium, where success is defined as resisting disturbance or rapid rebound to the original state (Tilman and Downing, 1994, Holling, 1996). The traditional engineering approach is to design for this single equilibrium with a deliberate effort to avoid designs that may fail or suddenly shift in form or behaviour following a disturbance (Gunderson, 1999, Davoudi, 2012). This is reflected in efforts to adapt to climate change through increases in the scale and rigidity of assets to withstand and defend against climate risks.

Ecological perspectives of resilience, on the other hand, incorporate unpredictability, change, and the potential for multiple locally stable equilibria (Walker et al., 1981, Holling, 1996). Moving one step further, socio-ecological resilience theory seeks to also capture the characteristics and interrelationships of social and ecological systems. Here, disturbance is not only necessary, it is regenerative – releasing stored capital, catalysing innovation and building robustness within the system. These systems favour flexibility and adaptability, with real-time feedback loops which identify risk and vulnerability and respond accordingly (Kim and Lim, 2016).

More recently, Woods (2015) defines four regimes and characterises resilience as the capacity to move between these regimes. The first regime refers to how systems rebound from disruption to return to prior activities, the second looks at resilience as a synonym for robustness, while the third introduces a less common interpretation, one of graceful extensibility. Here, resilience is concerned with how a system extends its performance or calls on adaptive capacity in the face of disruption or surprise events. Finally, Woods (2015) proposes a form of resilience based on sustained adaptability, or the potential for continuous adaptation in response to changing conditions.

As shown in Table 1, socio-ecological resilience theories show that communities and ecosystems can in fact benefit from disturbance and reorganisation (Gunderson and Holling, 2002, Gibbs, 2009, Davoudi et al., 2013). In some sense, transport planners have witnessed similar outcomes in cities, such as in San Francisco after the Loma Prieta earthquake of 1989, which led to the removal of the Embarcadero Freeway and redesign of their inner-city transport and land use system, though this adaptation took many years. However in transport engineering, particularly at the asset scale, the resilience end-goal has largely remained one of minimising change and pursuing certainty and stability, with little exploration of the opportunity for regeneration, innovation and renewal following disruption. As such, these conceptualisations represent distinct and often contradictory understandings of resilience in systems.

Table 1. Engineering and socio-ecological approaches to resilience

Elements of engineering resilience	Elements of socio-ecological resilience	References
Single equilibrium or 'steady state'	Multiple equilibria or 'steady states', or dynamic non-equilibrium	(Gallopin, 2006, Walker et al., 2004, Holling, 1996, Davoudi et al., 2013, Gunderson and Holling, 2002, Meerow, 2016)
Assumes relative predictability and stability	Assumes unpredictability and change	(DeAngelis, 1980, Folke, 2002, Gunderson and Holling, 2002, Bahadur et al., 2010, Nelson, 2007)
Pre-defined engineering adaptations based on projected conditions	Real-time sensing and adaptation	(Folke, 2002, Gunderson and Holling, 2002, Wu and Wu, 2013, Bahadur et al., 2010, Adger and Brown, 2009, Annaswamy, 2016)
Designed to minimise or avoid change over time	Evolves over time	(Davoudi, 2012, Gunderson and Holling, 2002, Folke, 2006)
Focus on single operating objective	Focus on multi-functionality	(DeAngelis, 1980, Gunderson and Holling, 2002, Holling, 1996, Hector, 2007)
Prioritises optimisation of individual components	Prioritises whole-system optimisation	(Gunderson and Holling, 2002, Bahadur et al., 2010, Nelson, 2007, Walker and Salt, 2012)
Disruption leads to failure	Disruption leads to renewal and innovation	(Gunderson and Holling, 2002, Folke, 2006, Bahadur et al., 2010, Walker and Salt, 2012)
Ongoing maintenance required	Renewal is internal and automatic	(Gunderson and Holling, 2002, Wu and Wu, 2013, Moensch et al., 2011, Adger and Brown, 2009)
Incremental change in response to specific risks	Potential for transformative change	(Nelson, 2007, Brown, 2012, Davoudi et al., 2013)

In summary, resilience characteristics of uncertainty and volatility – foreign to the traditional engineering objectives of predictability and stability – are integral to resilience in socio-ecological systems. While engineering resilience goals may appear valid and justified in transport infrastructure design, these objectives alone may be overly reductive, limiting the capacity for infrastructure networks to flexibly adapt and transform over time in response to vulnerability.

Discussion

Although it may seem from the literature review results that the engineering and socio-ecological resilience paradigms are diametrically opposed, there are opportunities for these approaches to converge. In the context of infrastructure resilience to climate change, we ask, '*How might we deliver transport infrastructure that is not destroyed by disturbance and disruption, but regenerated by it*'? As suggested by Taleb (2014), this can be understood as being not only resilient but in fact 'antifragile'. By incorporating these socio-ecological resilience concepts *into* engineering approaches, infrastructure resilience could be measured in part by a capacity to sense and respond to vulnerability in real-time, to operate in the face of complexity and uncertainty, and to shift between multiple states of form or function in response to environmental conditions – a *sustained adaptation* response to climate-related risk, as opposed to a single-point-in-time design change to enhance rigidity.

This perspective recognises infrastructure as part of complex socio-eco-technological (SET) systems. Grabowski et al. (2017) reiterate the importance of understanding infrastructure within these systems, embedded within social considerations such as policy processes, knowledge systems, user behaviours and demographic changes, as well as environmental systems both in terms of environmental inputs and impacts. The presence of complexity in transport infrastructure engineering is not new, and many robust risk management approaches have developed as a result. Climate change, however, brings with it additional risk and vulnerability elements, including: extensive system interconnectedness between ecological, social and technological systems; widespread global scale of impact; potential to impact entire networks as well as individual assets; uncertainty associated with climate projections, including the impact of policy and behaviour changes over coming decades; and potential cumulative and flow-on impacts that may results from both chronic and acute climatic changes (Scheraga, 1998, Du Plessis, 2012).

Looking to a socio-ecological conception of resilience requires a shift from siloed and mechanistic 'steady-state' approaches to designing for risk reduction, towards a sustained adaptability approach that is only possible when infrastructure is recognised as part of a complex adaptive system, not separate to it.

Complexity and resilience through an adapted Cynefin Framework

Recognising complexity as distinct from complicated or simple systems, we use the Snowden and Boone (2007) Cynefin ('Habitat') Framework, to categorise current and emerging practices in transport infrastructure engineering against the overarching knowledge headings of Obvious (known), Complicated (knowable), Complex and Chaos. Existing approaches to addressing obvious and complicated risks in infrastructure engineering are highly refined, with comprehensive risk management frameworks and processes. This strong foundation has been pivotal to developing climate risk assessment processes to date. Nonetheless, it is becoming clear that this traditional approach necessitates significant simplification regarding both exposure and vulnerability to climate-change related risks. Given the level of interconnectedness, complexity and unknown impacts of climate change, it is important to also explore how climate risks to infrastructure may be addressed in 'Complex' situations and what tools and strategies might support efforts to manage complex, adaptive and evolving challenges within complex infrastructure systems.

Arguably, it will be necessary to manage risk and design transport infrastructure solutions in ways that recognise, and respond to, such uncertainty. Such solutions would seek to incorporate flexibility and sustained adaptation, complimenting existing discrete adaptation approaches with design solutions that allow for 'unknown unknowns' and surprise events. As noted by Ahern (2011), the shift from deterministic 'fail-safe' perspectives towards non-equilibrium 'safe-to-fail' perspectives has been led by the fields of ecology and resource management. Here, chaos theory has proposed that socio-ecological systems include uncertainty, variability and surprise events. Ahern (2011) proposes that design strategies of multifunctionality, redundancy and modularisation, diversity, multi-scale networks, connectivity and adaptive planning and design may help to deliver urban resilience capacity. Building on this proposition, we now consider how current design and engineering approaches could shift to incorporate these concepts and deliver an adjusted form of resilience or 'antifragility' in transport infrastructure engineering.

Resilience in complex systems through regenerative design

One emerging discipline that incorporates many of these considerations, is regenerative design. It seeks to deliver solutions that are holistic, adaptable and that create opportunities for disruption and change to lead to regenerative impacts. Regenerative design recognises the built environment as embedded within complex systems and calls for design approaches that not only minimise harm to these systems but that also regenerate them. Exploring resilience in this context, regenerative design may look to the broader SET system and ask *'What does resilience look like in this place?'*; *'What are the social and ecological functions that support resilience here?'*; and, *'How can these be measured, contributed to and learned from?'*.

Examples may include learning from the local ecosystem approaches to water diffusion and flood control; heat diffusion and temperature management – investigating local approaches to resilience and adaptation, evolved and refined by the local ecosystem and community, to inform locally-attuned design approaches. Regenerative design encourages a comprehensive consideration of these factors, to support resilience and regeneration through place-based design, where performance is measured against more holistic socio-eco-technological performance metrics. It supports design for agile and resilient transport infrastructure suited to that place.

Pursuing regenerative design through biomimicry

When looking to draw on the principles, patterns and strategies adopted by living systems, biomimicry presents a rational starting point. Based on the belief that biological organisms and ecosystems have – over almost 4 billion years - optimised strategies for dealing with complex challenges, 'biomimicry' as popularised by Benyus (1997), brings together various fields working to emulate natural strategies in design (Kenny et al., 2012, Fiksel, 2003). Biological organisms and ecosystems have refined design strategies, patterns and principles that support resilience, adaptability, multifunctionality and regeneration – all within the context of changing and often unpredictable conditions – creating a catalogue of methods which may be transferrable to engineered systems seeking to survive and thrive under these same conditions (Kennedy, 2016).

Distinct from 'bio-utilisation', where the organism is directly incorporated into design in its living form (i.e. bioremediation, mangroves for flood mitigation, or the inclusion of parkland to create habitat and other ecosystem services), or 'biophilia' with its focus on human-nature connections, here the end result may exhibit no obvious connection to nature in form or aesthetic. Instead, by drilling down to mechanisms and underlying design strategies employed by organisms and ecosystems to achieve desired functions, biomimics seek to extract a design approach that may then be translated to human design and engineering approaches. In this context, this means identifying how natural systems have evolved to build resilience and deal with climate changes and disturbances without experiencing systemic failure, but rather evolving to flourish under such conditions.

Adapted Cynefin framework

With this in mind, we propose that together, biomimicry and the broader design approach of regenerative design offer approaches to managing complex, evolving challenges to resilience, where risks may not be known or certain. Figure 1 situates these within an adapted Cynefin framework (Snowden and Boone, 2007) for resilient transport infrastructure, to reflect their potential role in supporting management of complex risks and vulnerabilities within complex systems.

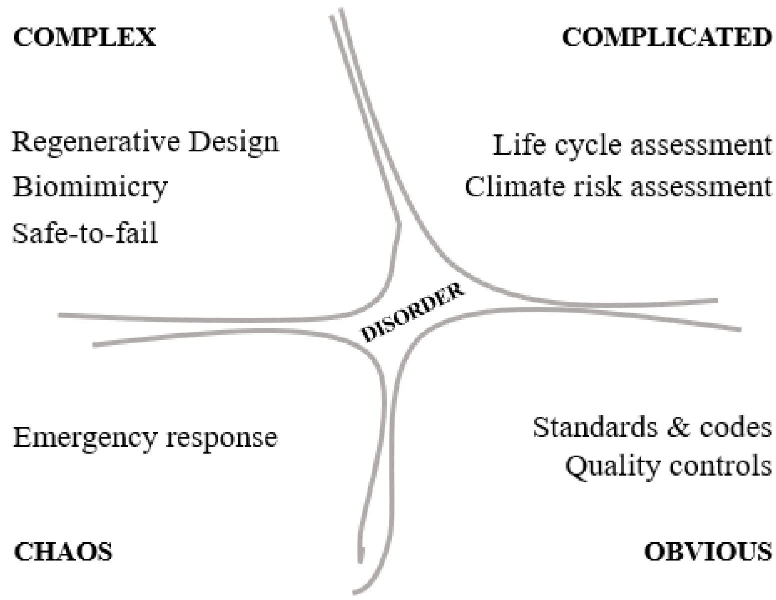

Figure 1. Adapted Cynefin framework for resilient transport infrastructure

(Adapted from Snowden and Boone, 2007)

In adopting this view of infrastructure as part of complex socio-eco-technological systems, the concept of 'place' becomes particularly important and the relationships between the asset and its socio-ecological context become paramount. Drawing on regenerative design literature we ask, *'How can regenerative and resilient performance be promoted and measured in that place?'*. Looking at the design concepts that may support these kinds of outcomes, regenerative design discussions point to two important ideas (adapted from Mang and Reed (2012):

1. Place: including the questions, *'What is the (hi)story of that place?'* and, *'What are the design and adaptation strategies that have allowed organisms to survive and thrive there?*
2. Pattern: including the questions, *'What can be recognised with regard to locally relevant living systems and their interrelationships.'* and, *'What are the key patterns supporting resilience and sustainability in that place?'*

In shifting the appreciation of resilience in built or 'non-living' systems to more closely align with resilience in 'living' systems, it is logical to look to nature for guidance on strategies and applied frameworks. Biological systems have continuously adapted to changing climatic conditions and built robustness and resilience by embracing flexibility, adaptability and real-time feedback loops – features in contrast to traditional infrastructure engineering resilience efforts, which often centre primarily on enhancing stability, rigidity and impermeability to disruption. Successful ecosystems have evolved to manage and thrive under climate conditions likely to be impacted by anthropogenic climate change – from high winds to extreme heat, flood events and variable rainfall (Zari, 2010). The following section details emergent tools and developments from biomimicry that may be applied to address transport infrastructure resilience, including place-based design strategies, overarching design principles and approaches to measuring performance.

Applying Biomimicry tools for resilient transport infrastructure

The following paragraphs bring together three emerging tools and frameworks in biomimicry that may help to operationalise the concepts of place, pattern literacy and performance in the context of enhancing transport infrastructure resilience.

1. Design Strategies - 'Genius of Place':

'Genius of Place' studies seek to uncover and investigate strategies and mechanisms that organisms have developed in a specific place, in response to localised operating conditions of that place. This may include, for example, how organisms have adapted to deal with extreme flood events, or how local species survive and thrive in conditions of extreme heat. It involves detailed investigation of these organisms, to identify strategies and mechanisms that can then be used to inform approaches to built environment design and engineering. The Genius of Place process can operate in two ways – 'Challenge to biology', or 'Biology to design' (Baumeister et al., 2013). In the former, the project team would start by identifying their primary challenges for that site. They would then direct their biological research to identify local organisms that have developed particularly successful strategies for dealing with that challenge (Biomimicry Oregon, 2013, Allen et al., 2015). These strategies can then be translated to design principles by stripping away the 'biology' to reveal the underlying design and engineering strategies that have been adopted; a translation from biology to engineering (Baumeister et al., 2013).

In the biology to design approach, the project team would instead investigate the ecosystem 'as a whole', looking for examples of organisms or processes that support adaptation, resilience and sustainability in the face of a wide range of challenges. In this way, the material issues of that place are revealed through the strategies and patterns evident in the biology. By looking directly to the form, process and system-level strategies that have evolved in that place, it is possible to extract design solutions that are suited and resilient to local conditions. In a region experiencing particularly high rainfall, for example, this may mean shifting from current design approaches that seek simply to capture and reuse this water, to investigating how local organisms and systems optimise water management cycles in that location to reduce risk and enhance resilience.

A transport infrastructure example can be found in work undertaken by the Open Space and Mountain Park's (OSMP) team at City of Boulder, Colorado. Here, the team was faced with a need to repair and upgrade a walking trail and access road following extreme flooding in the region (Allen et al., 2015). Recognising that local ecosystems in that area had evolved to effectively manage extreme rainfall events, overland flow and flooding, OSMP conducted a Genius of Place study to investigate local organisms that had developed particularly successful strategies for managing these challenges and remaining resilient in the face of flood events. Identifying seven key organisms and investigating the detailed design and operational strategies adopted, they then transferred these to design strategies for use in design charettes. For example, they learned from the morphology of the local Yucca plant to inform water drainage design, and from the bone structure of the Rocky Mountain Elk to inspire design solutions to minimise deformation under stress and regain original shape. More broadly, limited examples of this technique exist in relation to transport infrastructure, providing an opportunity for further research and development to determine opportunities and barriers to uptake.

2. Design Principles – Ecosystem Patterns:

Biomimicry design principles highlight patterns and strategies that have been consistently identified in resilient and successful organisms and ecosystems across the natural world (Baumeister et al., 2013). These commonly occurring characteristics have been collated as design principles that can be used both as a design prompt and an evaluation checklist for proposed design approaches (Pedersen Zari, 2018, Biomimicry 3.8, 2013). The 'Life's Principles' developed by Biomimicry 3.8 are shown in Figure 2.

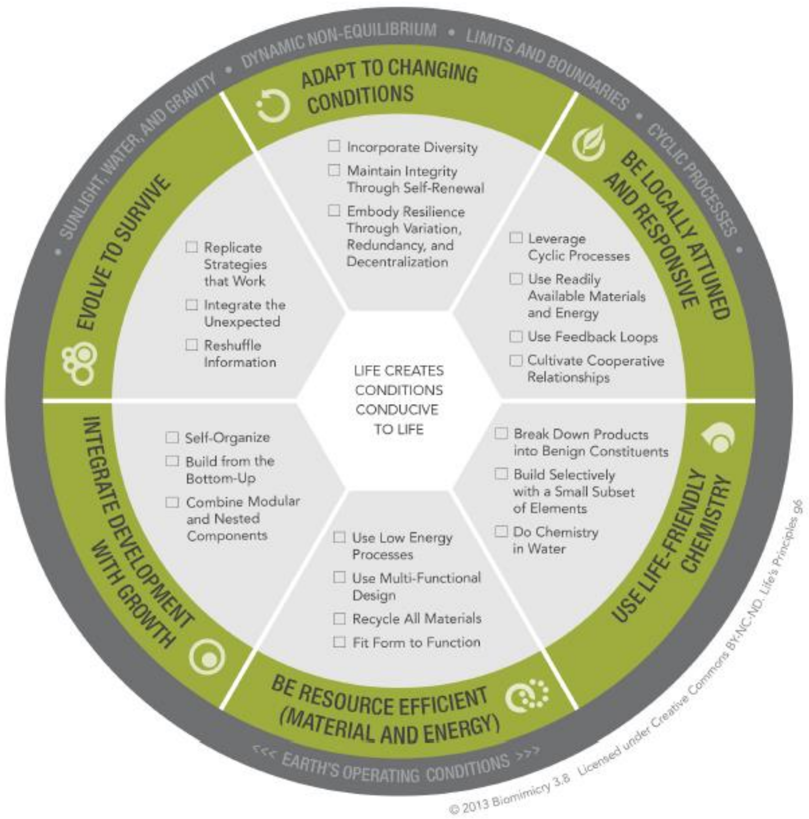

Figure 2. Life's Principles (Biomimicry 3.8, 2013)

These regenerative patterns and strategies reflect recurring characteristics of life (writ large) in ecological systems. Looking at these and others (such as Pedersen Zari (2018) Ecosystem Process Tiers) relative to key elements of socio-ecological resilience, it is evident that there are many overlapping and aligned principles, including multi-functionality, real-time feedback loops, evolution and adaptation, and self-repair. Given that biomimicry has developed clear and actionable frameworks for transferring strategies from biology to design and engineering, it may well provide a useful guide for pursuing socio-ecological resilience attributes in infrastructure engineering – establishing a tangible stepping stone for shifting resilience approaches from a solely 'engineering resilience' approach, to one which aligns with a socio-ecological resilience perspective.

Similar to limitations of narrowly targeted adaptation measures, biomimetic solutions designed to address just one of the design principles tend to fail in satisfying others. While they may perform strongly in one area, overall resilience and sustainability is not necessarily improved (Reap et al., 2005). Further to this, the satisfied principle or criteria may deliver operational or productivity benefits without necessarily achieving improved social or environmental outcomes. The systems approach supports solutions which satisfy all or most of these principles and therefore more holistically reflect the source systems which inspired them. In looking to enhance resilience in engineered systems, this systems-level approach becomes particularly important. In infrastructure systems, for example, where designers may traditionally look to adapt one changing condition, Life's Principles ask us to instead support an ability to adapt to changing conditions over time – sustained adaptability. Using this framework we could seek to design solutions that evolve and are locally attuned and responsive. In this way, the framework supports a shift from siloed adaptation actions towards comprehensive adaptive capacity. Elements such as self-repair, self-assembly and self-organisation further support this, and begin a shift towards assets and networks that can sense risk and damage in real-time, are sufficiently flexible and agile to minimise risk where possible, incorporating self-repair mechanisms where necessary. The framework encourages a more holistic systems approach to design, that pursues not one, but many of these strategies to support whole-system resilience and sustainability.

3. Measuring performance – 'Ecological Performance Standards':

Ecological Performance Standards' (EPS) allow for nuanced, quantifiable and location-specific enquiry into the functional *performance* potential of a site, looking to either the ecosystem of the site (if undisturbed), or a local reference habitat, to identify measurable ecosystem characteristics, services and functions generated by that system. This information is used to establish a baseline estimate of ecosystem services that would have been delivered by the local ecosystem on that site should it have remained intact (Stack, 2014).

By understanding benefits delivered by the existing or prior ecosystem, it is possible to comprehend the unique balance of ecological cycles and functions that had contributed to a successful ecosystem balance in that place. Identifying these measures enables development of quantitative design metrics and performance targets, where transport asset design seeks to mimic these ecosystem services in order to support ongoing resilience and sustainability of both the asset and the socio-ecological systems it inhabits. This could include, for example, quantifying energy that the ecosystem on that site would have generated, carbon that would have been sequestered, cultural services provided, natural water cycles (for example the proportion of total rainfall evapotranspirated, absorbed, shed and captured for future use), and a range of other services and functions supporting resilience and regeneration. Rather than (or in combination with) the more common approach of procuring ecological offsets or including planting and greenspace within the project site to offset the loss of ecosystem, the EPS approach encourages consideration of biomimetic design solutions to support delivery of ecosystem services. It offers a novel approach wherein built environment design consciously seeks to deliver ecosystem services, where the generation of such services and benefits becomes the responsibility of ‘grey’ infrastructure as well as ‘green’.

Measuring ecosystem functions and services encourages consideration and pursuit of regenerative ecological cycles, as opposed to measuring performance solely as discrete improvements from ‘business as usual’ impact. While current transport infrastructure sustainability approaches typically begin by modelling environmental and social impacts of proposed project designs, then seeking a percentage improvement on baseline damages, the EPS approach instead starts by looking at socio-ecological performance of the 'reference' site (i.e. as an intact ecosystem) and creating a performance baseline from there. In doing so, it provides insight into the various cycles and services that would have supported a successful balance in that place. Instead of looking solely at reducing energy consumption, for example, it would quantify how much energy would have been generated by the reference ecosystem there, how much would have been consumed, emissions that would have been generated, and sequestration. Using this approach, designs could then seek to mimic these proportions, pursuing an energy balance appropriate for, and resilient in that location towards future unknowns and surprise events. Importantly, while prior work has focussed on incorporating nature into design to support these ecosystem services (e.g. planting to support carbon sequestration and purification of air), the EPS framework explores how these services may be delivered through built environment design and engineering.

4. Other opportunities for biomimicry:

Biomimicry is largely understood to occur at three key levels – Form, Process and System (Baumeister et al., 2013). The three tools and frameworks identified above relate to biomimicry at the 'system' level, where overarching design approaches are informed by ecosystem strategies, patterns and principles. There are also other interesting opportunities for biomimicry to support transport infrastructure resilience.

Recognising that primary physical risks to transport infrastructure relate to materials degradation (gradual) and component failure (sudden), the areas of transport infrastructure operations, maintenance and repair are an obvious focus for the identification and application of technological solutions. Pertinent advances within biomimicry at the form and process levels include materials that are able to self-repair, including major transport infrastructure materials such as asphalt (Schlangen and Sangadji, 2013) and concrete (Li and Meng, 2015). These materials offer the potential to dramatically reduce maintenance and repair burden otherwise expected to increase as a result of climatic changes. Similarly, research is underway to develop material and structural health monitoring systems and sensors that mimic the ability of organisms to sense damage, stressors and changes in operating conditions in real-time. This research is inspired by nervous systems, neural networks, hair-cell sensors and skin to more effectively monitor and respond to vulnerability, as well as creating impact indicators on composite materials, mimicking bioluminescence to create visual indicators of damage to materials (Olawale et al., 2011, Xu et al., 2010, Liu, 2007). In other work, researchers are exploring opportunities for self-assembly of materials and structures (Ramesh Kumar et al., 2011, Ellery, 2018) that, while currently not scalable for transport infrastructure, reflect an emerging trend in materials science likely to create opportunities for rapid rebuilding and repair into the future.

These opportunities, while in varying stages of research and commercialisation, may play an important role in managing the increased maintenance and repair requirements forecast for transport infrastructure assets resulting from climate change, while facilitating enhanced adaptability and flexibility in the face of changing conditions.

Limitations and assumptions

Given the emergent nature of this work, there are a number of opportunities for developing, testing and refining these approaches for transport infrastructure. At each level, biomimicry approaches outlined above have seen limited application in transport infrastructure applications. While this reflects the emerging state of the field more broadly, it will be important to build a robust research base moving forward.

The concept of looking to ecology for tried and tested solutions to design and engineering challenges has strong theoretical foundations. It has worked well previously in transport engineering, such as in the redesign of Japan's Shinkansen high-speed train based on the beak of a Kingfisher to minimise resistance, reduce noise impacts and increase speed and efficiency. However, the extent to which this can be translated to material resilience improvements for transport infrastructure requires further investigation, both in research and application. The tools and frameworks outlined above offer foundations for this, however, they have not been applied consistently or in combination to transport infrastructure context with resilience as a driving focus. Similarly, opportunities for scaling these approaches to support widespread implementation within complex systems, have not been fully explored. These limitations will require further investigation and as such, key research opportunities have been outlined below.

Conclusions and implications for future research

This paper recognises the intercept of a number of emerging trends, challenges and innovations. Efforts to enhance resilience in transport infrastructure have gained momentum internationally, with many emerging examples of design changes to reduce climate risk. It is now increasingly recognised that managing climate risk to transport infrastructure must move beyond single-point-in-time design changes in response to individual parameters, and instead seek to build overall adaptive capacity of infrastructure assets and networks, recognising these as components of complex socio-eco-technological systems. At the same time, research into biomimicry and opportunities to learn from ecosystems to inform design and engineering approaches are rapidly emerging, though with limited application to transport infrastructure.

This paper unites these fields of research and practice, to propose that system-level biomimicry, in combination with advances in materials and technologies at the form and process levels, may provide a promising framework for enhancing holistic adaptive capacity in assets and networks. Much could be gained in the field of transport engineering by mimicking the design strategies and principles that have supported such resilience in living systems. Previous resilience approaches that consider each asset as an independent, discrete and standalone asset, and where the objective is to pursue a steady state, maintain stability and avoid change, exhibit fundamental weaknesses that limit their usefulness in an era of great (climate-related) uncertainty. We highlight the opportunity to move towards a socio-ecological interpretation of resilience. Under this interpretation, advances from the biomimicry field could be united to support design and engineering approaches that overcome limitations of previous approaches. While Allen et al. (2015) have begun to explore the use of Genius of Place and Life's Principles in transport contexts, and BiomimicrySA and partners (unpublished) have explored opportunities for Ecological Performance Standards to support resilience in development (though not transport specific), these three frameworks have not yet been considered together in the context of a shift towards resilience for transport infrastructure. Practitioners may find benefit adopting these approaches in transport engineering, at different levels.

Through trial and error over almost four billion years, ecosystems have tested, discarded and refined strategies to establish sustainable and resilient systems. In these systems, resilience and sustainability are not static end-points but rather functions of dynamic and ever-changing relationships, forms and processes. Typically, successful approaches have resulted not from a single, permanent design change, but through the constant use of feedback loops to identify environmental conditions and make minor adjustments, often including the ability to successfully shift between multiple operating states. For this kind of adaptive resilience to be adopted in transportation, it will require a transformed approach to design, engineering and operation. These are emerging concepts for which many questions remain unanswered. Extensive work has been undertaken to explore barriers to mainstreaming of niche innovations e.g. (Geels, 2005), and investigation and articulation of conceptual and applied barriers to implementation will be necessary for progressing work in this area.

Research into the application of system-level biomimetic design approaches remains limited, particularly within infrastructure engineering, and even more so within a transport context. While there are projects underway in industry, the research base to support, investigate and refine these approaches requires further development, and investigation is required to measure the potential and realised resilience and sustainability benefits of these projects. Peer-reviewed case studies of existing projects piloting these approaches, including robust investigation of outcomes, benefits, challenges and learnings, would help to establish a foundation for ongoing development. Where transport-specific examples are not available, other built environment applications may provide a useful foundation.

Capacity building within government and industry will play an important role in supporting uptake of the proposed biomimetic products and design frameworks in transport infrastructure. Piloting and implementation of biomimetic products and design frameworks, should be followed by rigorous evaluation and adaptation of project approaches, and communication of research outcomes to key public and private sector parties involved in infrastructure planning, design, construction and operation. To support mainstreaming of these approaches, opportunities should be taken to align with existing frameworks, standards and schemes. For transport infrastructure, this could include infrastructure sustainability rating schemes, key international standards and specifications, as well as research and practice in fields closely links to biomimicry, including industrial ecology, regenerative design, biophilia, ecosystem services and materials science among others.

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