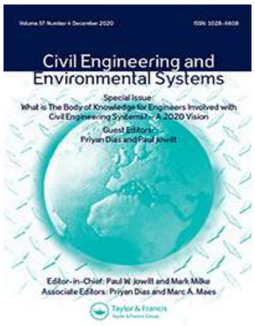

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A research agenda on systems approaches to infrastructure

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ABSTRACT

At a time of system shocks, significant underlying challenges are revealed in current approaches to delivering infrastructure, including that infrastructure users in many societies feel distant from nature. We set out a research agenda on systems approaches to infrastructure, drawing on ten years of interdisciplinary work on operating infrastructure, infrastructure interventions and lifecycles. Research insights and directions on *complexity, systems integration*, *data-driven systems engineering*, *infrastructure life-cycles*, and the *transition towards zero pollution* are summarised. This work identifies a need to better understand the natural and societal impacts of infrastructure interventions under uncertainty. We argue for a change in current approaches to infrastructure: starting from the natural environment and its resources, encompassing societal use of infrastructure and the supporting infrastructure assets and services. To support such proposed new systems approaches to infrastructure, researchers need to develop novel modelling methods, forms of model integration, and multi-criteria indicators.

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Systems engineering; systems integration; complexity; infrastructure; modelling

Introduction

Civil infrastructure systems, such as transport, energy, housing and water, are important to the functioning of societies. At a time of system shocks, such as Covid-19, current approaches to delivering infrastructure reveal significant underlying challenges. Rather than building more infrastructure in the same way, to achieve sustainability there is a need for government-led changes to the way societies use infrastructure (Moser 2019). The importance of resilient infrastructure is recognised by the United Nations, with infrastructure included as a sustainability goal and seen as an enabler underpinning other goals (UN 2015). The disruption of a lockdown has allowed us to reflect on how civil infrastructure might be better understood and reconfigured, how complexity and uncertainty might be addressed, and also how key infrastructure sectors support human wellbeing and quality of life.

One significant challenge that we identify is that infrastructure users in many societies feel distant from the natural environment, i.e. assuming that water comes from the tap,

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without questioning the taken-for-granted infrastructure and its connections with nature. While interdependent civil infrastructure systems depend upon and directly embed natural resources, such as land, water and construction minerals, the delivery of infrastructure displaces natural activities both *in situ* and in distributed locations across supply-chains. Society can feel distant from nature as these connections become obscured by complexity: it has, for example, become increasingly difficult to establish complete value chains of materials used in infrastructure.

This paper sets out a research agenda on systems approaches to infrastructure, drawing on ten years of interdisciplinary work on *operating* infrastructure, *interventions* into operating infrastructure (from small maintenance upgrades to major projects); and infrastructure *lifecycles*. It builds on the broad heritage of systems approaches to civil engineering in the Department of Civil and Environmental Engineering at Imperial College London, as recounted by Jowitt (2010), where Professor Ian Munro, a co-founding editor of this journal, was Head of the Department from 1982 to 1985. It has been fostered through the Centre for Systems Engineering and Innovation, which is celebrating its ten year anniversary in 2020, providing a hub for interdisciplinary work that brings systems approaches to civil infrastructure research. This celebration has been an opportunity to collectively consider questions: How can we better operate infrastructure systems? How can we better intervene? How can we make infrastructure adaptable over the longer term?

Revisiting the body of knowledge for engineers involved in civil engineering systems, our interdisciplinary work identifies a pressing need to better understand the natural and societal impacts of infrastructure interventions under uncertainty. The case is developed across three following sections. The next section describes research insights and directions on *complexity*, *systems integration*, *data-driven systems engineering*, *infrastructure life-cycles*, and the transition from *carbon neutral towards zero pollution*. The following section then argues for a change in current approaches to infrastructure: redrawing the boundaries of the system to start from the natural environment and its resources, encompassing societal use of infrastructure and the supporting infrastructure assets and services. We review the various ways of describing infrastructure and its relationship with nature in the existing literatures that we draw on, and set out a research agenda, arguing that to support proposed new systems approaches to infrastructure, researchers need to develop novel modelling methods, forms of model integration, and multi-criteria indicators. Finally, we draw conclusions and set out implications for engineers, for educators, and for researchers.

Systems approaches to infrastructure: research insights and directions

We build on and contribute to a related trajectory of work on systems approaches to infrastructure (e.g. Hall et al. 2013; Blockley and Godfrey 2017; De Graaf, Vromen, and Boes 2017), and more broadly on work on engineering systems as open and socially as well as technologically complex (De Weck, Roos, and Magee 2011; INCOSE 2014), where our ongoing work is drawing together and developing new insights into infrastructure systems by making connections across the research communities that study natural and built environments.

This work is timely as there is growing policy and industry interest in systems approaches to infrastructure. For example, the Institution of Civil Engineers (ICE) is currently conducting a review of Systems Approaches to Infrastructure; the Royal Academy of Engineering has initiatives on Safer Complex Systems, on Sustainable Living Places, on Decarbonizing Construction and Net Zero; and the World Economic Forum sees infrastructure adding significant value to quality of life and being important to delivering sustainable futures (WEF 2019). A recent report on Flourishing Systems calls for understanding of infrastructure that starts from the user (CDBB 2020).

As discussed below, five emerging areas in which interdisciplinary research is developing new scientific insights and directions are around complexity, systems integration, data-driven systems engineering, infrastructure lifecycles and the transition from carbon neutral to net zero pollution.

Complexity in infrastructure systems

In one sense of the word, complexity can be measured as the size of the element of a system that cannot be further simplified (Fisk 2004). The more complex a system, the more integral it is, with interdependencies across it. There is a natural tendency in society to make a system more complex, which then creates an elite status for those few who can understand it. That does not mean that we cannot explore a system to tease out what order it might still be hiding. We have shown for example that the connectivity within the world's major metro systems follows very similar patterns (Angeloudis and Fisk 2006). Most metros provide resilient travel despite an interruption on a line as a consequence of these patterns. In contrast, the different pattern of complexity in the international airways leaves open plenty of opportunity for disruption. As interconnectivity grows, Fisk and Kerherve (2006) argue that it cannot be assumed that complex systems will maintaining dynamic stability. Questions arise as to whether systems need to be resilient, i.e. able to move back to their original state after a shock, or antifragile, i.e. able to accommodate the shock and move to a new state. The emergence of dual-use infrastructure projects (where assets can be repurposed during emergencies), such as the SMART tunnel in Kuala Lumpur (Soon et al. 2017), provide new means of enhancing the resilience of infrastructure – their implications to infrastructure network design and their resilience will be examined further in the years to come.

Matters are different if the intention is to create a process rather than product. A process can be thought of as transforming one product to another (transformation), distributing a product from one place to another (distribution), or storing a product (storage). An algorithm that is asserted to reproduce the process can only be verified by running it. There cannot logically be a general test to see if an algorithm meets this requirement. In one sense this is self-evident. The programmer naturally runs a programme to see if the programme does what is intended. The classic systems engineering approach to assembling products verifies and validates the integration of implemented systems against the systems archietcture, moving up and down the levels through a V diagram. This had to be abandoned in software development in the 1980s because it could leave discovery that something would not work until the last stage. In an 'agile' alternative the design process focuses first on what is the fundamental requirement. Once that works, other programmes are added one by one, in order of priority, each tested in its own right, to ensure the product works as intended.

There is growing cyber-physical complexity in infrastructure. The failure to guarantee that a programme that controls/informs the operational decisions will do what is required unless it is tested exposes the need for the system designer to consider how the system should work when an input does not produce the expected output. The 2003 North East Northern American blackout occurred because an undetected (until then) bug interfered with how the grid control system presented data (Andersson et al. 2005). That kind of occasional software problem has occurred ever since. As recently as August 2019 the U.K. suffered a controlled blackout because the software being commissioned for a large offshore wind farm failed to understand what was happening to it (Bialek 2020). In this case matters were exacerbated by one type of train whose software shut it down permanently even though power was always available. Processes like the control of a rocket are now tested for months to improve assurance that the software can manage whatever it might have to contend with. The examples emphasise the need to address the complexity from a process rather than product perspective and develop methods to test the operation of the coupled system under a wide range of historical and hypothetical scenarios.

Systems integration – projects as interventions

To achieve desired outcomes, deliberate interventions are made into operating civil infrastructure systems. There are different places to intervene into a system with different levels of effectiveness (Meadows 1999). Interventions may take the form of either a change in *use* or a change in *physical assets*. Each intervention (whether in use or in physical assets) is conceived and undertaken in a project and then realised in operations. Physical interventions in infrastructure may be anything from a small maintenance project (Adey et al. 2019) to an infrastructure megaproject. Starting from the outcome means that the different options may be considered: if the problem is insufficient capacity to satisfy peak demand, the usage could be altered to reduce the peak, as an alternative to building new infrastructure to support the existing peak.

Systems integration is the process of making constituent parts of an engineered system work together (Whyte 2016; Whyte and Davies 2020), where this system includes physical components, services and knowledge. Traditionally it has been considered within the project, as the systems architecture is partitioned into sub-assemblies and components, and then these, and the interfaces between them, are tested (both verified, to ensure they meet regulations, specifications and requirements; and validated, to ensure they meet stakeholder needs). Considering projects as interventions in infrastructure (Grafius, Kim, and Whyte 2017; Whyte, Fitzgerald, et al. 2019) suggests understanding of associated complexity and uncertainty within and across project boundaries, spanning the technological, environmental and social issues.

More complex interventions may involve many different types of engineering knowledge and there is a need to partition the project, giving responsibilities to different organisations and professions, and then a need to test the integration of deliverables to ensure that the intervention achieves the desired outcomes. Many systems engineering techniques designed for closed systems, such as applications in the military and space, have been found to work poorly in the systems-of-systems contexts that characterise infrastructure (Hughes 1998). However, the idea of a 'V' diagram, which focuses attention on the verification and validation of designs at every stage (connecting between requirements and deliverables, systems design and systems testing, sub-systems design and sub-

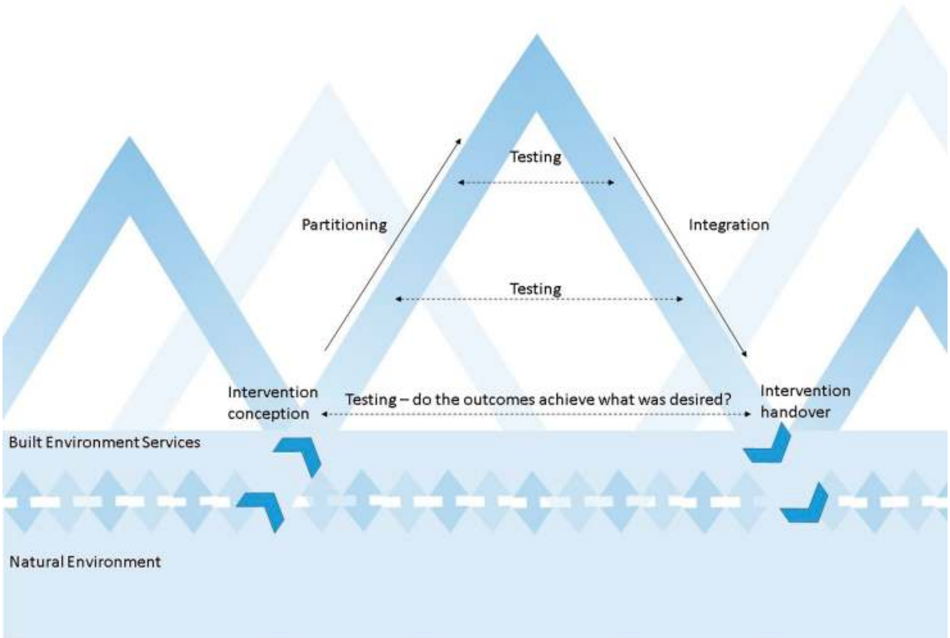

Figure 1. Inverting the classic 'V' diagram, projects are shown as interventions into the natural environment and built environment services provided by operating infrastructure.

system testing, etc), has been found to be useful in systems approaches to delivery (Leidraadse 2013), and is used at both to deliver individual systems and across systems (described as the meta-systems level) in large infrastructure projects (Davies and MacKenzie 2014). Considering the project as an intervention in an existing socio-environmental system, suggests inverting the classic systems engineering 'V' diagram to consider the natural environment and the built environment services that that the project draws on, as shown in Figure 1. For the delivery of complex infrastructure products, the 'V' shows the intervention, conceived and handed over in relation to existing infrastructure, and tested at different levels, from component, to sub-system to system in delivery, supporting the concept of adaptability and flexibility of infrastructure systems.

In the literature on infrastructure projects, recent work has begun to problematise the beginning and end of projects, with Locatelli, Mancini, and Romano (2014), for example, arguing for understandings of governance to be extended across the life-cycle and approaches such as circular economy to be implemented in infrastructure planning and operation (UKGBC 2019).

Data-driven systems engineering

Research on systems approaches to infrastructure is increasingly data-driven, with work beginning to organise data in new ways and to analyse data-sets to enable researchers to find new patterns using machine learning and/or artificial intelligence (AI). Engineering and design data are increasingly generated and accumulated in infrastructure operations, project planning, and delivery. Examples of our work that uses this increasingly rich data extensively includes work to develop data, tools and methods to model the physical economy (Myers et al. 2018; Myers, Reck, and Graedel 2019), to create more flexibility in design (Cardin et al. 2017), to the operation of water systems (Nerantzis, Pecci, and Stoianov 2020) and internet of things (e.g. Benkhelifa et al. 2020). The idea of a 'digital twin' to the physical infrastructure suggests a new way to use a set of digital data on operating systems (the component asset characteristics and geometry, systems behaviours, and social systems), that sits alongside the physical infrastructure (and is updated and recalibrated using sensor data) and can also be a testbed for new interventions (Bolton et al. 2018; Whyte, Coca, et al. 2019).

The scale of data can create unprecedented challenges but also provide unmatched opportunities in advancing the theory, methods, tools and practice of data-driven systems engineering. For example, we are doing work to enable better economic performance, sustainability and resilience in infrastructure systems by exploiting *Flexibility in Design* as a core unifying, value-enhancing paradigm to deal with uncertainty (Cardin 2014). Flexibility promotes sustainability on the one hand by recognising the ability to change and make better use of limited resources, with an eye towards future generations (e.g. expanding capacity *if and when* needed, deferring a project until the right market conditions arise). It enables better resilience by allowing a system to adapt and reconfigure quickly after an unexpected shock or disruption, so as to regain (or even surpass) pre-disruption conditions and performance, supporting the concept of antifragility. Inspired from real options theory (Dixit and Pindyck 1994; Trigeorgis 1996), flexibility helps generate designs that reduce infrastructure exposure to downside risks (like an insurance policy), and capitalise on upside opportunities (seizing better profit or demand than expected). For these properties to be impactful, they need to be embedded in the early design phases through careful engineering technology, so as to extract better value in future operations. This creates important challenges from computational design and managerial standpoints (Cardin et al. 2017). Our research focuses on developing the computational tools, digital processes, stochastic optimisation, and machine learning algorithms that will support better design and decision-making in such a deeply uncertain, and heavily data-driven environment (de Neufville et al. 2019; Kuznetsova et al. 2019).

Our goal is not only limited to discovering the dots (i.e. patterns, insights and knowledge) from data analysis. Instead, the future ultimate ambition is to develop new systematic methods that connect the dots for engineering design in order to improve overall design decision-making in highly-challenging complex engineering and commercial contexts. New methods are needed, especially considering the threats and uncertainty arising from climate change, physical and cyber terrorism, and pandemics. One ambition is to develop smart algorithms that will systematically identify and recommend the best methods from the data itself, depending on the phase of the design process (i.e. concept generation, design space exploration.) Therefore, in the future, the outputs (patterns, insights, and knowledge discovered from data) of the different work packages we have done will eventually be connected together and evolve together to be aligned with the high level objects: the large societal issues – greater resilience, sustainability, technological novelty and uncertainty in complex systems, and people-centric design, etc.

The work on flexibility in design is an example of the wide range of research underway to explore and exploit huge, versatile, complex and highly contextualised engineering data to uncover patterns, novel insights, and knowledge for the operation and design of infrastructure under uncertainty. Some of this work also involves the national institute for data science, the Alan Turing Institute, through the Lloyds Register Foundation/Alan Turing Institute 'Data Centric Engineering' Programme. The ambition is to harness the power of large-scale engineering data, as well as to develop methods for engineering design that improve overall decision-making in highly-challenging complex engineering and commercial contexts.

Infrastructure life-cycles

Their high social importance and high initial investments, are key reasons why single infrastructure systems are characteristically maintained for long periods. Infrastructure may be owned, operated, and maintained in different ways. For example, the London Underground, initially constructed and operated by the Metropolitan Railway in the mid-1800s, is currently operated by Transport for London, whereas Network Rail own and manage the track and rail franchises operate services. These key aspects distinguish the 'product' life cycles of an infrastructure system (Pamenter and Myers 2020), i.e. including extraction, production, manufacturing (construction), use, and end-of-life stages (Figure 2), as 'service-oriented' rather than 'production-oriented', whereas the latter is common to most other products, e.g. clothes and fast-moving consumer goods. Therefore, infrastructure systems already embody the core 'service-oriented' element of the circular economy. The key for a sustainable infrastructure system is thus to reliably deliver its social service(s) without excess economic cost(s) (to the managing organisation and society) and environmental impacts.

Opportunities to improve infrastructure systems exist along their life cycles. During use, regular field sampling and measurement of durability indicators should be implemented to predictively spotlight material degradation, enabling smaller targeted maintenance rather than larger and more costly repairs. Data-driven approaches and sensor technology will be key here, and provenance of infrastructure materials in databases will be built up.

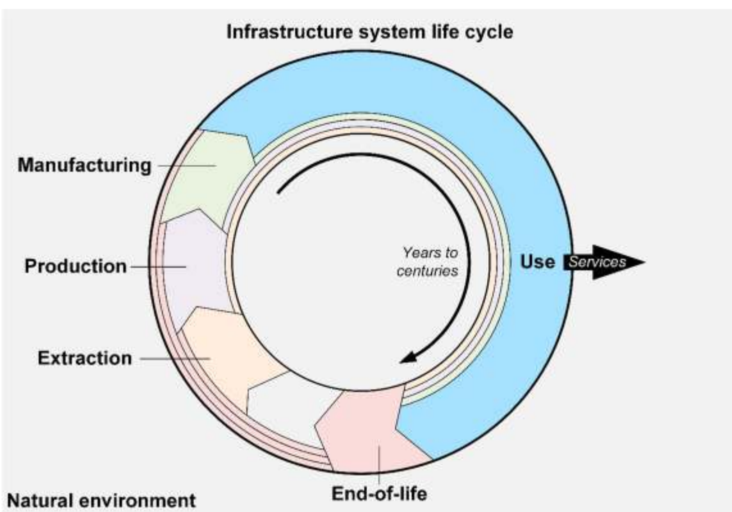

Figure 2. The infrastructure system life cycle.

This raises the question whether electronic technologies that may be procured and installed during future construction of an infrastructure system will become obsolete during its use. Such risks can be mitigated by implementing infrastructure subsystems, such as a monitoring system, in a modular fashion, so that they can be replaced and/or upgraded with minimal disturbance on use of the wider infrastructure system. This may lead to side benefits, such as increased speed of construction, due to modularisation and thus improved replicability of implementing subsystems in different infrastructure systems.

Ultimately these data will underpin a good understanding of the quantity and quality of the 'material bank' stored in existing infrastructure, which should be leveraged at end-of-life to facilitate reuse and recycling; the infrastructure manager will take on the role of a material supplier. Here, the potential of reuse and recycling to reduce environmental impacts should be balanced with component and build complexity, e.g. modular/upgradable/replicable vs. in-situ/unique construction, since simpler materials and components are more readily recycled, and facilitate reduced construction complexity. This balance should also account for environmental benefits that may be achieved through use of multi-functional materials and components, e.g. permeable concrete (Kia, Wong, and Cheeseman 2020). Therefore, infrastructure systems should preferably employ simple and multi-functional materials and components, which in turn must be facilitated through good materials selection and design.

During the early stages in the design process, functional and ideally modular (due to their different lifetimes, see above) subsystems should be systematically developed to meet the social need(s)/service(s) of the whole infrastructure system, and, complementarily/concurrently, scenarios of their physical embodiments should be screened using life cycle assessments at this same (whole infrastructure system) level. Use of life cycle assessment to authentically indicate environmental performance of the infrastructure system, i.e. of the (physical) 'product' life cycle rather than (conceptual) 'project' life cycle, must be driven/sought by the infrastructure owner-operator and facilitated by other key stakeholders (e.g. capital investors), and go beyond check-box type certifications: a sustainable infrastructure system must reliably provide its service(s) and meet both the specified product-based and project-based life cycle economic and environmental performance criteria. This is especially challenging for infrastructure products since they are systems-of-systems, since their use stage can involve various stakeholders in complex networks to provide its services (Wilke, Majumdar, and Ochieng 2014). Understanding the interdependencies of the infrastructure system life cycle and these stakeholders, particularly but not exclusively during use, at times of system disturbances, and at an appropriately high detail to capture service demand and provision to users (Goldbeck, Angeloudis, and Ochieng 2019), is a key ongoing challenge. Ultimately, this assessment must demonstrate benefits to the owner-operator, material suppliers, designer, investors, and other key stakeholders along the infrastructure life cycle.

Carbon neutral to net zero pollution

Infrastructure is vital to society and provides us with energy, water, transport, telecommunications, and waste management. For most of human development, infrastructure was separated from the environment. However, as the scope of human activities changed creating significant environmental impacts, the role of infrastructure has transitioned from supporting human systems to also managing the natural environment (Chester, Markolf, and Allenby 2019). This raises a question of addressing systemic impacts of infrastructure projects and the role of civil and environmental engineering in creating and maintaining the built environment (Allenby 2007).

The global focus is currently on reducing greenhouse gas (GHG) emissions through setting Net Zero Carbon targets at national levels (Rogelj et al. 2015) and science-based targets for companies.[1] This is of course beneficial to tackling climate change. However, systemic impacts that refer to both direct and indirect long-term impacts extend beyond the carbon footprint (climate change) and spatial boundaries of an infrastructure project (Bidstrup, Pizzol, and Schmidt 2015). These impacts, which cause environmental damage – including biodiversity loss, and severe air, water, and soil pollution – are due, at least in part, to direct environmental pollution[2] in some form or another. In addition, indirect environmental impacts related to infrastructure, e.g. in the form of embodied pollution associated with infrastructure materials, and water and land footprints, pose additional strain on the natural environment and affect its ecosystem services (Johansson 1990). The data portray devastating impacts of pollution at a global scale, with 19 million annual premature deaths linked to the use of natural resources and environmental damage (Ramaswami et al. 2016).

Our infrastructure decisions contribute to the pollution that our society generates; however, they will also determine how we manage the trends of population growth, urbanisation, and growing consumption. Within that context, infrastructure is critical in shaping the set of viable routes to reducing environmental pollution in the future. We argue that civil and environmental engineers must pay a crucial role in creating solutions that will promote sustainable development (Allenby 2007). This raises the question: how can we continue to improve quality of life through infrastructure provision, while minimising our impacts of pollution on the natural environment in the world that we have already created?

Our understanding of pollution and impact pathways continues to evolve and improve, and while we understand some pathways quite well (e.g. the toxicity of leaded fuels (Levin et al. 2020)), new forms of pollution continue to emerge, such as microplastics and nanomaterials (Falinski et al. 2018), which pollute our air, water and soil. A particularly challenging aspect of the impact pathways assessment is the feedback between the environmental damage, which alters ecosystems and consequently impacts both humans and non-humans, and the structure of built environment. Concepts such as the natural capital have been developed to assess the value of ecosystem services provision for people (Costanza et al. 1997), however, the link between the direct and indirect impacts assessment, as well as the implications for non-humans is still a scientific and practical challenge (Rugani et al. 2019). What is evident, however, is that at a global scale human quality of life measured by indicators such as Human Development Index is directly linked with our ecological footprint (Cumming and von Cramon-Taubadel 2018; Kaklauskas et al. 2018).

The need for holistic assessment, i.e. including natural and built environments, is justified by four key aspects of the sustainable development debate. Firstly, focusing on a single issue could potentially result in a range of unintended consequences that are already known, or yet to emerge ('burden shifting'); for example the growth in the diesel cars market in the UK in the early 2000s, partly driven by lower taxes to reward their lower carbon dioxide emissions, degraded air quality in cities (Carslaw et al. 2011; Jonson et al. 2017; O'Driscoll et al. 2018). Secondly, focussing on a single form of pollution could miss synergistic opportunities for regenerative solutions: for example, there are often co-benefits of reducing carbon emissions and improving flood management and other ecosystem services that strengthen the case for change (Ossa-Moreno, Smith, and Mijic 2017). Thirdly, when discussing the future of infrastructure systems we need to recognise their importance not only in the context of industry, innovation, and affordable and clean energy, but also for achieving other aspects of sustainable development, as embodied in multiple Sustainable Development Goals such as clean water and sanitation, sustainable cities and responsible consumption (Thacker et al. 2019). Finally, reframing the debate in the context of a systems-level pollution expands the 'burden of proof' from regulators to include those causing or facilitating pollution, which is important for forms of pollution whose impact pathway is not well understood.[3]

Systems-level pollution thinking will require fundamental revaluation of our infrastructure systems that necessitates inter-disciplinary research, innovation, and collaboration. Expanding the scope of analysis beyond approaches narrowly dealing with single environmental issues or pollutants, e.g. carbon accounting, has already revealed opportunities for thinking differently about infrastructure operations and planning. Analysis in the aviation sector has shown that minor changes to the altitude at which aircraft fly could significantly reduce the climate impact of flying attributable to contrails without significantly increasing CO_2 emissions (Teoh et al. 2020). The most effective way of achieving environmentally- and pedestrian- friendly urban design is to integrate transport infrastructure and public space planning, in addition to reducing pollution (Yang et al. 2020). Systems modelling of the urban water-energy nexus enabled us to analyse impacts of carbon policies on water infrastructure planning (De Stercke et al. 2018), while the water abstraction operational rules discovered through integrated modelling of urban water infrastructure have shown a potential to provide infrastructure equivalent benefits of up to £200 million (Dobson and Mijic 2020). Finally, life cycle assessment has emphasised the role that materials can play in reducing environmental impacts of infrastructure systems, such as using alternative cement binders with lower CO_2 emissions relative to conventional blended Portland cement binder (Miller and Myers 2020).

Examples across multiple infrastructure sectors provide a new conceptualisation of a system that is designed to support both built and natural environments and explicitly account for feedbacks between the two interlinked systems. Understanding of pollution and impact pathways resulting from human activities – and importantly environmental damage – is crucial for assessing the overall sustainability of the complex anthropogenic Earth system. We refer to this concept as a net zero pollution, which aims to achieve a systems-level balance between human footprint and the capacity of natural system to support life on Earth (Figure 3). This concept supports the debate about development within planetary boundaries (Raworth 2017), which needs to be revisited considering the role of the built environment in managing natural systems (Lade et al. 2020).

For direct pollution, the concept implies either elimination of all pollution sources to the natural environment (zero pollution), or in case pollution is released into the natural environment, its removal to minimise damage, which could be in a different place or at a different time (net zero pollution). This principle works well in the context of managing

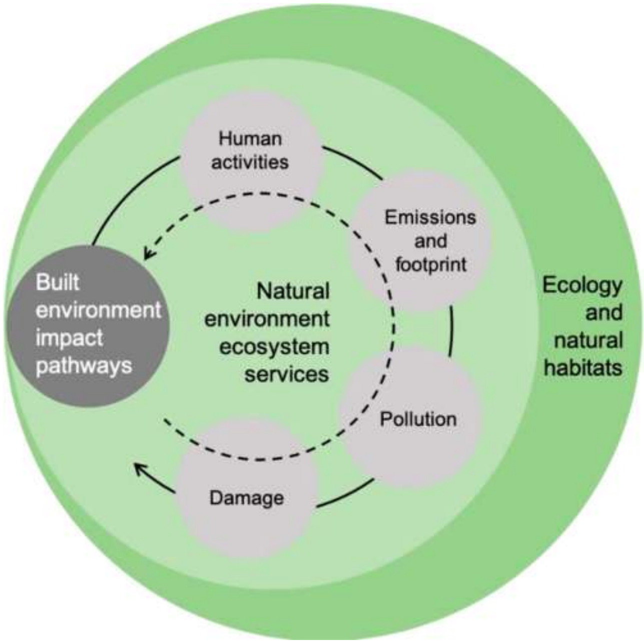

Figure 3. Net zero pollution concept in the context of built and natural environment, which promotes balancing built environmental impacts with the capacity of the natural system to support life for all its inhabitants.

GHG emissions through Net Zero Carbon accounting. It could also work in some cases where habitats are destroyed and rebuilt somewhere else, which is promoted by the biodiversity net gain approach (Maron et al. 2020). However, the net zero pollution concept may be particularly challenging for the forms of pollution or cases when environmental damage is non-linear, spatially dependent, and/or poorly known. Such examples include impacts of agricultural diffuse pollution on river water quality, which needs to be removed at some point downstream for a water treatment, however, with potential significant damage in between the source of pollution and the abstraction location. In the context of air pollution, local impacts on health due to GHG emissions cannot be mitigated if pollutants can be taken out of the air somewhere else. Finally, the destruction of unique, old habitats due to development and resources extraction may be impossible to mitigate.

Seeing the coupled human-natural system through a net zero pollution lens poses multiple challenges with respect to understanding and quantifying the complexity of interactions across system components. It increases importance of, and need for, data and models to describe both infrastructure systems at the engineering level, and the infrastructure system-of-systems at the societal level, including:

- Modelling interdependences between physical (built and natural environment) and socio-economic (human activities) systems. Here, approaches such as system dynamics, surrogate and agent-based modelling may prove to be invaluable.
- Assessing feedbacks between environmental impacts, damage and state of the natural environment. This could be done by applying industrial ecology methods such life cycle

assessment, material flow analysis, and footprint analyses, which could play a significant role in evaluating systems-level sustainability indicators.
- Interdisciplinary expertise required to effectively develop and use these data and models to perform the more systematic analysis. This will be particularly important in the context of informing important societal decisions (Saltelli et al. 2020).

The natural world is in crisis and a different perspective is needed – transitioning to net zero pollution enhances focus on the natural environment from a systems perspective, with a potential to facilitate better planning and decision making, and hopefully also environmental protection for the sake of future generations. In order to achieve that, we all need to change the way how we think about infrastructure systems and see them as enablers of the transition to zero pollution rather than as barriers to sustainable development.

Changing current approaches to infrastructure: a research agenda

Development of this paper brings together different kinds of engineering research. It has required us to make explicit and where possible agree shared understandings of infrastructure, and relationships between natural and built environments. Below we articulate the different starting points and approaches to infrastructure systems and their relationship with nature. We then argue for modelling that brings natural as well as built environments within the system boundaries to better understand infrastructure and to better assess sustainability.

Different approaches to infrastructure

Civil infrastructure is as a long-term, interconnected and evolving system-of-systems, in which modifications (both in use and in assets) are interventions. However, it is variously conceived in the extant literature as physical assets (e.g. as a technological system, or a systems of systems), as a process, or as delivering services (see Table 1). The framing is consequential, and as we worked across disciplines, we needed to understand how other engineers and researchers approached infrastructure.

Relationship with nature

Across these literatures there are also different ways of framing the relationship between natural and built environments.

The first is to focus almost exclusively on the built environment, and to see the natural environment as external to the system, as has traditionally been done in engineering and architectural education. This framing suggests that modelling should focus on the built environment only. In this manner writers have argued that ‘Humans are transforming earth environments so radically that we increasingly live in a world largely of our own making’ (Bartuska 2007, 33); or that

> our species is currently unique in that it lives in an environment that is largely of its own construction, built in order to fine-tune the job done by evolution […] We are thus in the rather novel position of creating our own econiche, … . (Warren 1995, 121)

Table 1. Different starting points and approaches to infrastructure systems.

Key Ideas	Scope	Authors/Literatures
Infrastructure as physical assets – *technological systems*	Broad category of infrastructure as (all) mature technological systems that support society – including computer networks and weather forecasting as well as transport, water networks and buildings. A key idea is that these become seen as taken-for-granted, only noticed by users when they fail [also argues there is too much focus on novelty, rather than the role of technological systems in providing underpinning infrastructure]	Infrastructure studies (Edwards 2003; Edwards et al. 2009) – this work is developed by a community of technological change (as opposed to innovation), management and digital scholars, interests in history and change over longer timescales.
Infrastructure as physical assets – *systems of systems* (interdependent, open, etc.)	National critical infrastructure – this is an area of work that was initiated before but has been significantly developed post 9/11, also has concerns in cyber-physical complexity of infrastructure.	Work on interdependencies, complexity and national critical infrastructure (e.g. Perrow 1999; Hall et al. 2013; Moloney, Fitzgibbon, and McKeogh 2017); projects as interventions (Whyte et al. 2019).
Infrastructure as a *process*	All interventions into infrastructure as embedded in systems behaviours, operations or social or knowledge-generating processes, and enacted across different timescales.	Work on infrastructure transformation (Bolton and Foxon 2015); also on systems as process (Blockley 2010), and its application – originally to construction, revised with a focus on infrastructure (Blockley and Godfrey 2017).
infrastructure as *service* – Infrastructure services	Rather than treating infrastructure as physical assets, this perspective frames infrastructure in terms of the services that are delivered.	Development studies, local government, policy and economics; for example to analyse irrigation water systems that support wellbeing in India (O'Keeffe et al. 2018; O'Keeffe et al. 2020)

We would argue that at a time of systems shocks and climate emergency it is no longer legitimate for engineers to focus solely on the built environment outside of a consideration of the natural environment.

The second approach is to treat as equivalent the natural and built environments. For example, the natural environment can be seen as a kind of infrastructure system, where the built environment is the source of all other infrastructure systems. From this approach 'grey infrastructure' may be contrasted with 'green infrastructure' (Czechowski, Hauck, and Hausladen 2018), 'blue–green infrastructure' (Bozovic et al. 2017) or natural infrastructure (such as coasts) (Sutton-Grier, Wowk, and Bamford 2015). The different infrastructure systems become seen as equal and comparable, as they do also in the term civil and environmental systems. This would suggest equal attention to modelling the natural and built environments, or attention to modelling the relationships between them, however typically including aspects of the natural system as pre-defined boundary conditions. A focus on services – infrastructure services, or environmental services through natural capital approach (Bateman and Mace 2020), brings to this debate a stronger focus on use.

A third approach, which we advocate, is to see the natural environment as all pervasive, where the built environment is inseparable from it and an adaptation of the natural environment to suit societal needs, using its materials and resources.

New approaches to modelling

We are interested in how we can define parameters and model infrastructure systems, in ways that simplify without oversimplifying, and that recognise and make explicit the modelling assumptions to develop new way of understanding infrastructure and its connections.

We recognise that to model a system requires assumptions and simplifications – a systems of interest is defined and bounded, and key parameters are included in the model, while others are not included. However we argue for renewed attention to that process of setting up models, to ensure that the parameters we include involve more than the 'grey infrastructure'; or technological systems delivered in interventions, but rather start with the operation of natural systems, and understandings of use of the built environment.

Examples of approaches that we have tried include systems dynamics modelling to synthesise across different domain models, co-modelling, flexibility in design and real options, global sensitivities analyses, etc. We envision a need for more systematic computational tools, digital processes and modelling, as well as novel optimisation and machine learning algorithms to better leverage emerging access to large and complex datasets in infrastructures. We need more tools to help engineers take action and better support the design decision-making process with industry and government leaders, considering the significant uncertainties we are facing. All of this is needed, with a view to enable better value delivery, either economic or social, for generations to come.

There are broader questions about uncertain futures. For example, whether growth can be decoupled from emissions and resource use or whether environmental regulation becomes much more rigorous than it is now. We do not believe the current approach to infrastructure delivery can address the potentially changing environments that societies will face. Hence we argue for modelling approaches that would provide policy evidence and underpin new ways of managing current infrastructure and building new infrastructure that creates a link back to the nature. The questions are hence around how to appropriately define infrastructure systems in sustainability assessments such as life cycle assessment, footprint analysis and supply chains to drive better engineering at a practical and technical (rather than mainly conceptual) level, how we produce systems modelling and how we share that information through forms of visualisation and decision rooms that get all relevant stakeholders to look at the same data, see their role in the system and accept their responsibility for system change.

Conclusions and implications

We are not alone in making the case for systems approaches to infrastructure. The contribution that we make is to consider the implications for engineers involved in civil engineering systems. We set out a research agenda, arguing for the need to develop novel modelling methods, forms of model integration, and multi-criteria indicators to better understand the natural and societal impacts of infrastructure interventions under uncertainty. Systems approaches need to be operationalised by modellers to develop quantitative approaches to modelling infrastructure. Researchers might develop new approaches to integrate existing models and to understanding the complexities and uncertainties that arise in models, and in their relationship with the real natural world in which we live.

The underlying challenges of current approaches to infrastructure include the distance from nature and the sustainability of human existence, and associated challenges of equity, addressing systems shocks and changing lifestyles. There are large inequalities associated with current approaches to delivering infrastructure, with disparities in infrastructure across the globe, where richer societies that can invest in infrastructure generally have higher quality of life and better state of the environment, while those that cannot suffer from both inadequate supply and environmental degradation. The challenges also include addressing systems shocks, and better understanding both the fragility of existing infrastructure, and how it may become more resilient or antifragile in a highly uncertain future. The pandemic has provided an opportunity for insight into which infrastructure services are essential and where aspects of our lifestyle might change to address the increasing disconnection of society from nature.

Having considered what has been learnt in the last 10 years, and the challenges of current approaches, we argue for an approach that starts from the natural environment and its resources, encompassing societal use of infrastructure and the supporting infrastructure assets and services. While a number of scholars promote systems thinking, for example with a focus on the social processes of infrastructure construction (Blockley and Godfrey 2017), we argue that engineering researchers need to utilise such systems thinking to develop novel modelling approaches, decision-support systems, new forms of model integration, and multi-criteria indicators to recognise economic and social value, in order to enable new insights into natural and societal impacts of infrastructure interventions under uncertainty. These developments need to be replicated in the civil engineering curriculum, as the generations to come are those that will need to deal with the problems/world we have created.

Notes

1. For example, using science based targets: https://sciencebasedtargets.org/
2. In this article, we define direct pollution to be the addition/change in quantity of any substance (solid, liquid, or gas) or any form of energy (such as heat, sound, or radioactivity) to the environment at a rate faster than it can be dispersed, diluted, decomposed, recycled, or stored in some harmless form. Sources of pollution are extremely diverse, and the specific harm caused by different pollutants depends on the environment in which they is released.
3. It has been argued that the precautionary principle shifts the burden of proof onto the proponent of an activity, i.e. the proponent of an activity must show any resulting pollution does not cause harm (European Commission 2017).

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