Imperial College London

SYSTEMS APPROACHES TO INFRASTRUCTURE

- A SHARED PERSPECTIVE -

CENTRE FOR SYSTEMS ENGINEERING AND INNOVATION

WORKING PAPER SERIES, NUMBER 2

MOTT MACDONALD · RAMBOLL · LAING O'ROURKE · semp · Balfour Beatty · Environment Agency · EDF ENERGY

CENTRE FOR SYSTEMS ENGINEERING AND INNOVATION

IMPERIAL COLLEGE LONDON

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RECOMMENDED CITATION

Mijic, A., Giambona, J., & Puchol-Salort, P. (2023). *Systems Approaches to Infrastructure: A Shared Perspective.* Centre for Systems Engineering and Innovation, Working Paper Series, No. 2. Imperial College London, UK.

Acknowledgements

CSEI centre members

We would like to thank Centre for Systems Engineering and Innovation member organisations for the continued support and for sponsoring this WP (in alphabetical order).

Balfour Beatty

EDF Energy

Environment Agency

Laing O'Rourke

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Ramboll

Semp Ltd

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This WP has been a truly collaborative effort with like-minded members of our systems community. We would like to thank the following people for generously gifting their time and knowledge. Without their input this work wouldn't have been possible (in alphabetical order by surname):

- Temi Afolabi – The Nichols Group
- Doug Baldock – Ramboll
- Dr Alex Berry – Imperial College London
- Dr Michel Alexandre Cardin – Imperial College London
- Dr Simone Cenci – Imperial College London
- Professor Peter Childs – Imperial College London
- Andrew Chilvers – Royal Academy of Engineering
- Dr Alexandra Collins – Imperial College London
- Dr John Craske – Imperial College London
- Paul Eastwood – SEMP Ltd
- Professor David Fisk – Imperial College London)
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- Gary Kass – Natural England
- Graeme Kasselman – Thames Water
- Martin Kelley – Costain
- Holger Kessler – Geospatial Commission
- Stuart Kirk – Environment Agency

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- Sally Watson – Mott MacDonald
- Dr Jem Woods – Imperial College London
- Dr Andrew Wright – Imperial College London

1. Introduction

Infrastructures are complex sociotechnical systems (Trist, 1981) and they play a vital role in providing enabling services that directly impact people and society (Oughton et al., 2018; Hickford et al., 2018). That is the reason why, to solve the challenges we face in today's world in achieving climate resilience and sustainable development, we need to start from approaching infrastructure in a different way, departing from traditional approaches to embrace systems methods that provide holistic solutions to systemic challenges. This is because systems-based policies, strategies, and tools can help us understand and manage the built environment effectively, leading to better outcomes for people, society, and nature (ICE, 2020; Environment, 2021). While there is growing recognition of the importance of systems thinking in high-level policy and industry (ICE, 2020; Whyte et al., 2020; Voulvoulis et al., 2022), a wide-scale application of systems approaches to infrastructure is still fragmented (Saidi et al., 2018).

The benefits of adopting systems methods include problem-based approaches that foster collaboration and innovation. However, infrastructure interdependencies require system integration to achieve outcomes such as reliability, resilience, sustainability, safety, and security, promoting coordination between natural and human-built systems (Hobday et al., 2005; Davies et al., 2011; Gholz et al., 2018; IPA, 2020). A systems approach emphasises thinking in terms of outcomes rather than isolated projects, understanding the systemic nature of infrastructure, considering the entire lifecycle, and implementing systems-level solutions (Environment, 2021; Muruganandan et al., 2022). This Working Paper aims to provide a shared understanding of the definition and role of systems approaches in the context of 21st-century infrastructure challenges and to propose high-level principles for infrastructure systems' outcome-based planning, design, and operation. By 'a shared' we mean an accepted and agreed-upon understanding at which we have arrived through engagement with over 30 stakeholders involved in researching, designing, and delivering the built infrastructure.

Our approach combines qualitative research methods, mainly integrating literature review with data collected at participatory workshops (W). Firstly, this work identifies the key challenges in applying systems approaches based on literature insights on how we currently plan, design, and manage infrastructure. The review followed standard procedures (Stanley and Doucouliagos, 2012) and analysed not only papers published in peer-reviewed journals but also working papers and reports with a focus on policy-relevant work. Secondly, the Working Paper collects feedback from participatory activities where a variety of stakeholders provided their perspectives from multiple domains on what an integrated systems approach means to them and what academia can do to practically enable the scaling of such an approach. The selection of participants was based on their roles within a lifecycle view of an infrastructure system (from planning to operation). Information was collected through four participatory workshops that involved open-ended discussions, group activities, and multi-stakeholder decision-making processes (Hansman et al., 2006; Kabir and Tesfamariam, 2014; De Bakker et al., 2019). Finally, the Working Paper proposes high-level integration principles that aim to support the conceptualisation of complex infrastructure as a basis for systems methods application to achieve agreed outcomes.

2. Systems domains to analyse approaches to infrastructure

To comprehensively analyse systems approaches to infrastructure, we select the work of Sillitto (2012) who has highlighted the importance of understanding the differences among three different system domains: Systems Thinking, Systems Engineering and Systems Science (Table 1). She argues that there is a need for an 'integrated systems approach' which brings together elements of all three domains and recognises systems-level problems to define appropriate responses, providing a few examples such as Jack Ring's "system value cycle" and Bud Lawson's "system coupling model". We use the three domains to guide the Working Paper literature review.

Table 1. *The overview of three system domains' functions from Sillitto (2012).*

Domain	Core function
Systems Thinking	Understanding systems in a human context.
Systems Engineering	Making choices about how to create and adjust a new system or modify an existing one better to achieve a purpose.
Systems Science	Theory that defines systems and system properties.

3. Literature review of systems domains

3.1 Understanding systems: definitions, boundaries, and complexity

Although there are different definitions of a system depending on the area of study (e.g., engineering, social sciences, biological sciences, etc.), they all highlight the interaction between different elements or components and the pursuit of a common purpose or objective (Backlund, 2000; Sillitto, 2012; SEBoK Editorial Board, 2023). Early definitions such as Miller (1978) see a system as "a set of interacting units with relationships among them" while Ackoff (1994) defined a system as "a whole consisting of two or more parts each of which can affect the performance or properties of the whole". Notably, these interconnected parts or elements will exhibit together a behaviour or meaning that the individual constituents do not (Sillitto, 2012; IPA, 2020). Another important aspect of the definition of a system is the system boundaries. These are the limits that determine what is included within and outside the system and are crucial to establish its scope, interactions, and interdependencies (BKCASE, 2012).

An incomplete or inaccurate assessment of the boundaries of a system, and so of its dependencies, might lead to unintended consequences (Meadows, 2010; Silitto, 2012). For example, there is strong evidence that the increase in the use of heavier electric vehicles has led to a significant generation of tyre wear pollution with potentially devastating implications for human and environmental health (Tan et al., 2023).

Complex systems are those that have many interconnected parts, often being adaptive or highly dynamic. The key characteristics of complex systems are (Quinn et al., 2023):

(i) they are open and integrated with other elements in their environment;
(ii) they are networked and defined by their connections rather than the properties of the individual parts;
(iii) they are emergent from the interaction between the parts without any specific order or without being pre-specified or pre-designed; and,
(iv) they are dynamically interconnected, changing over time through processes of evolution and transformation.

An example of a complex system is an urban water infrastructure that interacts with the natural environment through abstraction and discharge processes and people through water use (Dobson and Mijic, 2020). Its systems-level performance will depend on the functioning of both water supply and wastewater systems, and the impacts will propagate beyond its core purpose by affecting the river water quality, as evident from the recently published data on combined sewer overflows (Giakoumis and Voulvoulis, 2023).

Given the definition of complex systems (Quinn et al. 2023), a systems approach can improve the reliability of the operation of a system by facilitating the identification and management of its interdependencies and so ensure better achievement of the agreed intended outcomes from both the system and any interventions that might change its performance.

3.2 Making choices: outcomes, interventions, and infrastructure lifecycle

The outcome of a system is understood as the final overarching purpose or services provided by a given infrastructure system (ICE, 2020; Environment, 2021). *Our Vision for the Built Environment* report (Environment, 2021) proposes that we need to understand the natural and built environment as interconnected complex systems that provide essential services for our wellbeing and the flourishing of the natural environment. In this work, we understand these services as outcomes, which should be defined for both people (e.g., water and energy supply) and nature (e.g., water and air quality) to thrive together for future generations. This alignment at different levels (from global to local scales) will enable systems integration of infrastructure projects to achieve the set outcomes, meeting the needs of both users and the natural environment and not just delivering physical infrastructure (ICE, 2020; Environment, 2021). In this context, systems thinking is seen as an effective way to understand sustainability challenges and linked outcomes to enable the transition to a sustainable world based on the Sustainable Development Goals (Stevenson et al., 2021; Voulvoulis et al., 2022). The authors from *Our Shared Understanding* report (Environment, 2023) suggest combining systems and design thinking to overcome deep-rooted silos and to increase the links between organisations across sectors.

An infrastructure project is inevitably an intervention into pre-existing systems, including nature (Whyte et al., 2020; Whyte and Mottee, 2022). Far from seeing it as an exploitation of nature, the authors believe that a systems approach to infrastructure allows it to be correctly interconnected with the pre-existing systems on which it intervenes and thus enabling better outcomes for our planet. This holistic view highlights, however, a series of challenges too, such as shifting the current mindset, developing the necessary skills, modelling to understand natural and technological behaviours, and bringing a multidisciplinary approach to infrastructure lifecycle and leadership (Whyte and Mottee, 2022; Kortantamer, 2023).

Finally, achieving better outcomes will require to focus on the expected use of the built environment. This use is supported by essential processes such as operation, maintenance, planning, design, construction, decommissioning, and reuse (Environment, 2021). This notion aligns with the concept of infrastructure pathways developed through a collaborative effort involving the International Coalition for Sustainable Infrastructure (ICSI), The Resilience Shift, and Arup (2020). Although using different terminology, these concepts are also in alignment with the project stages outlined by IPA in 2020, aiming to integrate systems for project success (i.e., assess feasibility; appraise and select; define; deliver; operate, embed, and close). These stages are interlinked with the project's "Routemap modules," which guide the inception of planning and the application of project principles (IPA, 2020). We emphasise the need to address the development of a systems approach to infrastructure considering its lifecycle.

3.3 Principles: Systems integration

The idea of a project as an intervention and the need to consider all stages of an infrastructure system lifecycle create a need for the concept of systems integration. Originally emerging in the aerospace and defence industry in the 1950s and 1960s, systems integration is a core component of systems engineering that brings engineered components and subsystems together to achieve a desired outcome (Johnson, 2003; Davies, 2017; Whyte et al., 2022). While scholars in project management and innovation have recognised systems integration's importance since the 1990s, recent work by Whyte and Davies (2021) highlights the role of systems integration as a core competency in complex projects and products. Moreover, Muruganandan et al. (2022) emphasise systems integration's role in addressing emergent complexities, fostering disciplined flexibility, and adapting to dynamic interdependencies throughout the project lifecycle. Multiple definitions are relevant to the topic of this paper. For instance, Whyte and Davies (2021) define systems integration as “the process of making constituents parts of systems work together", while Whyte et al. (2022) define systems integration as "the set of activities to be undertaken to bring engineered components and subsystems together and achieve desired outcomes by delivering a whole system that is operable, maintainable and safe". As mentioned, the principles of systems integration have a significant role to play in addressing the complexity of infrastructure systems.

Systems integration requires underlying principles that will guide its implementation. There are several examples in the literature of frameworks that look at the integration of the built and natural environments. For instance, Wan Rosely and Voulvoulis (2022) presented a systems thinking framework that looked at the interactions of the elements inside the urban water systems; Hoseinpoori, Woods, and Shah (2023) developed a framework that integrates gas and electricity systems to achieve a system-informed heating technology design in buildings; Puchol-Salort et al. (2021) proposed an urban infrastructure ecology framework that integrated design, evaluation and the UK's urban planning system; while the Royal Academy of Engineering (2017) developed a healthcare systems framework that aimed to integrate people, systems, design, and risk in a structured and ordered way (Clarkson et al., 2017). However, high-level principles that can guide the integration of system elements, expected outcomes, and the required tools and skills from different system domains are still missing in the theory and practice of complex infrastructure systems. This Working Paper aims to be a positive step towards teasing them out.

4. Participatory workshops to inform systems integration principles

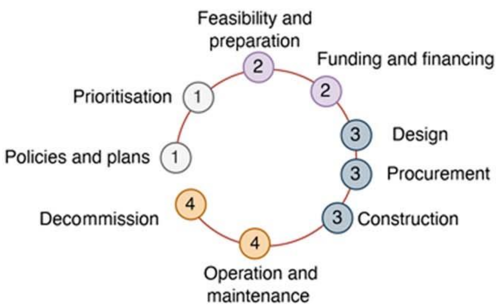
To inform the conceptualisation of an integrated systems approach through participatory engagement, we use insights from the review based on Sillitto's (2012) systems domains to design the workshops structure. In our analysis, we focus on practical aspects that are needed to develop and implement the integrated system approach, for which we replace the Systems Science domain with a more actionable Systems Research category. To get the stakeholders' perspectives on the systems domain concepts, discussions in the workshops focused on the following questions:

- Why do we need systems thinking and how do we define a system and its elements?
- What are the tools, skills and people needed to implement systems engineering approaches?
- What is the role of academia in enabling this systems transition and what programmes are needed to enable the transition from projects to infrastructure systems?

The first two workshops (W1 in October 2022 and W2 in January 2023) involved 18 stakeholders from industry and policy sectors, who mapped themselves to an infrastructure pathways conceptualisation shown in Figure 1A (ICSI, The Resilience Shift and Arup, 2020). The classification was grouped into the four areas and sub-areas that constitute the infrastructure lifecycle. Participation from each area was ensured as much as possible. However, we acknowledge that the operation, maintenance, and decommission areas did not have as much representation as the other areas. The third workshop (W3 in May 2023) was attended by scientists and academics, who provided input from a scientific perspective on the same systems domains. The information obtained from academics in W3 was combined with the industry and policy perspectives from W1 and W2. Finally, the fourth workshop (W4 in June 2023) served as a collective gathering bringing together participants from the three previous events. In this case, a total of 25 participants from the three different sectors (industry, policy, and academia) were present. The aim of this final workshop was to validate the draft findings and to capture any further emerging views stimulated by viewing the processed data as a larger group. Before W4, participants had already reviewed the draft of this Working Paper providing preliminary feedback.

A)

INFRASTRUCTURE PATHWAYS CLASSIFICATION	
Name	**Code**
Policies and Plans	1a
Prioritisation	1b
Feasability and Preparation	2a
Funding and financing	2b
Design	3a
Procurement	3b
Construction	3c
Operation and Maintenance	4a
Decommission	4b



B)

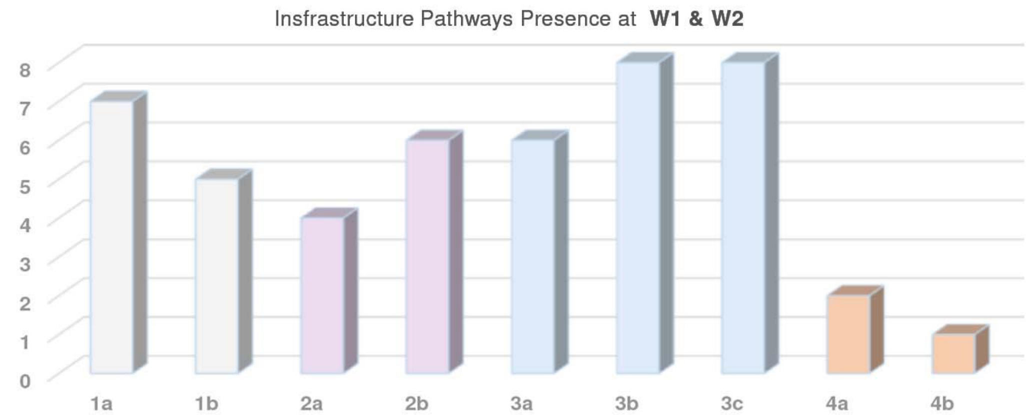


***Figure 1**. Infrastructure Pathways classification (A) and participants attendance in W1 and W2 (B).*

The four workshops encouraged active participation and facilitated dialogue among the participants to share their insights (Figure 2). To probe diverse views and opinions, they incorporated a combination of individual and group activities, allowing participants to express their perceptions and share their experiences. Following the workshops, we collected all the data generated during the sessions to systematically explore key findings, particularly to identify keywords and key messages derived from the participatory discussions. The findings are presented as a summary of the input from all workshops.

Figure 2. *Photos from participatory workshops.*

4.1 Participatory workshops: Understanding systems

The first set of questions in the workshops was aimed at getting a shared perspective on the definition of a system, the need for systems thinking and what the implications are for the practical implementation to analyse infrastructure systems. Inputs aligned with the insights and definitions obtained from the literature review. Participants agreed that a system should be defined as "*an interconnected set of elements that lead to a defined outcome*" which "*always delivers/achieves a purpose (deliberate or not)*". The role of a system boundary and the emergent property was also emphasised:

"*The combination of these [system] elements in certain boundaries (time and space) delivers more than the sum of the parts."*

Participants greatly expanded on the original definition of systems thinking to understand infrastructure systems in a human context. Specific aspects that were emphasised included the need for systems thinking to help "*to reduce complexity and uncertainty*" resulting from "*different interactions*" in order to "*deal with unintended consequences and dynamic impacts*". This results in the need to "*improve understanding and communication of systems and their feedback loops*". It was argued that this will lead to important changes in the way we design, plan, and operate infrastructure systems, including:

"*To better understand the risks" and "inform policy and decision-makers about [the] overall picture, trade-offs and long-term benefits."*

Discussion on the implementation of systems thinking for understanding infrastructure systems pointed to the need for:

"*Developing practical tools that enable better decisions (i.e., informing policy) following a mapping and integration approach."*

The integration was seen from the perspective of both "*intended and unintended consequences*" and "*technical, operational and organisational*" system elements.

4.2 Participatory workshops: Making choices

While the literature review primarily emphasised the need for improved alignment between the natural and built environments to achieve better outcomes across different scales, participants' input was more focused on the systems engineer role and the need and barriers for systems engineering skills and training enhancement.

The role of a systems engineer was seen as one of overarching coordination of the integrated systems approach implementation. Systems engineers should have the capability to "*integrate[s] system components with related people to provide a combined outcome*" and to "*promote[s] systems thinking, engage[s] with stakeholders, challenge[s] silos, break[s] barriers and always sees [a] bigger picture*". Such a role would require a range of skills, from "*listening, leading, oversighting, convincing, influencing, passion, storytelling, etc*." to more quantitative ones including "*analytics, data collection, risk management, design programmes, measuring impact, etc*", as it was pointed out that lack of usable data is one of the challenges to build the evidence needed to support the case for a systems approach. It was also recognised that a systems engineer should have a "*passion for digital work and tools*". Overall, this role was seen as having:

"*Very wide breadth and not too much depth in technical knowledge*."

The barriers to creating systems engineer roles were seen in "*hierarchies and skill sets [that] are not always easy to acquire and measure"* and a "*still very limited [concept] due to silos in education and a very heterogenous group*".

Finally, participants expressed their concern regarding the distinction between a systems engineer and a systems leader role. While the role of a systems engineer is seen as managing and overseeing the entire infrastructure project, a systems leader is perceived as the overall process owner, integrating systems thinking and engineering. Systems leaders are seen as being the bridge that ensures engagement and collaboration among stakeholders, both within and outside an organisation. The systems leader will have an eagle view of the project that transcends siloed views and never loses sight of the intended purposes and outcomes.

4.3 Participatory workshops: Systems research

The final part of the workshops' discussions was dedicated to answering what the role of systems research is in creating and delivering an integrated systems approach to infrastructure. The answers added depth to insights from the literature review, which emphasised the role of systems integration in complex infrastructure projects and the lack of underlying high-level principles.

The role academia was seen primarily in:

"*Building novel and integrated tools/methods to demonstrate how these tools/methods can be better [than existing approaches]" and "To enable cultural change by providing leadership [in championing systems approaches]".*

This should be done "*with public and community engagement*" and by "*using technical practices to drive strategic outcomes and break legislative barriers*". A need for "*evidence-based examples that show how to practically implement theory into practice in the real world*" was particularly highlighted, which could be facilitated through "*innovation labs and idea generation [hubs]*". The research should be aimed to "*influence regulations and to work with national academics and professional bodies*".

A strong link between research and education was also emphasised. It was noted that "*collaborative and multi-disciplinary research groups [should be embedded] in a holistic educational approach*". We should also aim to build "*enterprise and education programmes to support systems management and delivery*" and "*training in problem-solving to become system thinkers/engineer*s".

Finally, the participants pointed to the need to "*use the right language to improve awareness and knowledge, sorting out a clear narrative*". The agreement was that this would enable better understanding and foster collaboration.

5. High-level principles for a systems approach to infrastructure

Based on the insights gathered from the literature review and the workshops, we outline four high-level principles designed to guide the development of an integrated systems approach to infrastructure planning, analysis, operation, and delivery. Furthermore, we map the areas of this work that would require further collaboration and research.

Principle 1. Infrastructure system framing and leadership. An infrastructure system should be defined as a set of interacting elements that contribute to the delivery of a shared purpose or objective and is delimited by a system's boundary. It should be recognised that complex infrastructure systems are characterised by their dynamic, emergent, and interconnected nature, evolving over time through non-linear, iterative processes. A combination of system elements will lead to an outcome, which could be intended or unintended. The role of systems thinking is not only to improve understanding of a system and corresponding risks but also to better manage risk and uncertainty in complex infrastructure systems. The role of a systems leader is seen as pivotal to ensure that the intended purposes and outcomes of an infrastructure system are realised.

Principle 2. Linking an infrastructure system with outcomes and interventions. Infrastructure projects should be seen as interventions into pre-existing socio-technical and natural systems. Better alignment between the natural and built environments ensures the achievement of agreed outcomes from the local to the global scale (Figure 3). Systems integration, a core aspect of systems engineering, is crucial for complex projects to address sustainability challenges, especially when combined with systems thinking. We highlight the importance of defining the boundary for system analysis, considering various factors such as the desired outcomes and the nature of the intervention. This will ensure better management of interdependencies and, consequently, minimise unintended consequences. Overall, understanding the relationship between the system boundary, outcomes, and intervention will be crucial for a successful system analysis and integration in infrastructure projects. Once the decision about an intervention is made, then the project delivery should be done following the principles of systems integration for complex projects (Quinn et al., 2023). The role of a systems engineer will be essential to provide integration not only from a technical side but also in terms of alignment between different stakeholders, agreeing outcomes and trade-offs, and ensuring that the right language is used to promote collaboration and coordination.

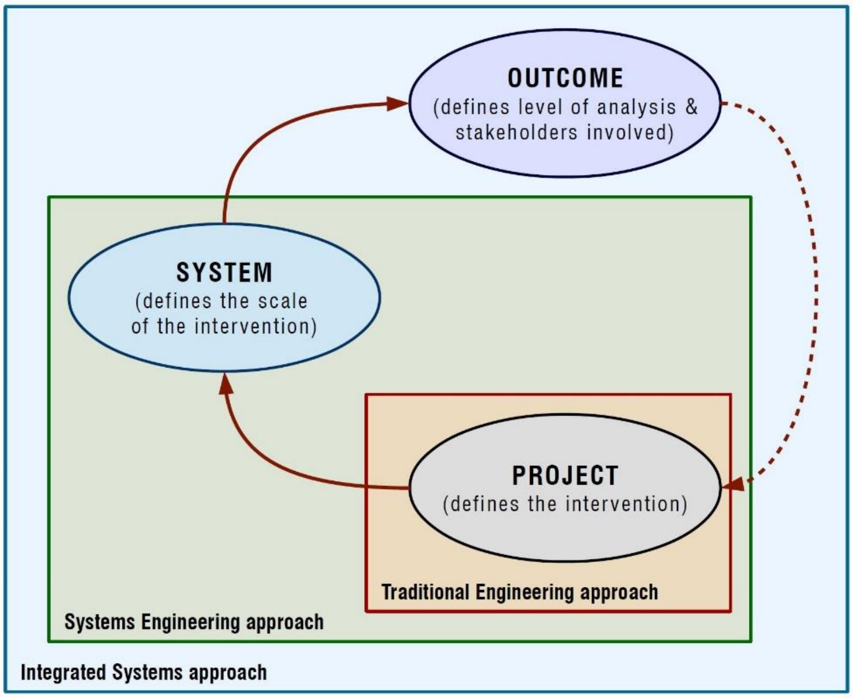


Figure 3. *A high-level overview of an outcome-based infrastructure system with a project as an intervention.*

Principle 3. Tools, skills, and systems research for integration of infrastructure systems. To demonstrate the added value of systems approaches to infrastructure, a set of tools and skills in participatory engagement and systems analysis should be explored and published. Nowadays, even small projects should be perceived as interventions in existing contexts that provide essential benefits to people and nature (ICE, 2020; Environment, 2021). Looking ahead, as infrastructure systems become increasingly technology-driven, a new combination of tools and skills will be imperative for effectively performing those interventions (ICE, 2020). Although the skill requirements for each system domain and scale might vary, there are fundamental principles rooted in systems theory that can enhance the efficiency of an integrated systems approach across all domains. In general, the choice of qualitative or modelling tools will depend on the agreed boundaries and intervention of the system. Methods such as participatory system dynamics could be used for effective system mapping, stakeholder engagement and scenario analysis (Salvia et al., 2022). Analysis of future scenarios and outcome-based infrastructure planning will require simulation models that can integrate a physical and natural system with decisions and behaviour, such as in the example of the water systems integration analysis (Dobson, Liu, and Mijic, 2023). If the appropriate tools are available, training may be necessary to enable their use; if the tools are lacking, further research will be required as a co-designed process between academic institutions, industry, and policy. In both options, digitalisation should guide our choices and bring us towards the socio-technical change that the fourth industrial revolution requires (IPA, 2020; Environment, 2021). This is a domain where academia can provide an invaluable contribution, especially when working together with industry and policymakers.

Principle 4. The role of engagement, shared language, and culture change. The role of stakeholders is crucial in the context of infrastructure interventions and how they influence the selection of infrastructure system outcomes. Key stakeholders are those who are directly involved in the interventions throughout the system lifecycle and are impacted by the resulting outcomes. Hence, it is crucial to understand their viewpoints as that might influence the use of the infrastructure system. Employing a front-end project development enhances the definition of the intervention, fosters a stable delivery of the infrastructure system, and improves stakeholder engagement. As part of an integrated systems approach, employing effective methods to engage and work with stakeholders such as workshops and focus groups, interactive visualisation tools, and online collaboration platforms will ensure their active participation throughout the process. These strategies will play a crucial role in fostering collaboration and understanding among stakeholders. Finally, to ensure the engagement necessary to enable an effective co-creation process, it is necessary to create a shared language in the context of infrastructure systems. This will enable a much-needed cultural change which can contribute to scaling the adoption of systems approaches and embed them into the way we plan, design, deliver, maintain, decommission and reuse infrastructure. Besides, it is important to acknowledge the crucial role that narratives play in fostering innovation (Ninan, Sergeeva and Winch, 2022). However, these narratives would lose impact without the use of a shared language.

6. Conclusions and future steps

The principles proposed in this Working Paper set high-level thinking about systems approaches to infrastructure. They also create a need for a range of case studies to turn these principles into a framework that can be used to inform specific interventions and outcomes. Current policy and planning cycles, such as the upcoming Asset Management Plan (AMP 8) for Ofwat investments or future UK Government energy and rail initiatives, could provide an excellent platform for sharing the evidence.

In the post-COVID world and in the era of digitisation, we see an opportunity to enhance visualisation and data-driven decision-making support tools to represent infrastructure systems complexity more effectively, potentially by creating web applications that support knowledge management and facilitate knowledge sharing across and within different organisations.

The findings of this Working Paper emphasise the need to consistently provide examples of and training for existing methods and techniques that can be used to support the defined principles. This is particularly important in the context of integrating traditional social sciences and STEM educational domains and educating senior management towards creating the role of a systems leader.

Finally, it is crucial that any future case study or research project that may arise from this work is used to explore collaborative opportunities with multiple institutions, including Government and policy bodies, to share evidence, foster valuable joint initiatives and enable policy and practice change. We hope that further exploration of the four principles will provide a valuable resource for systems thinkers, engineers, and researchers to navigate the complexities of infrastructure planning, development, and management more effectively.

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