EVIDENCE FOR THE VALUE OF A SYSTEMS APPROACH TO INFRASTRUCTURE PLANNING, DELIVERY AND OPERATION

Neil Carhart[1], Aksel Ersoy[2], Colin Taylor[1], Shima Beigi[1]

[1] University of Bristol, [2] Oxford Brookes University

Who Should Read This White Paper?

This White Paper is aimed at those involved in the planning, delivery and operation of infrastructure. The information and recommendations it contains have broad applications, but are of particular relevance for consideration in national infrastructure policy, strategy and governance, as well as senior figures involved in engineering and construction management.

Key Messages from the White Paper

1. The current approaches to infrastructure are largely fragmented and reactive. This is true temporally in the planning, construction and operational phases, as well as at different scales: from specific projects to the policy and governance of the whole infrastructure system-of-systems.
2. Infrastructures can be viewed as systems with emergent properties that can present challenges and opportunities which the traditional fragmented approaches tend to overlook.
3. There are practical tools through which the systems approach can be proactively applied to infrastructure planning, construction and operation. These can help identify and manage complexity and emergent properties, reducing costs and deliver additional benefits to ultimately enhance the infrastructure’s value proposition.

Abstract

The paper discusses the notion of infrastructure as a system, the nature of the systems approach in the context of infrastructure, and how this could complement the shortfalls of more dominant approaches. It argues that taking a systems perspective is a route to unlocking additional value from national and regional infrastructure system-of-systems, where value is a measure of the benefits derived by stakeholders in relation to the costs they have incurred. Thinking about infrastructure challenges, assets and services in terms of systems comprising multiple dynamic interactions and perspectives can enhance understanding of how value is created and captured. Examples are presented of infrastructure projects where interactions were overlooked, leading to increased cost and reduced benefits, and where interdependencies were recognised and manged to reduce cost and increase benefits.

The paper concludes by outlining recently developed practical tools and techniques which have been designed specifically for the application of a systems approach to infrastructure.

Key Words

Systems Approach; Infrastructure Interdependency; Complexity; Emergent Properties; Value Proposition.

Connections to Other ICIF White Papers

This paper makes reference to:

- Emerging Approaches and Issues in Regulation and Governance of Infrastructure Based Services
- Infrastructure Governance for the 21st Century
- Reduction in the Cost of Execution of Current Infrastructure Business Models
- Infrastructure Resilience: a multi-disciplinary perspective
- Learning Journeys and Infrastructure Services: a game changer for effectiveness

Where Can I Find Out More?

For more information please contact Dr Neil Carhart: neil.carhart@bristol.ac.uk

Acknowledgements

ICIF is funded by the Engineering and Physical Sciences Research Council and the Economic and Social Research Council (Grant reference: EP/K012347/1).

This is a draft copy, available online pending publication as a book chapter in the ICIF White Paper Collection, UCL Press [TBC Autumn/Winter 2016]. Prior to publication reference as:

> *Carhart, N., Ersoy, A., Taylor, T. and Beigi ,S. (2016) Evidence for the Value of a Systems Approach to Infrastructure Planning, Delivery and Operation (advanced copy) In: Dolan, T and Collins, B, (eds.) ICIF White Paper Collection (in Press), UCL Press, London, UK. Available online at: www.icif.ac.uk*

Evidence for the value of a systems approach to infrastructure planning, delivery and operation

1 Who Should Read this White Paper?

This White Paper is aimed at those involved in the planning, delivery and operation of infrastructure. The information and recommendations it contains have broad applications, but are presented here to be of particular relevance for consideration in national infrastructure policy and governance, infrastructure finance, engineering and construction management, infrastructure operation and service provision, and other related fields. It argues that the current approaches to infrastructure planning, delivery and operation present issues that may be addressed through the adoption of a complementary holistic systems approach. The shortfalls of the existing approaches in dealing with complex infrastructures are discussed along with practical examples of the value which could be derived from the use of the systems approach. The nature of the approach is described together with tools and methods which aid its implementation.

2 Introduction

The current approach to infrastructure planning and delivery within the UK is "fragmented and reactive" (HM Treasury and Infrastructure UK, 2011). The delivery (planning, construction and operation) of individual infrastructure systems have historically been viewed in relative isolation from one another. New infrastructure projects are treated as separate from the social, economic and environmental contexts in which they will be placed, and occasionally even from the existing legacy infrastructure. The Armitt Review of Infrastructure reported that "when long term decisions are made, they can be taken in silos with little acknowledgement of the interdependencies between sectors" (Armitt, 2013). This is in contradiction to the widely held view of infrastructure as an interdependent network of smaller networks (Council for Science and Technology, 2009).

The UK's National Infrastructure Plan has previously noted that "opportunities to maximise infrastructure's potential as a system of networks have not been exploited" (HM Treasury and Infrastructure UK, 2011). These opportunities exist throughout infrastructures' lifecycles, from the initial strategic policy decisions, through construction to the management of infrastructure services and eventual renewal or replacement. Such a shortfall could be addressed through the implementation of a systems approach to infrastructure planning, construction and operation.

This ICIF White Paper discusses infrastructure as systems, the nature of the systems approach in the context of infrastructure, and how this could complement the shortfalls of the dominant approaches. The ultimate claim is that **taking a systems perspective is a route to unlocking additional value from the infrastructure system-of-systems**. Value is a measure of the benefits derived by stakeholders in relation to the costs they have incurred. It is not limited to direct financial gain and may be experienced and perceived differently by each actor within the system. Thinking about infrastructure challenges, assets and services in terms of systems with multiple dynamic interactions and perspectives can enhance understanding of how value is created and captured.

While this White Paper does not go into the detail of the tools and techniques available, it provides practical case studies of these approaches in action, the benefits they delivered and guidance on finding out more.

3 What is The Systems Approach?

A system is "a set of parts which, when combined, have qualities that are not present in any of the parts themselves" (The Royal Academy of Engineering, 2007). The parts interact with each other and the environment they inhabit in numerous complex ways. A purposeful system will be structured such that its parts interact in a way that facilitates a desired and valued function or outcome. Technical engineered systems such as power stations sit within and interact with wider social systems which themselves exist with and within natural systems. The operation of the engineered system is provided with purpose and intentionality by the social systems.

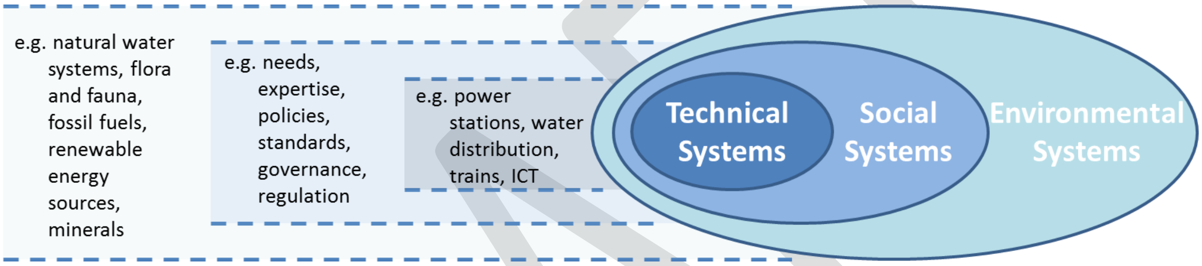


Figure 1 - Infrastructure as Nested Systems

Systems based approaches developed in reaction to problems that were not suited to classical methods of analysis that require the interaction between parts to be negligible (Von Bertalanffy, 1968). The alternative to the systems approach is either to view the whole as a homogenous black-box or rely on a piecemeal understanding of the components in isolation from one another and from their operational context (Ackoff, 1979).

These classical approaches, which favour reducing the system to its component parts, are based on an assumption that the optimisation of the components in isolation will lead to an optimal system when they are combined. This is not always the case, particularly in dynamic, complex systems.

The systems' perceived purpose, against which its value, quality and success will be judged, may change with the demands of their environment. Large-scale complex systems often have multiple stakeholders, frequently with competing perspectives on, and expectations regarding, the system's performance.

Avoidable challenges arise and opportunities are missed when the interactions between the components of the technical system, and of the technical system with the wider social and environmental systems, are neglected. A systems approach seeks to understand the nature and structure of the relationships between the component parts and the wider environment, and how these relate to the overall purpose and performance of the system they create. In this respect, systems approaches and classical approaches are complementary to one another. The systems approach is not a replacement for any other method - it has shortfalls of its own - but it can provide access to delivering qualities and value that other approaches cannot.

System approaches can be applied to a range of areas and tasks, from the design of engineered technological systems such as mobile phones and aircraft carriers to the management of complex social systems such as hospitals. *Systems Engineering* of complex objects and software is prevalent as a formalised sub-discipline but it should not overshadow or be mistaken for the more fundamental concept of *Systems Thinking* which is also pervasive in areas of policy and strategic management, albeit often implicitly. Thinking in terms of systems is relevant to the challenges of planning and managing large-scale infrastructure projects, and in forming the strategy for the infrastructure system-of-systems as a whole.

4 Infrastructure as a System

Infrastructures, such as rail networks and water distribution pipelines, are complex socio-technical systems (Trist, 1981). They are more than a set of physical assets and artefacts. They encompass the people who operate them, the organisations which govern them, the users from which their purpose is derived, and the wider environment from which they draw resources.

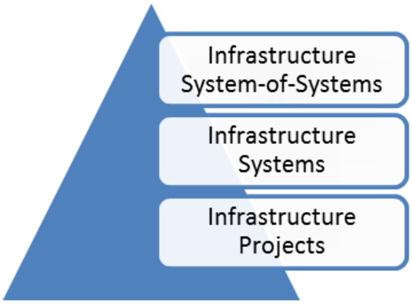


Figure 2 - The Infrastructure Hierarchy

At one level a road network or electricity grid can be viewed as a single **infrastructure system**. For many working within the infrastructure sector these infrastructure systems are experienced through the individual **infrastructure projects** from which they are comprised. These projects may concern the construction of new infrastructure components or the operation of existing services. In each case they are intended to address specific national or regional needs. Each individual project is a complex socio-technical system in its own right.

Crossrail, currently the biggest construction project in Europe, brings together over 10,000 people from different disciplines to resolve a wide variety of connected technical, economic and cultural challenges. Thames Water employs over 14,000 people to provide water and wastewater services to 15 million customers. These projects aim to meet the needs of a multitude of diverse stakeholders and will affect the lives of many more.

None of these projects exist in isolation from one another. There are many different ways in which they are interdependent (Carhart and Rosenberg, 2015). Construction projects such as Crossrail exist with temporal, organisational and strategic interdependencies. Once constructed the operation of one infrastructure system, such as a water treatment facility, may be dependent on the operation of others, such as the electricity generation and distribution systems. These operations can be interdependent by virtue of their spatial proximity, their organisation or governance, their purpose or their physical, functional and digital connectivity (Rinaldi et al., 2001).

Through these interactions and interdependencies infrastructure systems also form part of the larger continuum that makes up a region or nation's **infrastructure system-of-systems**. Hence a hierarchy is formed. Individual infrastructure projects combine into infrastructure systems which also interact to form a system-of-systems.

Box 1: Wicked Characteristics

Rittel and Webber describe the characteristics of a 'wicked' problem as:

1. There is no definitive formulation;
2. There is no stopping rule;
3. Solutions are good or bad, rather than true or false;
4. There is no immediate and no ultimate test for a solution;
5. There is no opportunity for trial-and-error;
6. There is no way of ensuring all potential solutions have been considered;
7. Each one is essentially unique;
8. They can be considered a symptom of another problem;
9. They can be explained in a number of ways and the choice of explanation will determine the solution.

Situations with a high degree of complex interaction between the elements of the system or problem have been described as 'messy problems' (Ackoff, 1997) and, where this has been compounded by multiple conflicting viewpoints, as 'wicked problems' (Rittel and Webber, 1973). These are characterised by an evolving set of interacting issues, requirements and constraints which render them intractable and difficult to define (see Box 1). Overcoming such challenges is critical to realising value at the planning, delivery and operations phases, but particularly in relation to shaping and executing national strategies and policies for infrastructure. They require substantially different approaches to the types of problem characterised by sequential, deterministic processes and broadly agreed, known outcomes (Hancock, 2010).

5 Infrastructure Planning, Delivery and Operation

The nature of infrastructure, its requirements and behaviours, vary through the physical continuum of the system-of-systems and at different levels of the hierarchy described above. The requirements and behaviours also vary through the infrastructure's lifecycle. For the purposes here, the infrastructure lifecycle will be simplified to three broad phases. The first phase concerns **planning**, policy and strategy. It looks at the outcomes that are required, the capabilities necessary to facilitate those outcomes and the assets which will enable those capabilities. This should also include planning for the replacement, recycling and renewal of the infrastructure. The second phase in this simplified lifecycle concerns the **delivery** of the infrastructure assets. This involves the detailed design and construction of specific physical infrastructure components.

Figure 3 - Simplified Infrastructure Lifecycle

The third phase concerns the **operation** of the infrastructure in order to create valued outcomes. The desired outcomes may require the interaction of multiple infrastructure systems and change over time, even if the physical assets do not. The operation may need to adapt accordingly.

6 Why Adopt a Systems Approach to Infrastructure Planning, Delivery and Operation?

The previous sections have suggested that infrastructures (from the national level down to specific projects) can be viewed as complex socio-technical systems, and their planning, delivery and operation exhibit the characteristics of so-called wicked problems. Furthermore, traditional linear, reductionist problem solving methods are inefficient at tackling these problems (Conklin and Weil, 1997). It has been long advocated that the tools and methods of a systems approach are of value in navigating the complexity and resolving the challenges associated with such problems (Checkland, 2000). This perspective supports the identification of opportunities and hazards which may not be apparent from a segmented project-by-project, system-by-system or sector-by-sector view.

This section explores in further detail the nature of infrastructure as a complex system at the three different phases, and at different levels of the hierarchy. It begins to build the case for a systems approach by looking at the relationships which characterise infrastructure systems and the consequences of overlooking these relationships. The subsequent section provides examples of where value has arisen from understanding and addressing the relationships, and the properties which emerge from them.

6.1 Phase 1: Planning

The UK National Infrastructure Delivery Plan (HM Treasury et al., 2016) outlines over £400bn of future infrastructure projects. There is an estimated global need for $57 trillion of infrastructure investment by 2030 to keep pace with current global rates of growth (McKinsey Global Institute, 2013). Many projects are still at the planning stage, identifying the nature of the outcomes that need to be delivered. The outcomes will often require the interaction of multiple infrastructure systems and will fit into a landscape of legacy infrastructure. The relationships with these other systems, whether they already exist or need to be co-developed can influence the success of the projects.

Interdependencies between policies, strategies and plans may affect the ability to release value in subsequent phases. Project-by-project economic appraisal methods overlook emergent properties at the system-of-systems level that impact on the risk of infrastructure investments (Young and Hall, 2015).

In the planning phase large complex projects are frequently treated in a way that assumes little crosses the system-of-interest's boundary beyond that which is functionally necessary. This is known as a 'closed system' view. This helps to simplify the challenge. However a global study of transport projects (Omega Centre, 2012a, 2012b, 2011; Omega Centre et al., 2010) concluded that infrastructure should be viewed as an 'open system', allowing internal and external socio-economic, natural and technical interactions to be considered in the planning, appraisal and design processes. Cases such as the Northern Line Extension show that projects can be intrinsically linked in the planning phase (Carhart et al., 2014).

The Armitt Review of Infrastructure (2013) described the current lack of appreciation for these interconnections in infrastructure planning as “silo-thinking” offering an example: “the debate around High Speed Two is taking place independently of any assessment of options for the strategic roads network”. The Royal Academy of Engineering (2013) submitted to this review that: “A systems approach to infrastructure planning will be essential, noting the interdependencies between infrastructure sectors, and the opportunities for creating dual use infrastructure and co-locating services where possible”.

Past President of the Institution of Civil Engineers Prof Paul Jowitt also advocated “a systems view” to strategic infrastructure planning. He wrote that “the need for systems-level decision-making for large-scale infrastructure proposals has never been greater. One way or the other, it comes down to our ability to take a systems view and make decisions accordingly” (Jowitt, 2015). The adoption of a systems approach could be beneficial at the strategic level for planning the infrastructure system-of-systems.

At the other end of the hierarchy a catalogue of specific infrastructure projects have seen their value affected though planning which did not acknowledge them as complex systems, or as parts of larger systems. Box 2 provides examples of such projects.

6.2 Phase 2: Construction

Projects such as Crossrail illustrate the scale and complexity infrastructure construction can reach. During this phase some projects demonstrate substantial physical, temporal and organisational interdependencies between their own processes, and with other existing and planned infrastructure projects. This includes multiple projects competing for limited physical or human resources, interacting activities by virtue of their proximity, or the outputs of one process providing value to another.

Box 2: Infrastructure Projects as Complex Systems: Planning

2005 – present - Olikiluto Nuclear Power Plant, Finland
The nuclear power operator commissioned the construction of a new power plant by a consortium at a fixed price of €3 billion. Current costs are estimated to exceed €8 billion and completion has been delayed from 2010 to a forecast 2018-20. There have been problems in managing the supply chain relationships between the operator, construction consortium and sub-contractors, and it has been suggested that some of the workforce were unprepared for the requirements of construction. Planning requires consideration of the related pipeline of skills and capabilities.

2006 – present - Berlin Brandenburg Airport, Germany
Planning started in the 1990s, with the opening scheduled for 2010 at a cost of €2.83 billion. The project has been delayed until 2018/19 and the costs have increased to over €6 billion. Delays have been accredited to poor planning, management and construction. Interaction between the back-up power and fire suppression system was overlooked meaning there would be inadequate power for the sprinklers. Interactions with the wider social context were also overlooked, for example the cost of providing soundproofing for homes has inflated the original budget.

2008 – 2014 - Edinburgh Tram Network, UK
Construction began in 2008 at an estimated cost of £521 million. The final cost was £776 million when the network opened three years later than scheduled in 2014. Problems arose due to funding issues and significant contractual disputes. Disruption to businesses was significant, and it has been suggested that earlier engagement with the stakeholders and wider social context may have provided greater appreciation for the complex needs and challenges.

An analysis by Frontier Economics indicated substantial one-off and on-going economic opportunities arising from these interdependencies (Frontier Economics, 2012), further supported in analysis of the High Speed 2 and the Lower Thames Crossing projects (Carhart et al., 2014).

Recognition for the deficiencies of the dominant approach within construction is not new. The Egan Report (1998) observed that the industry was "typically dealing with the project process as a series of sequential and largely separate operations" and called for "an integrated project process". It highlighted that "the most successful enterprises do not fragment their operations". Systems approaches for rethinking the construction industry were explicitly outlined in response to the Egan Report (Blockley and Godfrey, 2000). The authors promoted a way of meeting targets to (a) deliver new customer focused strategies, (b) work back from success, (c) realise values by integrating people and process, (d) generate simplicity out of complexity by process mind mapping, (e) inject practical rigour and (f) create tools for managing uncertainty. They suggested adopting *interacting object-process holons* as an integrating concept. These *holons* are processes that can be seen as both wholes and parts at the same time. An upcoming second edition of the book is based on the lessons of the last 15 years and aimed at the new infrastructure challenges in the light of a changing climate. It states 5 axioms of systems thinking, along with 17 corollaries and 7 principles. The axioms concern 'impelling purpose, appropriate layers, complex interdependence, ubiquity of change and evolutionary learning'.

The 2011 UK Government Construction Strategy concluded that public sector construction was not delivering value, citing among other things that fragmentation was still an issue. It recommended procurement methods that integrate supply teams and transition to outcome-based specifications. One year later, an update stated £72 million of savings from shifts towards this approach (HM Government Cabinet Office, 2012).

Box 3 illustrates the sorts of issues which can emerge during the construction phase of an infrastructure project if they are treated as technical problems within tightly-bounded closed-systems rather than as complex open-systems which form part of a wider system-of-systems.

Box 3: Infrastructure Projects as Complex Systems: Construction

1992 – 2015: Hallandsås Tunnel, Sweden
Construction began in 1992 with a planned opening in 1995. Unforeseen water seepage and ground conditions, a broken drilling machine, and bankruptcy of the original contractor initially caused delays. The potential effects of corrective actions on the wider environment were not appropriately considered. A grouting compound used to seal the leaks was linked to the poisoning of livestock and fish in the local area as well as worker illness. Construction was halted from 1997 to 2005. The final costs are estimated at 10x the initial projections.

1994 - Heathrow Tunnel Collapse & Jubilee Line Extension, UK
The collapse during construction of the Heathrow Tunnel in 1994 delayed the construction of the Jubilee Line Extension which was using similar construction methods. This demonstrates interdependency between the two otherwise unconnected projects which emerged within the construction stage, but the potential for which could have only have been identified from a strategic planning perspective.

6.3 Phase 3: Operation

Phase 3 concerns the operation of the infrastructure systems constructed in Phase 2, in order to deliver the outcomes identified in Phase 1. These outcomes often require the interaction of multiple infrastructure systems. For example domestic hot water requires the interaction of systems from the water sector with those from the energy sector.

Historically, much of the focus on infrastructure as systems and the interdependencies which characterise them has been on the spatial proximity of assets or the functional reliance of components upon one another. One important issue is cascade failure. This is where a disruption to the function of one system can have a knock-on impact on another (See Box 4 for examples).

Functional dependencies can also impact on recovery from failure. A systems approach can enhance the reliability (Little, 2004) and resilience (ICIF, 2016a) of the operation of a system-of-systems by facilitating the identification and management of these dependencies. Box 5 looks at the different ways in which these interdependencies can manifest, while the following section looks at how they can be exploited to add value and avoid costs.

Box 4: Infrastructure as Complex Systems: Operation

2003 Power Outage, Italy
In September 2003 storms affected transmission cables carrying electricity between Switzerland and Italy, this increased demand on other interconnectors into and out of Italy, causing them to trip. The resulting electricity blackout affected the majority of Italy, disrupting the delivery of railway, communication, healthcare and financial services. The disruption to communication systems affected the ability to recover the electricity system.

2003 Power Outage, USA
A similar outage occurred in north-east USA in August of the same year when a line faulted and subsequent lines tripped as they were unable to compensate for the increased demand. The cascading effects resulted in nuclear power plants shutting down, further exacerbating the problem. Water pumps also shut down disrupting the supply to many millions of people. Trains, flights and communication systems were affected along with fuel manufacturers; disrupting supplies for a prolonged period after power was restored.

7 Evidence of Value: Reducing Costs and Delivering Benefits

In addition to overcoming the challenges which result from approaching complex infrastructure systems as simple discrete projects, adopting a systems approach can also proactively enhance the potential to deliver value by reducing costs (both capital and operational) and by increasing the realisation of benefits. Fundamentally this requires an acknowledgement of the relationships and interdependencies that make infrastructures' complex systems. This can be achieved through the implementation of methods and tools developed under the systems approach in complement to the traditional methods.

Box 5: Infrastructure Interdependency

Rinaldi et al (2001) provide the foundation for the characterisation of infrastructure interdependency, suggesting a framework of six dimensions. Others looked at the structure of the interaction and co-operation (Raven and Verbong, 2007). The table below shows a collection of the wide variety of characteristics of infrastructure interdependency (Carhart and Rosenberg, 2015). Some (marked with an *) require specification of the system/element from which the perspective is derived.

DIRECTIONALITY	*Whether the reliance of one element on another is mutual*	Bi-Directional Non-reciprocal
ORDER*	*Whether the relationship is direct or via an intermediary.*	First Order Second Order Higher Order
COUPLING	*Whether the effects of the relationship are felt closely in time and space or not.*	Loose Tight
TYPE	*The nature of the relationship, spatially or in terms of resource flow.*	Physical Digital Geographic Organisational
INTERACTION TYPE	*The degree of co-operation and structure of the relationship.*	Competition Symbiosis Integration Spill Over
FUNCTIONALITY	*Whether the relationship is an integral part of the function of the elements or not.*	Functional Non-Functional
NECESSITY*	*Whether the relationship is unavoidable or required, or whether there is flexibility.*	Necessary Optional
OUTCOME*	*Whether the effect of the relationship on the element of interest in positive or negative.*	Benefit Dis-benefit
LIFE-CYCLE IMPACT STAGE	*The phase of the project during which the effects of the relationship are relevant.*	Planning Construction Operation End of Life Scenario
GEOGRAPHIC SCALE	*The spatial distribution of the relationship or its effects.*	Project Local National International
SECTORAL SCALE	*Whether the relationship is contained within one infrastructure sector or not*	Intra-Sector Inter-Sector

Timelines of known UK infrastructure projects and policies up to 2040 were produced by Engineering the Future (2011). An expert-led application of a systems approach (the Interdependency Planning and Management Framework) identified over 90 interdependencies within the projects and policies of each sector and over 80 which acted between sectors. This knowledge can be used to avoid conflict and hazards, and utilise beneficial opportunities. These include opportunities to use waste products as a feedstock for electricity generation via anaerobic digestion, the use of ICT to release transport capacity, and the need for co-operation between the energy, waste and transport sectors over changes in policies and use of electric vehicles (Engineering the Future, 2013; The Systems Centre, University of Bristol, 2013).

While the previous section explored the issues that can arise from not approaching infrastructures as systems, the remainder of this section presents evidence from real cases of the value that can be derived form a conscious appreciation of the interactions within and between infrastructures. While the degree to which formal systems-based methods have been implemented is variable, it can be argued that each has implicitly adopted a view of infrastructure as a complex system in order to harness an opportunity to reduce cost and deliver additional benefits. Therefore it is suggested that these examples support the consideration of a more proactive application of the systems approach perspective, as outlined in the following section. Broader opportunities of adopting the systems approach can also be seen in the context of 'smart cities' as discussed in Box 7.

King's Cross Development, UK

Frontier Economics (2012) noted that the £2billion development at King's Cross in central London had adopted systems approaches to land use planning (i.e. in Phase 1) and a co-ordinated approach to delivering all of the utilities to the site during construction (Phase 2) and operation (Phase 3). Planning was dependent on the routing of the Channel Tunnel Rail Link, which was ultimately located as far north as possible to enable maximum space for the development. Metropolitan Infrastructure Ltd. was established to represent multiple utilities which is thought to have produced savings through efficient decision making, activity co-ordination, providing a single point of contact and knowledge sharing.

ElecLink Channel Tunnel Interconnector, UK/France

The ElecLink Channel Tunnel Interconnector, also described by Frontier Economics (2012) creates an interdependency between transport and energy infrastructure assets by co-locating them in the same geographical space. The Interconnector will facilitate the movement of electrical energy between France and the United Kingdom by virtue of a cables placed in the existing Channel Tunnel. This is thought to have provided a £60 million saving compared to running a seabed cable.

Crossrail Nature Reserve, UK

Over 4 million tonnes of material excavated during the construction phase of London's Crossrail project was used to create a wetland nature reserve at Wallasea Island ("Wallasea Island jetty completed as Crossrail helps RSPB shape Europe's largest new nature reserve - Crossrail," 2012). Thus, the project disposed of its waste material in such a way as to create additional benefits to society and the environment.

London 2012 Olympics, UK

The Olympic Delivery Authority (ODA) for the 2012 games delivered £6billion worth of construction. The Delivery Partner, a consortium of CH2M Hill, Laing O'Rourke and Mace, was overall Programme Manager and Project Manager for the construction projects. The ODA documented how a systems approach was of value, with the Head of Venues and Infrastructure Programme stating that: "This was preferred over the alternative approach of separating project and programme management as it was judged that there were clear synergistic benefits of a common programme and project manager" (Kintrea, 2012). The consortium were integrated into the governance structure providing efficient communications, decision making, resource and activity planning and constant alignment in the face of contextual change. A study of the project found different levels of systems integration, each with clearly identified and defined interfaces (Davies and Mackenzie, 2014).

Meadowhall Shopping Centre and Transport Interchange, UK

Projects such as Meadowhall Shopping Centre in Sheffield demonstrate an operational and financial interdependency. The shopping centre also houses a bus, rail and tram interchange, while also being located on the M1. This creates a synergy whereby the centre is very accessible, and the rent provides a revenue stream to investors.

8 How can a Systems Approach to Infrastructure be Implemented?

Earlier sections have discussed the sorts of challenges which can arise from a fragmented approach to the planning, delivery and operation of infrastructure. The previous section argued that additional value can be delivered from a consideration of the interactions within and between infrastructure projects and systems. Practical examples have shown where this has occurred, either through serendipity or through a deliberate application of formal systems methods. This section provides examples of emerging tools and methods which formalise and facilitate a systems approach to infrastructure planning, delivery and operation. The implementation of these tools will assist in delivering the sorts of benefits discussed above in more proactive way.

National Infrastructure Systems Model (NISMOD)

The Infrastructure Transitions Research Consortium (ITRC) has developed a suite of models for the UK's national infrastructure (Hall et al., 2016). This consists of a database of infrastructure networks, demand and performance (NISMOD-DB), a model of long term performance for the infrastructure system-of-systems (NISMOD-LP), a model of risk and vulnerability for the system-of-systems (NISMOD-RV) and a model looking at the relationship between regional development and infrastructure provision (NISMOD-RD). These models are of significant value at all levels of the infrastructure hierarchy, from strategic planning of the system-of-systems to individual projects. For example, NISMOD-LP has helped inform National Grid's needs analysis tool, and its output will be incorporated into National Grid's Future Energy Scenarios forecasting. NISMOD has also been used by Infrastructure UK to analyse the current infrastructure pipeline, and by Lincolnshire County Council to analyse geo-hazards to Lincolnshire's roads. .

Building Information Modelling

Building Information Modelling (BIM) allows for detailed holistic, multi-stakeholder models of structures throughout their lifecycle. It is a process that enables virtual models which capture physical assets, behavioural data and the rules governing the assets' interactions. Suggested benefits include improved feasibility studies and performance, quick reaction to design changes, discovery of errors, leaner construction processes, synchronisation of procurement with design and construction, improved commissioning and handover, better management and operation, and better integration of the operation and management systems (Eastman et al., 2011).

The Interdependency Planning and Management Framework

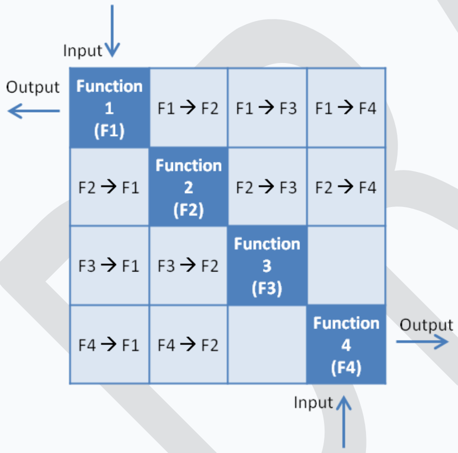
The Interdependency Planning and Management Framework (IP&MF) was developed as a means to proactively identify and manage infrastructure interdependencies. It incorporates principles and tools grounded in a holistic, open-systems based approach, complementing guidance set out in HM Treasury's Green Book (2003). The principles aim to drive infrastructure proposers and delivery teams to look for beneficial interdependencies to exploit and problematic interdependencies (systemic vulnerabilities or conflicts) to be managed. The framework can be summarised by as a set of activities based around problem structuring, measurement and appraisal and creating stakeholder understanding.

The IP&MF principles have been actualised using the matrix-based tool described in Box 6. It has been used to look at High Speed 2 – Phase 2 (Rosenberg and Carhart, 2014), the Northern Line Extension (Ward, 2014) and the Lower Thames Crossing (Carhart, 2014).

Box 6: IP&MF Matrix-Based Tool

The matrix-based tool has been developed from the N^2 Chart created by R. J. Lano for the analysis of interfaces and relationships widely used in Systems Engineering.

The N^2 Chart consists of matrix showing the interactions between N functions. The functions are located along the diagonal of the matrix, leaving the remaining locations to illustrate the interactions between them.



In this example, the functions F1, F2, F3 and F4 can be seen in the darker boxes running from the top left corner to the bottom right corner. The off-diagonal boxes show the relationships between these functions. The box labelled “F1 → F2”, for example, indicates a one-directional relationship from Function 1 to Function 2. The IP&MF enables additional data to be captured in the of-diagonal boxes.

Holistic Performance Measurement

Performance measurement is often disconnected from the outcomes infrastructure is intended to deliver. It focuses on specific elements or assets. While this may be important, it can be at the expense of understanding the performance of the system as part of a necessary wider system-of-systems. Processes for developing performance indicators (Bossel, 1999) highlight the pre-requisite of understanding the complex and dynamic workings of the system, the need for evaluation measures that reflect on how well needs are being met, and the need for stakeholder participation. Systemic approaches can enhance the value of projects by providing a framework to consider the outcomes which are meaningful to stakeholders (ICIF, 2016b, 2016c).

Organisational Learning and Knowledge Management

As sectors and projects do not exist in isolation from one another it is important that mechanisms are in place for sharing information and best practice. Generic, transferable lessons and guidance in adopting a systemic approach can be developed. Trial and error is not feasible within most infrastructure systems (at any phase) so there is an imperative to share learning. This requires a suitable process. With the involvement of multiple interacting stakeholders it is also necessary to be able to structure communications in such a way as to harmonise their varied perceptions and values. The Learning Journey Framework provides a process to scaffold learning in an efficient and effective way. Further information can be found in the accompanying White Paper (ICIF, 2016d).

Systems Thinking for Efficient Energy Planning

Systems Thinking for Efficient Energy Planning (STEEP) is a European project bringing together the cities of San Sebastian in Spain, Bristol in the UK and Florence in Italy. These cities have adopted a ‘systems thinking’ methodology to take a holistic view of their energy usage. In particular, Hierarchical Process Modelling has been employed as a problem structuring method which formalises the systems approach for this context. It facilitates an understanding of the whole systems performance in terms of the performance of the components and their relationships. Its continuous and iterative usage with stakeholders enables the identification of areas for improvement, actions to be taken and progress to be monitored. The projects resources are open source and available for adoption by other cities and organisations (“Project Resources - STEEP,” 2015)

8.1 Conclusions

In their planning, construction and operation, individual infrastructure projects can be viewed as complex socio-technical systems. These projects combine to form infrastructure systems, which in turn combine to form the infrastructure system-of-systems.

Box 7: Cities as Complex Systems

The interconnections between the parts of a system are central in city planning. At the beginning of the 20th century, it was claimed that cities and their regions were analogous to living organisms (Geddes, 1915). However, traditional planning theory underestimated the necessity to undertake a systemic approach in building cities. This was criticised by scholars as planners seemed to lack an appreciation of the complex interrelationships in cities (Alexander, 1965; Jacobs, 1961). It was argued that a change in one part of the city would cause changes to other parts, and that elements interact with each other to produce outcomes that cannot be simply attributed to individual parts.

The planning process, which was viewed in terms of design and aesthetics, was no longer valid in analysing and understanding how cities and regions functioned in economic and social terms. In the UK, so called strategic or ‘structure’ planning was introduced and acknowledged by the Town and Country Planning Act 1968. The reconceptualization of the town planning in terms of systems theory brought in modelling, quantification, and the use of computers to model complex systems. Taken together with the process accounts of planning, i.e. the rational view, the systems view of planning attempts to reconceptualised the ways cities are constructed. One example is the planning system in Rio de Janeiro in Brazil.

Being located just above sea level, the city is vulnerable to floods and landslides – natural disasters that are expected to increase with climate change. The city’s slum areas (favelas) are mostly built along the sides of the mountains so are particularly prone to natural disasters (UNICEF, 2012). Heavy rains have caused hundreds of casualties and destroyed homes. To address these issues, and in preparation for hosting both the 2014 FIFA World Cup and the 2016 Olympic Games, Rio’s mayor, Eduardo Paes, commissioned a City Operations Centre. It was designed by IBM and opened in 2010. The centre co-ordinates the activities of more than 300 municipal and state departments, plus private utility and transportation companies, integrating them into a single digital command-and-control system (Hamm, 2012). Cameras send information back to the control centre’s hundreds of screens that show what is happening across the city in real time, and data analytics software is used to predict where traffic will flow, where accidents may happen and when flooding might hit. The centre uses a weather and flood forecasting program that predicts emergencies up to two days ahead of time. So the city can position police, fire and rescue teams close to where problems are likely to occur, close off streets and use sirens to alert people to the danger, and residents can also sign up to receive messages to their mobile phones. Citizens can also access the cameras to see what’s happening across the city.

There are other examples across the world which can be labelled under the ‘smart city’ category today. The concept is currently the ‘most popular formulation for the future city, and is becoming a globally recognised term (Government Office for Science, 2014). Even though the term ‘smart city’ has been taken for granted, it has potential to become an interface amongst different dimensions and link different infrastructures by bringing together stakeholders (government, business, universities, community organisations, public services and citizens) to explore the complexity of the issues they face, and involve them in collaborative decision making and future planning of their city. This will be the start of a journey in which the city understands its issues and explores solutions which might include smart technology solutions.

In each phase interdependencies of many types exist within infrastructure projects, between the infrastructure projects and their wider social, environmental and economic contexts, and with the other projects in the infrastructure system-of-systems.

These interdependencies present opportunities and challenges that are often overlooked by the dominant approach to infrastructure, which tends to rely on methods that are relatively siloed and piecemeal.

Significant value exists in being able to identify and manage these interdependencies in order to exploit the opportunities and reduce the hazards. This can enable the reduction of costs and the delivery of additional benefits.

The Systems Approach provides tools and methods for identifying and structuring the relationships within infrastructure projects, and between infrastructure projects and systems, in order to achieve this. It is a broad area of study, with a long history of practice in many different domains. The tools and applications described here are a small sample of those available.

While many of the practical examples discussed here draw on specific projects, the realisation of maximum value through the complementary application of a Systems Approach can only be fully realised if embedded in a holistic and strategic planning perspective for the infrastructure system-of-systems. It is at this level that the necessary collaborations and relationships between projects can be most effectively governed in order to produce maximum benefit to society from infrastructure.

References

Ackoff, R.L., 1979. The Future of Operational Research is Past. J. Oper. Res. Soc. 30, 93–104.

Ackoff, R.L., 1997. Systems, Messes and Interactive Planning. In: Trist, E., Emery, F., Murray, H. (Eds.), The Social Engagement of Social Science: A Tavistock Anthology: The Socio-Ecological Perspective. University of Pennsylvania Press, Philadelphia, pp. 417–438.

Alexander, C., 1965. A city is not a tree. Archit. Forum 122.

Armitt, J., 2013. The Armitt Review.

Blockley, D.I., Godfrey, P., 2000. Doing It Differently. Thomas Telford Books, London.

Bossel, H., 1999. Indicators for Sustainable Development: Theory, method, applications. Winnipeg, Manitoba, Canada.

Carhart, N., 2014. Identification of High-level Infrastructure Interdependencies for the Lower Thames Crossing.

Carhart, N., Rosenberg, G., 2015. Towards a Common Language of Infrastructure Interdependency. In: International Symposium for Next Generation Infrastructure Conference Proceedings: 30 September - 1 October 2014 International Institute of Applied Systems Analysis (IIASA),Schloss Laxenburg, Vienna, Austria. UCL STEaPP, pp. 125–130.

Carhart, N., Rosenberg, G., Edkins, A., Ward, E., Dean, M., 2014. A Proposed Interdependency Planning and Management Framework: Development and Application for UK Infrastructure.

Checkland, P., 2000. Soft systems methodology: a thirty year retrospective. Syst. Res. Behav. Sci. 17, S11–S58.

Conklin, E.J., Weil, W., 1997. Wicked Problems: Naming the Pain in Organizations.

Council for Science and Technology, 2009. A National Infrastructure for the 21st Century.

Davies, A., Mackenzie, I., 2014. Project complexity and systems integration: Constructing the London 2012 Olympics and Paralympics Games. Int. J. Proj. Manag. 32, 773–790.

Eastman, C., Teicholz, P., Sacks, R., Liston, K., 2011. BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors. John Wiley & Sons.

Egan, J., 1998. Rethinking Construction: report of the Construction Task Force.

Engineering the Future, 2011. UK Infrastructure Timelines.

Engineering the Future, 2013. Infrastructure Interdependencies Timelines.

Frontier Economics, 2012. Systemic Risks and Opportunities in UK Infrastructure - A Report Prepared for HM Treasury & Infrastructure UK.

Geddes, S.P., 1915. Cities in Evolution: An Introduction to the Town Planning Movement and to the Study of Civics. Williams & Norgate.

Hall, J.W., Tran, M., Hickford, A.J., Nicholls, R.J. (Eds.), 2016. The Future of National Infrastructure: A System-of-Syetems Approach.

Hamm, S., 2012. Smarter Leadership: How Rio de Janeiro Created an Intelligent Operations Center « A Smarter Planet Blog [WWW Document]. URL http://asmarterplanet.com/blog/2012/03/smarter-leadership-how-rio-de-janeiro-created-an-intelligent-operations-center.html (accessed 11.5.15).

Hancock, D., 2010. Tame, Messy and Wicked Risk Leadership. Gower, Farnham, England.

HM Government Cabinet Office, 2012. Government Construction Strategy: One Year On Report and Action Plan Update.

HM Treasury, 2003. The Green Book - Appraisal and Evaluation in Central Government. The Stationary Office.

HM Treasury, Infrastructure and Projects Authority, The Rt Hon George Osborne MP, 2016. National Infrastructure Delivery Plan 2016 to 2021.

HM Treasury, Infrastructure UK, 2011. National Infrastructure Plan 2011.

ICIF, 2016a. The Value of Resilience: what infrastructure practitioners need to know about resilience.

ICIF, 2016b. A Critique of Current Infrastructure Performance Indicators: Towards Best Practice.

ICIF, 2016c. The Potential Benefits of Outcome based Assessments of Infrastructure Performance.

ICIF, 2016d. Learning Journeys and Infrastructure Services: a game changer for effectiveness.

Jacobs, J., 1961. The Death and Life of Great American Cities. Vintage Books.

Jowitt, P., 2015. Why the Adonis Infrastructure Commission needs a systems approach [WWW Document]. Infrastruct. Intell. URL http://www.infrastructure-intelligence.com/article/oct-2015/why-adonis-infrastructure-commission-needs-systems-approach (accessed 11.2.15).

Kintrea, K., 2012. Learning Legacy - Programme Management.

Little, R.G., 2004. A socio-technical systems approach to understanding and enhancing the reliability of interdependent infrastructure systems. Int. J. Emerg. Manag. 2, 98–110.

McKinsey Global Institute, 2013. Infrastructur productivity: How to save $1 trillion a year.

Omega Centre, U.C.L., 2011. Mega Projects and Mega Risks: Lessons for Decision-makers through a Comparative Analysis of Selected Large-scale Transport Infrastructure Projects in Europe, USA and Asia Pacific, Final report of a five year international research programme. London.

Omega Centre, U.C.L., 2012a. Investigation into the Development of a Framework for the Identification and Appraisal of Infrastructure Interdependencies with Application to Critical UK Infrastructure. London.

Omega Centre, U.C.L., 2012b. Mega Projects and Mega Risks: Lessons for Decision-makers through a Comparative Analysis of Selected Large-scale Transport Infrastructure Projects in Europe, USA and Asia Pacific - Executive Summary. London.

Omega Centre, U.C.L., Dimitriou, H.T., Harman, R., Ward, E.J., 2010. Incorporating Principles of Sustainable Development within the Design and Delivery of Major Projects: An international study with particular reference to mega urban transport projects, Final

Report. OMEGA Centre, University College London, London.

Project Resources - STEEP [WWW Document], 2015. URL http://www.smartsteep.eu/resources/ (accessed 11.5.15).

Raven, R., Verbong, G., 2007. Multi-Regime Interactions in the Dutch Energy Sector: The Case of Combined Heat and Power Technologies in the Netherlands 1970–2000. Technol. Anal. Strateg. Manag. 19, 491–507.

Rinaldi, S.M., Peerenboom, J.P., Kelly, T.K., 2001. Identifying, understanding, and analyzing critical infrastructure interdependencies. IEEE Control Syst. Mag. 21, 11–25.

Rittel, H.W.J., Webber, M.M., 1973. Dilemmas in a general theory of planning. Policy Sci. 4, 155–169.

Rosenberg, G., Carhart, N., 2014. Review of Potential Infrastructure Interdependencies in Support of Proposed Route HS2 Phase 2 Consultation.

The Royal Academy of Engineering, 2007. Creating Systems that Work: Principles of engineering systems for the 21st Century.

The Royal Academy of Engineering, 2013. Independent Armitt Review of Infrastructure - Submitted by the Royal Academy of Engineering to Sir John Armitt.

The Systems Centre, University of Bristol, 2013. Workshop Application of a Matrix Based Approach to the Identification of Infrastructure Interdependencies - Workshop Report for Engineering the Future.

Trist, E., 1981. The Evolution of Socio-Technical Systems: A Conceptual Framework and an Action Research Program.

Von Bertalanffy, L., 1968. General System Theory: Foundations, Development, Applications. George Braziller.

Wallasea Island jetty completed as Crossrail helps RSPB shape Europe’s largest new nature reserve - Crossrail [WWW Document], 2012. URL http://www.crossrail.co.uk/news/articles/wallasea-isl-jetty-completed-as-crossrail-helps-rspb-shape-europes-largest-new-nature-reserve (accessed 5.19.15).

Ward, E., 2014. Phase 2 Desk Study Report of Northern Line Extension.

Young, K., Hall, J.W., 2015. Introducing system interdependency into infrastructure appraisal: from projects to portfolios to pathways. Infrastruct. Complex. 2, 2.