Systems Engineering:

Necessary but not Sufficient for 21st Century Infrastructure?

John Beckford, 12/07/2013

Summary

As acceptance of the idea of the infrastructure ‘system of systems’ gains momentum, it becomes increasingly important that the underpinning ideas of systems thinking and its breadth of methodologies and tools are fully appreciated.

The opportunity to bring systems thinking to bear on the whole infrastructure challenge – engineering, financing, society, policy, government and global interactions – is faced with a risk that Systems Engineering will be seen as the whole of systems thinking rather than a necessary but, on its own, insufficient element of it.

This brief paper explores the definitions of both and shows how the breadth and depth of systems thinking goes beyond Systems Engineering and is necessary for the achievement of the desired outcome – a resilient infrastructure for the 21st century.

Introduction

Systemic approaches to the problems and issues of the world have been developing, at least in modern western thinking, since Bogdanovs Tektology (1912) and von Bertalanffys General System Theory (1928). Others will argue that systems thinking has long been inherent in the oriental philosophies as represented in Hinduism, Buddhism and the Tao in particular.

That is not an argument we shall seek to settle here, but it helps to set the scene. If systems approaches have been maturing and delivering value in the western world for around 100 years, it is perhaps time they were more widely understood and adopted.

The concern underpinning this paper is that as the momentum builds in addressing the challenges of infrastructure from the perspective of ‘a system of systems’ then, because these challenges are mainly seen as the concern of engineers, Systems Engineering, which is reasonably widely taught and applied within (there is a clue) a variety of engineering disciplines, will come to be seen by engineers and others as the whole of systems thinking as it relates to infrastructure. A focus on Systems Engineering will undoubtedly assist in resolving the ‘how’ of resolving systems interdependencies, it will be less helpful in addressing ‘what’ should be done and will say nothing of ‘why’. As a result, we risk both not recognising and consequently failing to capitalise on the range and power of philosophies, methodologies and tools available across the whole systems landscape.

What is Systems Engineering?

Systems Engineering is defined by INCOSE (International Council on Systems Engineering) as:

> "an interdisciplinary approach and means to enable the realization of successful systems"

http://www.incose.org/practice/whatissystemseng.aspx

The definition extends across a development cycle commencing with customer needs and functional requirements and offers a multi-(engineering)-disciplinary team based approach to delivery of the required product or artefact. It is expected to embrace both the business and technical needs of the customer.

This definition is broadly consistent with some definitions of Total Quality Management, e.g. Oakland or Taguchi, with Prince 2 Project Management and with systems for Process Control, e.g. Deming, Juran or Feigenbaum (see Beckford 2010). It is, in its own terms, useful. However, INCOSE Fellows go on to state a definition of a system which perhaps acknowledges the notion of emergence:

> "The results include system level qualities, properties, characteristics, functions, behavior and performance"

http://www.incose.org/practice/fellowsconsensus.aspx

that is, properties and characteristics that belong only to the system as a whole, not to any of its parts; they are the results of interactions.

Systems Engineering then might be thought able to generate an approach to engineering the infrastructure 'system of interest' as a coherent whole and that would be good. However, although the Systems Engineering process starts with defining:

> "customer needs and required functionality"

this seems be relying on an initial assumption about the legitimacy of customer needs, their ability to prescribe functionality in engineering terms and to articulate them. It also assumes a direct relationship between the artefact to be 'system engineered', the 'customer' as owner of that artefact and the systems engineer as provider. At the level of 'how' to engineer a particular system this may well be legitimate, in the context of national infrastructure there are numerous issues of 'what' and 'why' which must be resolved before 'how' becomes relevant. It may be that the systemic 'function' of an infrastructure artefact is broader than its engineered capability and that cannot be addressed within the discipline.

The Systems Thinking Landscape

The systems paradigm is perhaps most usefully thought of as supra-disciplinary rather than inter-disciplinary. A systems approach transcends boundaries:

> 'Nature did not consist of physics, chemistry and biology,: these were *arbitrary* divisions, man-made, merely a convenient way of carving up the task of investigating Nature's mysteries'

Peter Checkland, Systems Thinking, Systems Practice, Wiley, 1981 (P4)

Checkland goes on:

> "What is a systems approach?....an approach to a problem which takes a broad view, which tries to take all aspects into account, which concentrates on interactions between the different parts of the problem"

Peter Checkland, Systems Thinking, Systems Practice, Wiley, 1981 (P5)

The challenge is to interpret the expression 'a broad view' – how broad is enough?

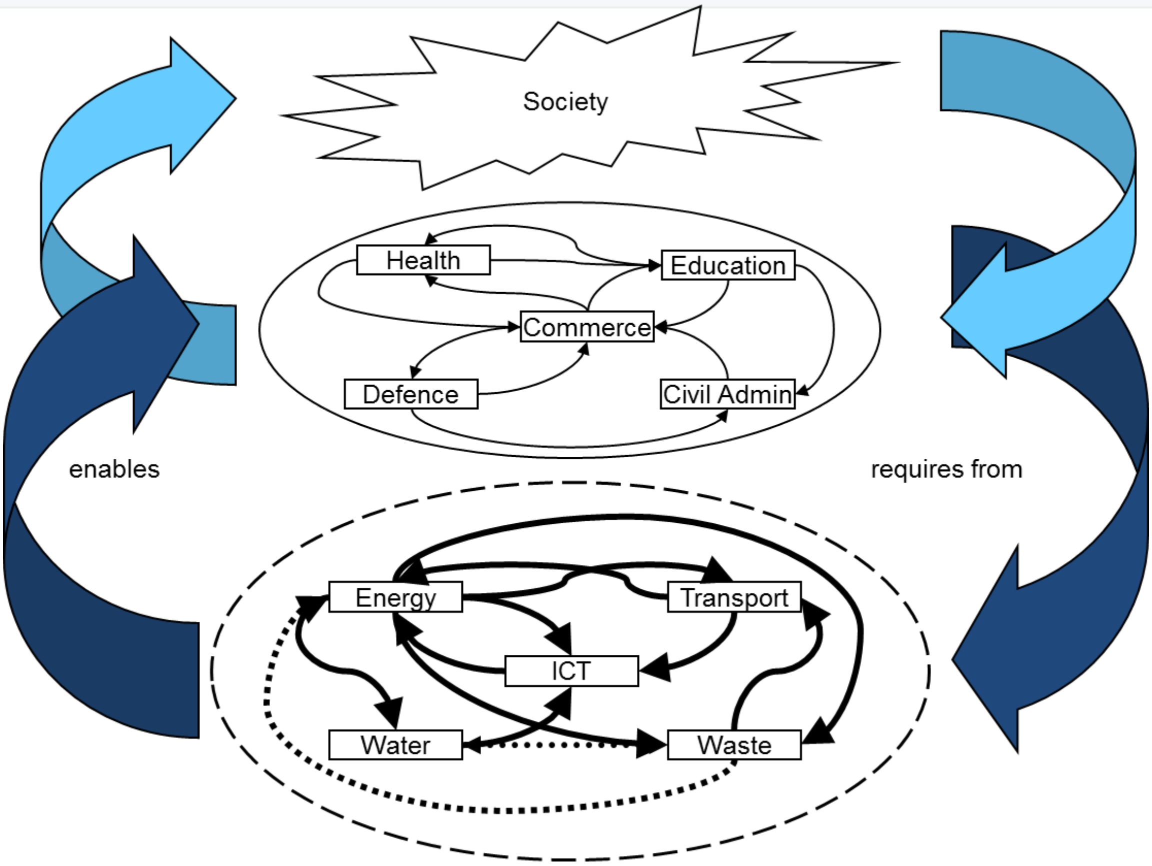
Ackoff describes a system thus:

> "A system is a set of two or more elements that satisfies the following three conditions.
>
> 1. The behaviour of each element has an effect on the behaviour of the whole.
> 2. The behaviour of the elements and their effects on the whole are interdependent.
> 3. However subgroups of the elements are formed, each has an effect on the behaviour of the whole and none has an independent effect on it."

Ackoff, Creating the Corporate Future, Wiley, New York, 1981

Whilst perhaps not directly helpful with defining the 'broad view', Ackoff provides a clue to boundary definition with the words 'interdependent' and 'effect'.

It may be that the boundary to Checkland's broad view can be defined in terms of the degree of interdependency and the measurability of the effect, i.e. whether it can be observed or measured. In defining the breadth of view of the 'system' we must then take account of both the set of elements *and* their interconnectedness *and* the effect of any one on any other or others. We must define as within the system of interest all those connected elements whose behaviour has a measurable effect on others. This takes us beyond the boundaries of Systems Engineering and requires us to consider wider elements and effects – both on and of, politics, economics and society as beneficiaries, users and elements of the system of concern. In the context of national infrastructure that will include all of those systems that are enabled by and depend upon the infrastructure, e.g. commerce, education, defence, healthcare and civil administration. This is represented in Figure 1.



An Infrastructure System of Systems

Figure 1

In looking at the much broader view now to be considered the work of Jackson (in New Directions in Management Science, Jackson and Keys, Gower, 1987) and Jackson and Keys (Towards a System of Systems Methodologies, Journal of the Operational Research Society, **35**, 473-86 1984) is helpful.

The 'System of Systems Methodologies' is an attempt to embrace a wide range of systems approaches and to classify them along two continua: simplicity to complexity, and unitary via pluralist to coercive.

Simple systems are considered as having a small number of elements, with few and/or regular interactions, they have well defined boundaries, they are rule based and closed to their environment. Complex systems are seen as having a large number of purposeful elements, high interaction and inter-relatedness. They are likely to be, at best, opaque to the observer, probabilistic in their behaviour and open to exchange with their environment. It might be argued that all systems involving human actors are complex.

Turning to the second of the continua, a unitary system is one in which the human actors truly agree about its purpose and objectives, whilst in a pluralist system there will be some level of disagreement about these things although sincere compromise can be achieved through some process of negotiation. In a coercive system consensus is achieved unilaterally; the powerful actors in the system, in effect, impose their views on the system via the exercise of power, the less powerful submit.

Jackson and Keys developed this approach into a six celled matrix and suggested that system problems could be classified according to it. They then explored the assumptions underpinning a variety of systems methodologies against the assumptions underpinning the problems and allocated methodologies to cells – the system of systems methodologies, figure 2.

	Unitary	Pluralist	Coercive
Simple	Operational Research	Social Systems	Critical Systems
	Systems Analysis	Strategic Assumption	
	Systems Engineering		
	Systems Dynamics		
Complex	Viable Systems Diagnosis	Interactive Planning	
	General Systems Theory	Soft Systems	
	Socio-technical Systems		
	Contingency Theory		

The System of Systems Methodologies

Figure 2

The boundaries between the cells are, perhaps, somewhat problematic, visually the representation acts to deny the notion of continuum, suggesting discrete and absolute breaks between both the problem classifications and the utility of the methodology. In practice these boundaries are often non-existent and never less than porous. An experienced practitioner and seasoned observer will recognise the necessity of approaching a truly systemic problem with multiple methodologies. Jackson and Flood (Creative Problem Solving, Wiley, 1991) began to recognise this with their 'Total Systems Intervention' approach which provided a meta-framework within which systems methodologies could be used sequentially. Beckford (Quality, Routledge, 2010) adopted a synthesised approach, one which attempted to identify the range of problem characteristics and use multiple methodologies simultaneously to explore the situation from several perspectives in parallel. This approach, demanding though it is, enables the elucidation of the situation studied and informs the observer-participant conversation with a range of interpretations, perspectives and choices – each methodology providing metadata (data about data) to the others. This process exposes underlying assumptions, clarifies how power is being exercised and enriches the conversation about the notion of 'rightness' in terms of the codification of the challenges and issues and the range of possible ways of resolving them.

	Unitary	Pluralist	Coercive
Simple	Operational Research	Social Systems Design	Critical Systems Heuristics
	Systems Analysis	Strategic Assumption Surfacing and Testing	
	Systems Engineering		
	Systems Dynamics		
Complex	Viable Systems Diagnosis	Interactive Planning	
	General Systems Theory	Soft Systems Methodology	
	Socio-technical Systems Thinking		
	Contingency Theory		

The System of Systems Methodologies Unbounded

Figure 3

The porous boundaries in figure 3 attempts to show that the various methodologies are not discrete but overlap with each other and, through the interpreter/observer, are able to add value in a number of areas.

Most importantly for this paper, the system shows where Systems Engineering sits in the wider systems landscape and highlights how other methodologies may provide different, perhaps richer, insights to the challenges of addressing the National Infrastructure as a system of systems. While an experienced 'Systems Engineer' would not take the literal interpretation of Systems Engineering as the boundary to enquiry, it would be desirable for the broader enquiry to be conducted by an appropriately qualified practitioner. As with any other professional activity, the formal application of an appropriately capable process of systemic intervention by a qualified practitioner will probably produce a more useful outcome than a simple recognition of some, apparently, extra-systemic factors.

Systems Methodologies and National Infrastructure

Given the breadth of the systems landscape and the range of possible approaches to problem solving, it is appropriate to consider the breadth and depth of the infrastructure challenge.

It is widely recognised that over the last fifty or sixty years there has been a significant shift in public investment away from the enabling infrastructure of water, waste, energy, transport and ICT towards more social infrastructure such as education, social welfare, healthcare and commerce. This has, in part, been accomplished by the privatisation of many of the infrastructure organisations leading to private investment, in part by the growth of social spending which perhaps reflects a shift in political emphasis rather than a change in infrastructure need. This situation is replicated in many of the worlds' mature economies.

At the same time there has been substantial growth in the use of much of the infrastructure and a focus on exploitation of existing artefacts has been coupled to what many regard as under-investment. Very simply the availability, quality and performance of the infrastructure have not kept pace with demand. In consequence many countries, not just the UK, are faced with the need for massive investment simply to maintain the status quo, let alone to deal with the demands of carbon emissions reduction and of climate change. At the same time the infrastructure has become more richly connected and more interdependent. Automation, electrification, the embedment of information technology based control and communication systems have all acted to generate this 'system of systems' in which not only do the human actors not fully understand the interactions, but critically, are unable to identify or control them. The system of systems has embedded in it the potential for both single points of failure and cascade failures.

The challenge of developing infrastructure for the 21st Century is not an easily tractable one. In terms of the 'System of Systems Methodologies' it can best be characterised as 'complex-pluralist'. The complexity resides in the large number of system elements and their very high degree of interaction – both by volume and frequency. The interactions of the system are, at best, opaque – they cannot be classified and codified in a simple manner even where they are recognised. We cannot easily determine which interactions are important nor which are critical, and hence we currently focus protection on individual artefacts rather than systems. The plurality rests in the absence of agreement about the purpose of either individual systems or that of the whole system. In a democratic state, there are choices to be made and there is, and always will be, some level of disagreement about objectives to be achieved. These objectives may cover a plethora of subjects – social well-being and welfare, distribution of wealth and opportunity, education, equality, environmental concerns, economic growth, sustainability, technological innovation, global business and a whole host of others.

These concerns demand that, being systemic, means attempting to engage in a complex conversation, one which is initially concerned with 'what' and 'why' at the level of UK society. This means employing a methodology (or methodologies) which enable and encourage participation in that debate by all those with a legitimate interest. They demand a pluralist approach, perhaps Soft Systems Methodology (Checkland) or Interactive Planning (Ackoff). This however is not sufficient since the range of possibilities to be explored must be constrained (as Ackoff demands) by what is technologically possible and, in times of austerity, financially affordable.

We therefore need to inform the pluralist inquiry with insights from other approaches. It might be useful to employ Systems Dynamics (Forrester) in the attempt to further understand the relationships between system elements and their impacts on each other. Viable Systems Diagnosis (Beer) could be used to formally study the organisational and structural design of the whole infrastructure operational, management, governance, regulatory and ownership systems. Given the pluralist nature of the inquiry it would be necessary to develop a range of possible scenarios, multiple versions of alternative arrangements, and to allow for them to be tested and explored by participants in the conversation. That is to allow the participants in the inquiry to explore the consequences of alternative choices and options:

> 'If we invest more in energy, what is the consequence for investment in healthcare or education'
>
> 'If we invest more in energy, is there a consequential relationship which will stimulate demand for education, healthcare, goods and services which will itself stimulate economic growth'
>
> 'If we invest more in healthcare and pay for it by reduced spending on transport, what are the societal consequences'

It is only when this process is pursued and all participants understand 'why' that government and infrastructure owners can make informed decisions about 'what' and systems engineers can make appropriate decisions about 'how'.

The breadth and depth of the systems paradigm enables, encourages, even necessitates, a much richer exploration of the options for National Infrastructure. Effective work around stakeholder engagement and exploration of options employing a wider range of approaches can act to generate options which are not only desirable but are agreed to be so; options which are not the product of partial, prejudicial or self-interested views. This process can help to identify and legitimise choices, to educate and inform government, public and infrastructure owners. It can create, regardless of the particular party in government, a mandate for the transformation of national infrastructure.

Systems Engineering will have a substantial role to play in delivering that infrastructure, but it cannot do so in isolation from the system of systems in which it is contained.

Exploring Infrastructure Challenges from a Systemic Perspective

As suggested, infrastructure in all countries faces substantial challenges – whether to build new in certain countries, to rebuild and 'climate-proof' in more mature economies, to address the challenges of resilience or simply to deal with the degree of hidden inter-dependency which has quietly evolved through the implementation of ICT based control systems. All will require substantial investment and no country can afford its infrastructure to fail if it is to sustain and develop its economic position. Failure of infrastructure will, surely, lead to economic failure – and the consequences of that failure for society are unacceptable. Both failure and success will be expressed in practical terms through the consequential failure or success of the enabled elements – commerce, education, healthcare, civil administration and defence. As was discovered with Hurricane Katrina, a modern civilisation collapses into insurrection and martial law in a matter of hours when the cash machines fail!

A Problem of Transport

Two major battles are being fought in the UK at present about transport capacity, one with regard to airports the other with regard to the railway.

The airport capacity problem is presented as:

> No new runway has been built in the UK since the end of the Second World War; anticipated growth in air travel demands more runway capacity; we are losing out to international competition.

The railway capacity problem is presented as:

> Anticipated growth in passenger numbers over the coming years demands additional capacity on the railway; additional capacity means a new high speed line.

Everything said about these two debates is, for somebody, valid – but each such view is partial and all solutions to the 'problems' as presented are expressed in terms which pre-suppose agreement about the problem – lack of capacity - and the solution - more capacity. One possible alternative solution – less travel – is not part of the debate.

In the case of the railway a solution, High Speed 2, has been proposed. In the case of the airports a variety of solutions are still in play from mixed-mode operation and/or a 3rd runway at Heathrow, additional runways at Gatwick and/or Stansted, perhaps a whole new airport in the Thames Estuary area. A separate debate about the advantages or otherwise of 'hub and spoke' operations and about shifting modes of travel (e.g. from air to rail) is, currently, dormant.

Every one of these 'solutions' is technically feasible, each will 'solve' a problem from somebody's perspective, none will solve every problem from every perspective. Such a universal solution may not be possible – but perhaps the right questions are not yet being asked? How can the most acceptable alternatives be developed?

Building on Beckford and Dudleys' "VSMethod" (Beckford, 2010) these transport challenges are addressed from a 'system of systems' perspective, the situations to be considered are 'complex' – they have a high number of elements, frequent and extensive interaction, they are highly inter-related and are somewhat opaque to the observer. Each is open to the environment. Similarly, the problems sit in a pluralist context; at the time of writing there is, no genuine agreement about even the nature of the challenges, let alone about the possible solutions.

	Unitary	Pluralist	Coercive
Simple			
Complex		Transport Capacity	

A Problem of Transport

Figure 4

The systems approaches that might lend themselves to such a situation are ones in which the initial work is to develop some level of agreement about the problem to be solved. In this context that would, most appropriately, include Checkland's Soft Systems Methodology (Wiley, 1981) or Beers' Team Syntegration' (Beyond Dispute, Wiley, 1994). Both of these methods focus on developing agreement around the purpose to be served by engaging the system stakeholders. It may be that Ulrich's 'Critical Systems Heuristics' (Critical Heuristics of Social Planning, 1983) can be adopted to assist in understanding how the interests of the multiple stakeholders are being addressed and to expose where political or positional power is being exploited to bring about a particular solution. These initial interventions will redefine the 'problem' and move to a new state of understanding. In figure 5 it is represented as 'Transport Capacity Problem State 1'.

In order to support and inform the conversations about 'purpose' it will be necessary to explore the implications of alternative possibilities. While the use of Strategic Assumption Surfacing and Testing (Challenging Strategic Planning Assumptions, Mason and Mitroff, 1981) can help to tease out the assumptions underpinning assertions being made, it is not helpful in other areas. It may be that Forresters' Systems Dynamics (Industrial Dynamics, MIT, 1961 and Principles of Systems, Wright-Allen, 1969) can be employed to consider the dynamic implications of a range of possible alternative solutions to the challenges. This might include for example, simulating the possible effects of each of the proposed alternatives to understand their likely impacts in a number of dimensions – not simply the 'capacity' question with which this started – but the effect on carbon emissions, resilience, inter-modal interaction, numbers of people employed, education and so on.

Systems dynamics modelling also provides an approach for addressing the question of inter-dependency. It will allow for the modelling of the core system of interest – but also for all those systems which it relies on, or which rely on it. For example, either the airport or the railway challenge will expose dependency OF the transport system on energy (oil, gas, avgas, electricity), water, communications technologies (satellites, weather systems, control systems), people – users, owners, passengers, operating staff and the dependency ON the transport system of both the transport system itself (many train drivers catch a train to work) and connected systems including the weather:

> “17 minutes late, frozen points at Effingham Junction”
>
> (The Fall and Rise of Reginald Perrin, David Nobbs, Mandarin, 1990)

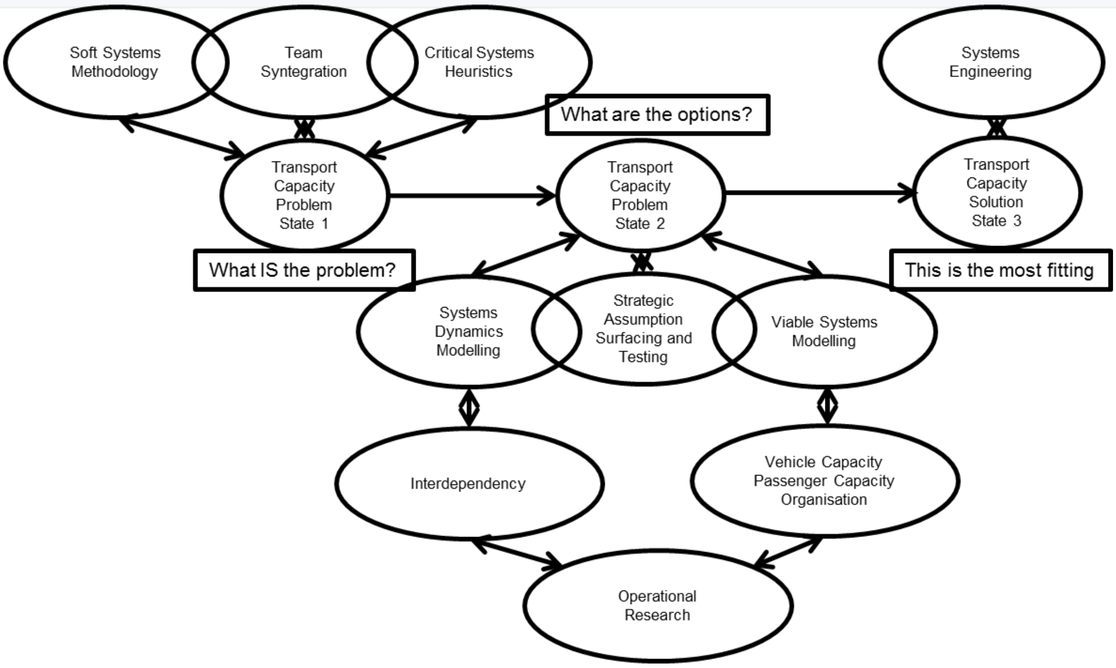
Viable Systems Modelling (Beer, 1979. 1981, 1985) offers the opportunity to understand the organisational relationships and, critically, to study the ‘capacity’ problem itself. Perhaps the capacity of a system is a function of how that system is organised. Looking at the railway problem two types of capacity can be observed:

> How many vehicles can run on the permanent way?
>
> How many people can ride on the vehicles?

The capacity ‘problem’ has, at least, these two dimensions, each of which might have its own range of solutions. Whilst the capacity challenge might be addressed through the application of ‘Operational Research’ techniques, Viable Systems Modelling would consider the organisational relationships between the elements of the railway or airport systems, the human and informational interactions that impact upon its effectiveness and the governance and regulatory structures that should focus it on the fulfilment of its purpose – and hence we are back to the ‘system of systems perspective’. This is represented in figure 5 as Transport Capacity Problem State 2’.

If the question ‘what is the system for’ can be answered, then all of the other embedded questions can also be answered; some of them will be amenable to the application of Systems Engineering. That does not mean that there will be universal agreement about those things but it should mean that more informed choices can be made and the implications of those choices for all stakeholders can be exposed and addressed. This may be seen as forcing a debate to be held at a supra-system level, suggesting that capacity is not a matter of local strategy for partisan owners but a matter of national interest. If that is the case then, so be it. A decision to invest substantial public funding in any infrastructure artefact must be one which is well and wisely taken. This is represented in figure 5 as Transport Capacity Solution State 3’.

It is one of the roles of government to act in the national interest, legislators and civil servants are not doing this if major investment decisions do not address the systemic questions of “why” and “what” before they address the question of “how”. Similarly, infrastructure owners and operators are acting only in their own, autopoietic, interests if they do not address these questions.



Solving the Problem of Transport

Figure 5

Conclusion

The systems thinking paradigm offers a rich landscape of philosophies and methods through which the challenges of building a resilient national infrastructure for the 21st century can be addressed. This brief paper has provided only a cursory overview of that potential but, I hope, has provided a framework in which the valuable insights possible from the whole of systems thinking can be understood and, specifically, the important role of Systems Engineering in that holistic view can be appreciated.

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