

Research Article

Infrastructure as a Complex Adaptive System

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National infrastructure systems spanning energy, transport, digital, waste, and water are well recognised as complex and interdependent. While some policy makers have been keen to adopt the narrative of complexity, the *application* of complexity-based methods in public policy decision-making has been restricted by the lack of innovation in associated methodologies and tools. In this paper we firstly evaluate the application of complex adaptive systems theory to infrastructure systems, comparing and contrasting this approach with traditional systems theory. We secondly identify five key theoretical properties of complex adaptive systems including adaptive agents, diverse agents, dynamics, irreversibility, and emergence, which are exhibited across three hierarchical levels ranging from agents, to networks, to systems. With these properties in mind, we then present a case study on the development of a system-of-systems modelling approach based on complex adaptive systems theory capable of modelling an emergent national infrastructure system, driven by agent-level decisions with explicitly modelled interdependencies between energy, transport, digital, waste, and water. Indeed, the novel contribution of the paper is the articulation of the case study describing a decade of research which applies complex adaptive systems properties to the development of a national infrastructure system-of-systems model. This approach has been used by the UK National Infrastructure Commission to produce a National Infrastructure Assessment which is capable of coordinating infrastructure policy across a historically fragmented governance landscape spanning eight government departments. The application will continue to be pertinent moving forward due to the continuing complexity of interdependent infrastructure systems, particularly the challenges of increased electrification and the proliferation of the Internet of Things.

1. Introduction

Infrastructure systems across the world are becoming increasingly challenged as a result of growing demand and the fact that many assets are coming to the end of their lifespan. One technological solution to these problems is the use of Information Communication Technology (ICT) to provide smart management in both the supply of and demand for infrastructure. However, the pervasive use of ICT means we have transitioned to a position where infrastructure sectors are becoming more and more interdependent [1–4]. Because of this interconnectivity, individual infrastructure sectors can no longer be assessed in isolation, motivating the increased use of decision support methods which utilise systems-based approaches.

When contrasted against the level of intellectual enquiry focusing on complexity, there has hitherto been relatively

limited *application* of complexity-based methods to support public policy decision-making. This is despite the dissatisfaction shown regarding the rigid application of the assumptions associated with general systems theory, neoclassical economics, and rational decision-making, in favour of more evolutionary, complexity-based approaches [5–10]. There needs to be greater understanding of how national infrastructure systems and their agents adapt and change across time and space. One approach that may prove promising in this endeavour is the application of complex adaptive system (CAS) theory, as it can help to generate new knowledge on how to model infrastructure systems. In this article we investigate the application of CAS to infrastructure systems by building on the work of others who have examined this problem [1, 11–14].

We first consider the characteristics of a national infrastructure system and secondly outline the basis of an approach

based on complex adaptive systems, including how it can be distinguished conceptually from general systems theory. We then examine how the properties of a CAS approach can be used to understand more about national infrastructure, before providing a case study of how this has been utilised by the UK's National Infrastructure Commission to model national infrastructure strategies.

2. The Key Characteristics of a National Infrastructure System

High-quality national infrastructure systems comprised of the energy, transport, ICT, water, and waste are essential for economic prosperity and a fully functioning society [17]. However, defining infrastructure is difficult as the term is used to refer to a variety of objects and technological artefacts and the human systems that enable their effective functioning. We synthesise a working definition within this context, whereby infrastructure is an enabling system that provides a range of different *services* to intermediate and end users.

Increasingly, infrastructure assets require inputs from other sectors to function, for example, as smart infrastructure systems increasingly rely on digital connectivity to operate. These assets are coordinated to undertake a variety of processes which provide business-to-business or business-to-consumer *infrastructure services*. Often this takes place in a hierarchical manner, with networks operating across multiple spatial layers [18, 19], resulting in nested processes. Two of the main processes which infrastructure assets can undertake are the *transformation* or *preservation* of different material and immaterial entities. These processes can be carried out to a range of materials and objects or to intangible forms of capital such as information. In addition, infrastructure assets are also able to *transmit* and distribute these material or intangible forms of capital across space. We therefore define infrastructure as *the coordinated operation and management of a group of physical assets to perform a range of processes, thereby providing infrastructure services to users* [20].

Given that infrastructure services having low substitutability [21], poor infrastructure decision-making can have severe economic and societal effects, with infrastructure assets being durable commodities which can last decades. These systems are frequently very large in scale and consequently, particularly with regard to the aforementioned factors, can become susceptible to path dependent “lock-in” effects [22]. Infrastructure investments, particularly once reinforced by increasing returns, can lock infrastructure systems on path dependent economic or environmental trajectories which are incredibly hard to break away from due to the substantial financial hurdles involved with path divergence.

Infrastructure is deeply intertwined in all economic and societal systems. It mediates the way we create new value, how we move across space, and the way we interact and communicate, as well as bringing a driver of technological uncertainty [23]. Transport, energy, and ICT are good examples as they can have the most dramatic economic

effects on productivity, location, and innovation, by enabling agglomeration benefits including increasing trade specialisation, labour market efficiency, and helping the spread of new ideas. Recent analysis indicates that infrastructure stocks can positively affect long-run economic output by somewhere between the range of 0.07 and 0.10 [24]. Although a variety of papers use different infrastructure stock definitions and econometric techniques, recent studies indicate that there are generally positive economic effects from infrastructure investment (although they can vary by infrastructure sector), even if they are relatively humble [25–30].

National infrastructure systems often have mixed planning, delivery, operation, ownership, and regulatory frameworks, where governance frequently extends across private firms and individuals, public institutions, and third-sector organisations [31]. This reflects the historical legacy of many infrastructure systems, which were once publicly owned and centralised systems. Past governance arrangements significantly shape the current character, structure, and operation of national infrastructure systems and continue to have profound hysteretic impacts in the future. As an example, Table 1 details the diverse attributes of the UK national infrastructure system.

Like all national infrastructure systems, the actors involved in Table 1 operate over a multitude of spatial scales including the local, regional, national, and international levels, with a wide range of motivations and constraints. This makes it a very challenging task for those trying to manoeuvre each system to provide economically efficient, spatially equitable, and environmentally sustainable outcomes [32].

In the next section we consider the key properties of a CAS and assess how it might assist in understanding national infrastructure. In making this assessment we draw upon the growing literature of CAS theory.

3. The Properties of a Complex Adaptive System

A complex system has a multitude of individual components and agents that are highly connected and interdependent, to the extent that “emergent” behavioural phenomena occur which cannot be explained using other reductionist approaches. Complexity theory is used as a form of guiding metatheory to understand a range of evolving natural and social systems, frequently applying computational simulation methodologies as the method of enquiry [33–37].

Many authors make the distinction between systems that are simple or complicated, but not *complex* [13, 38, 39]. This is because many find it easier to begin by defining what complexity *is not*, before attempting to define what *it is*. Table 2 draws upon the work of Arthur [10], Delorme [16], and Lei et al. [12] to compare the properties of general systems theory and a CAS approach.

In a complex system functionality arises not only from the multitude of (often nonlinear) interactions between the physical components and incumbent agents of the system, but also from interactions with the surrounding environment. Complex systems are seen to undergo a variety of possible

TABLE 1: Characteristics of the UK National Infrastructure System (adapted from Hall et al. [15]).

	Energy	Transport	Water	Waste	Digital	
				Wastewater	Solid Waste	Communications
Scale	National International	Regional National International	Regional	Regional	Regional	National International
Ownership	Private	Mixed (by mode)	Mixed (by region)	Mixed (by region)	Mixed (public responsibility with private operation)	Private
Governance and Regulation	Varies e.g. electricity has unregulated market prices but regulated network charges	Varies e.g. rail has regulated efficiency targets; roads and government planned with some private provision	For England and Wales, price and investment regulated by Ofwat, drinking water quality regulation by DWI, environmental regulation by EA.		Local Authority run. Environmental regulation by EA/DEFRA in England and Wales, SEPA in Scotland	Competition regulation by Ofcom; universal service obligations; spectrum licences and coverage obligations
Issues	Security of supply; GHG emissions	Congestion; high speed rail; airport capacity	Demand management; climate change; environmental regulation	Energy costs; environmental regulation	Waste minimisation and recycling targets; resource management	Technological innovation; rural coverage

TABLE 2: Properties of general systems and complex adaptive systems [10, 12, 16].

General Systems Theory	Complex Adaptive Systems Theory		
Key Properties	Key Properties	Property Category	Hierarchical Level
Complicated	Complex	Emergent behaviour and self-organisation	System level
Aggregable with functional decomposition	Emergent with limited functional decomposition		
Centralised control	Distributed control		
Determinate and Linear	Non-determinate and Non-linear	Instability and robustness	
Static	Perpetual Dynamics		Network level
Equilibrium	A Far-from- equilibrium State	Dynamics and evolution	
Closed	Open		
Reversible	Irreversible		
Rational, deductive behaviour	Adaptive, evolutionary behaviour	Adaptiveness	Agent level
Simplified assumptions and homogenous agents	Diversity among agents and more realistic assumptions	Agent diversity	

states. They are in a state of flux which, often resulting from self-organising tendencies, changes the configuration of the system. It is important to make the distinction between a complex system and the subsequent concept of a complex *adaptive* system. The word adaptive comes from the Latin “adaptation” which relates to the modification required to suit new conditions. Thus, to adapt is to improve over time in relation to one’s environment (whether natural, economic,

social, technical, institutional, or some other variant). But the key to the definition is the verb to *improve*.

Winder et al. [40] state that not all complex systems display evolutionary dynamics as some can exhibit mechanistic dynamics. The dynamic quantitative change which results from a complex system responding to an external stimulus may display only mechanistic, responsive change. The evolutionary dynamics evident in complex adaptive

systems only take place if the relationships between the parts of the system components *are modified*, in order to gain some form of advantageous position. Hence, the ability for a group of entities to generate a variety of responses to a changing selection environment is a defining feature of an evolutionary system. The absence of this changing, evolving behaviour may indicate that a system is only dynamically mechanistic, rather than evolutionary. Consequently, a CAS can be defined as containing a large number of agents which interact, learn, and, most crucially, *adapt* to changes in their selection environment in order to improve their future survival chances [41].

The main properties of a CAS can be identified as evolution, aggregate behaviour, and anticipation (Holland, 1992). Evolution is a key feature; while adaptation can be described as the improvements made by entities in response to external environmental stimuli, evolution is different as it is the algorithmic process that produces these improvements [42]. Yet the use of this metaphor as a transformational process is often ill-defined [43]. For a process to be described as evolutionary it must exhibit certain properties, specifically the generation of novelty endogenously, from within the system. A system is not evolutionary if change is only incorporated as some form of exogenous shock which momentarily changes the system's "equilibrium" position. Moreover, evolutionary systems are also dynamic and undergoing perpetual change, with the relationships between the key components in continual flux. Indeed, the process of evolution is discontinuous and irreversible.

4. Applying the Key Concepts to an Infrastructure System

Chaudet et al. [44] state that after considering key properties, infrastructures "can be considered excellent metaphors of complex systems". But to gain a true understanding of a specific system one must undertake an in-depth investigation. This section considers the extent to which the key features of a CAS appear to characterise the workings of a national infrastructure system. Following the structure presented in Table 2, the analysis is undertaken at the agent, network, and the system levels.

4.1. Agent-Level Properties

4.1.1. Adaptive, Evolutionary Behaviour. Although dynamic behaviour is a feature of many types of general systems, this property is especially prominent in complex adaptive systems and linked to perpetual dynamics at the network level. For example, individuals, households, and firms exhibit *adaptive behaviour* change driven by changing supply and demand conditions. This is particularly true for infrastructure service providers operating in market contexts. These behavioural changes can result from new technologies, new infrastructure assets, and flows of financial investment on the supply side. On the demand side, new technology drives change in how infrastructure services are used and where they are required. An example of this change is evident in the adoption of smartphones, 4G LTE services, and the subsequent explosion

in data demand associated with video streaming. Changes in user behaviour, coupled with the proliferation of new technologies, dramatically changed the supply and demand characteristics of mobile telecommunications infrastructure systems from 2008 onwards, following the release of the Apple iPhone and the proliferation of smartphones.

4.1.2. Diversity among Agents and More Realistic Assumptions.

The heterogeneous attributes of individuals, households, and firms, incumbent to the supply and demand of infrastructure services are visibly evident. A general characteristic that defines the demand side is the demographic group of particular consumers. For example, trends in broadband adoption associated with Internet Protocol Television (IPTV) (e.g., Netflix) are correlated with particular demographic groups, where older households generally have a lower propensity to adopt these services.

4.2. Network-Level Properties

4.2.1. Perpetual Dynamics. We witness *perpetual dynamic change* in the national infrastructure system in both the supply and demand for infrastructure. For example, the development of infrastructure is incremental, so the physical network according to current and expected demand undergoes a perpetual process of expansion, modification, and contraction at different points in space. Moreover, the flows across the physical network are also altered in accordance with these processes. Innovation has a particular impact on driving change in technological and institutional regimes in infrastructure systems [45]. Disruptive technologies and new forms of organisation combine with and result from the adaptive, self-organising behaviour of the firms, households, and individuals that produce and consume infrastructure services on a daily basis. The economy and society are thus seen to perpetually *coevolve* with changes in infrastructure networks, advancements in infrastructure technology and organisation, and the new trajectories of economic growth and development.

4.2.2. A Far-from-Equilibrium State. The factors that influence the demand for and supply of infrastructure are subject to continuous dynamic change and thus it would appear naive to adopt a theoretical perspective that assumes it is at an optimal equilibrium at some point in time. A CAS approach would appear more appropriate, as it pays more attention to the imperfections of the system.

4.2.3. Openness. National infrastructure systems are *open* entities characterised by inward and outward flows of goods, services, and capital. They have no precise, fixed boundary between the system under investigation, other nested systems in the hierarchy, and the wider environment. While we define "the national infrastructure system" purely for practical purposes in research, it is not an isolated, "closed" system. Instead it undergoes constant interaction and exchange with its economic, social, and natural environment. We have historically been quite poor at integrating long-term behavioural change into models of infrastructure systems.

The system requires a wide range of inputs to flow into different infrastructure sectors to enable functionality, such as energy, raw and intermediate materials, labour, information, and financial capital. This openness can result in the system behaving differently to ostensibly similar shocks from its environment, at different points in time. This is because national infrastructure systems can change their network structure over temporal periods, changing the system's complexity. Homogenous responses to perturbations are highly unlikely.

4.2.4. Irreversibility. The notion of irreversibility in infrastructure systems refers to the fact that time-independent decisions are rare. In fact, infrastructure providers are almost certainly taking decisions within a set of constrained capabilities, because they must work with durable, long-lived infrastructure assets and networks operating in market contexts. "Lock-in" effects with infrastructure assets often prevent viable transitions to other forms of organisation and operation. For example, in the energy sector many countries have addressed emissions controls by introducing regulatory mechanisms combined with energy demand management and renewable energy generation policies. These have inevitably affected the cost of energy because they attempt to move the system away from the existing "locked-in" state. Moreover, there are also microeconomic irreversibilities resulting from the adaptive behaviours of firms, households, individuals, regulators, and other institutions that inevitably explore, learn, and retain information relating to their activities.

4.3. System-Level Properties

4.3.1. Complexity. The system is complex because it is comprised of diverse adaptive agents, there is distributed control throughout the system, and infrastructure networks are joined by a range of different physical and cyber-interdependencies. Moreover, the functionality of the system arises not only from the multitude of (often nonlinear) interactions between the physical components and incumbent agents of the system, but also from how the system *per se* interacts with its *surrounding environment*.

4.3.2. Emergence and Limited Functional Decomposition. The highly dynamic structure of the national infrastructure system results from the high level of interconnection between incumbent networks. When the national infrastructure is driven by a set of exogenous drivers (demographic change, economic growth, climate scenarios, etc.), interdependencies between different sectors lead to second-order, indirect demands for infrastructure services. Hence, it is not straightforward to *functionally decompose the national infrastructure into individual stable parts*.

Moreover, unlike in the natural sciences where individual natural processes can often be isolated for experimentation, the sociotechnical processes pertaining to the economic, technological, spatial, demographic, institutional, and environmental aspects of national infrastructure systems need to

be considered and examined in the widest sense, because they are not readily decomposable [46].

4.3.3. Distributed Control. National infrastructure systems in developed, free market economies do not have one individual entity in control of the system. This can be problematic for coordination. Often top-down management approaches can yield undesirable outcomes as a result. This has increasingly been the case over the past three decades where nationalised industries have been opened to market-based competition between different actors. Whereas the state previously had a centralised command-and-control structure, now it only has limited regulatory control. Complexity approaches naturally lend themselves to being utilised to investigate the implications of different game-theoretic behaviours that play out in a decentralised market context, although there has been relatively limited application to infrastructure hitherto.

4.3.4. Indeterminateness and Nonlinearity. A consequence of increasing interdependency in national infrastructure means these systems become indeterminate and nonlinear. Additionally, feedback mechanisms arise when externalities in the system alter the costs and benefits which accrue from an individual's decisions, therefore causing behavioural change. Positive feedback often has a destabilising effect on a system, while negative feedback can create an effect which is homeostatic. Nonlinear feedback mechanisms can cause the system to undergo transitions to other organisational states. Moreover, endogenously created technologies can be responsible for this type of transition, inducing qualitative change in the relationships of key system components. For example, the evolution of energy and transportation systems over the past century has instigated organisational and operational transitions in the national infrastructure, encouraging coevolutionary change in tandem with the demand patterns.

The nonlinearities and the degree of technological innovation inherent in the system make *unpredictable outcomes* occur. These emergent outcomes might not have seemed logical or possible from close examination of the actions of individuals. Complex adaptive properties mean that the system can shift to a very wide variety of possible future states. Indeed, the path dependent properties of certain components often play a part in this. There is thus a need to move away from the past "predict and provide" planning approaches used for large technical systems and recognise the importance of greater understanding of the plethora of interacting technical and social processes which can push the system into states that arise unexpectedly. Rather than focusing solely on technology and infrastructure, we should shift our thinking to also include *sociotechnical regimes*, including the users and their behaviours in infrastructure analysis.

5. A System-of-Systems Approach to Infrastructure: A Case Study of the UK

We now present a case study which uses CAS properties to develop a system-of-systems (SoS) approach to infrastructure, as an example of a complexity-based method applied to

support public policy decision-making. As already identified, there has been growing recognition in recent decades of the importance that national infrastructure systems are interconnected. While infrastructure (especially energy) has underpinned many vital systems for over a century, the increasing proliferation of ICT has been a key driver and will continue to be, considering those technologies on the horizon such as the Internet of Things or Connected and Autonomous Vehicles. Past analytical approaches prevent thorough analysis of this complexity by ignoring interdependencies; therefore we need new tools and methodologies that position us to quantify these systems. This has the potential to revolutionise both the quality and quantity of infrastructure analytics available to public policy decision-makers, leading to the development of more effective infrastructure planning and resilience policies. This case study begins by detailing the main decision-makers and their goals and information requirements. Subsequently, a novel approach to infrastructure assessment is detailed before being critically reviewed.

5.1. Key Decision-Makers. An important issue with infrastructure policy is that responsibility has traditionally been fragmented and spread out across the UK Government. For example, energy, transport, ICT, water, and waste policy has included up to eight government departments, namely, (i) Business, Energy and Industrial Strategy, (ii) the Department for Transport, (iii) the Department for Digital, Culture, Media and Sport, (iv) the Department for the Environment, Farming and Rural Affairs, (v) HM Treasury, (vi) the Cabinet Office, (vii) the Ministry of Housing, Communities and Local Government, and (viii) the Department for International Trade.

Over the past decade the UK has attempted to take a far more strategic approach to infrastructure, as promoted by the release of the UK Council of Science and Technology (2009) report entitled *Infrastructure for the 21st Century*. Subsequently, under the labour government a white paper was published titled *Building Britain's Future*, promoting the infrastructure agenda as a way of dealing with the damage caused by the Global Financial Crisis. This led to a new body being created called Infrastructure UK (known as "IUK"), within HM Treasury, with the key responsibility of developing a National Infrastructure Plan.

In light of this fragmented governance landscape, the creation of a strategic high-level planning body within HM Treasury called the National Infrastructure Commission (NIC) was tasked with coordinating infrastructure policy across government. This body is like those that have been established in Australia (Infrastructure Australia) and New Zealand (National Infrastructure Advisory Board). The NIC operates via a set of infrastructure commissioners who have responsibility to develop a long-term strategy for the delivery of national infrastructure. There is a requirement to undertake a National Infrastructure Assessment at least once every parliament (5 years) as well as responding to emerging issues at the direction of the Chancellor, which have recently included smart power systems, 5G communications, the East-West transport corridor, and coordinating the development

of a digital twin of the UK's national infrastructure system. The NIC is the key decision-making body focused on within this analysis, given its need to coordinate across all areas of infrastructure policy.

The overall goal of the UK's infrastructure policy is to deliver efficient and effective infrastructure systems which are sustainable, enhance productivity, and provide economic opportunity for everyone in society. However, long-term infrastructure planning is a classic decision-making under uncertainty problem which needs to navigate changes in demography, economy, society, and environment. Infrastructure policy can also be highly political and subject to radical technological change.

5.2. Information Used for Decision-Making. Each infrastructure sector may have its own specific set of metrics required to assess the state of the current and future system. However, a general approach is to consider (i) system capacity, (ii) service coverage, (iii) investment costs, and (iv) potential emissions. The traditional approach to infrastructure analytics for public policy decision-making constitutes fragmented sector modelling, often taking place in individual government departments who derive information from a niche set of models pertinent to each infrastructure sector, including the UK TIMES energy model, DECC energy demand model, the National Transport Model, and the LTIS flood model. This is problematic because transport modellers may use completely different epistemological approaches, assumptions, and forward-looking scenarios when compared to energy, digital, water, or waste management. This firstly introduces additional uncertainty when comparing the potential results between these models and, secondly, completely ignores the feedback between infrastructure sectors. Hence, this leads to the treatment of infrastructure existing in a closed system, with centralised command and control which is considerably detached from reality and may lead to unintended outcomes. For example, new electrification strategies in one sector may work from the assumption that enough electricity is available to support this approach, which may not be true. Hence, by capturing the key characteristics of national infrastructure, by representing the interdependencies between the systems, more accurate information can be provided to decision-makers. This accuracy is achieved by reducing the level of uncertainty inherent in the data, models, and results.

5.3. The Infrastructure Transitions Research Consortium (ITRC) Approach. One example of where this methodology has been applied is by the ITRC (see Hall et al. [47]). Taking inspiration from the Council of Science and Technology (2009) report, the ITRC project was formed based on the proposition that modelling and simulation techniques can be highly important to understand and effectively manipulate complex systems. Moreover, the design and planning of infrastructure can be improved using powerful systems models as these techniques can help to optimise across a wide range of policy constraints. The ITRC subsequently collaborated with the newly created IUK to analyse the National Infrastructure Pipeline and undertake a "hotspots"

analysis of critical risks to infrastructure across the UK (see Thacker et al. [18, 19]). Following this the ITRC undertook the analysis for the UK's first National Needs Assessment (NNA) led by Sir John Armit, the then President of the Institution of Civil Engineers. Consequently, the modelling capability was utilised to inform the UK's first National Infrastructure Assessment published in 2018. Had the modelling approach not been available to undertake a holistic evaluation, these activities either would not have taken place or would have relied on fragmented modelling approaches for each individual sector used in the past, ignoring the interconnected and interdependent nature of national infrastructure. This would likely have led to an underestimation in total demand for future infrastructure services.

The framework developed by ITRC for conducting a National Infrastructure Assessment is based on an initial step which defines a set of "what if" questions pertinent to the current needs of policy makers. Four stages follow: firstly, collecting scenarios that represent future uncertainties such as demography, economic growth, and climate; secondly, developing both plausible and experimental infrastructure strategies for testing [48]; thirdly, applying a national infrastructure system-of-systems model to simulate the performance of infrastructure under various exogenous scenarios; finally, evaluating the performance of different strategies and identifying robust options.

ITRC and NIC have been working together to produce an original evidence base that underpins the NIC's strategic work. This evidence base has been augmented by utilising a national infrastructure system-of-systems model (NISMOD) consisting of a family of models. The NISMOD suite includes a model for long-term planning (-LP) and for the analysis of risk and vulnerability (-RV) of critical national infrastructure. NISMOD-LP implements the National Infrastructure Assessment approach developed by ITRC (see Hall et al. [47] for a more complete description). NISMOD-LP is an infrastructure system-of-systems model that enables users to explore strategic planning of multiple infrastructure sectors, while simulating the operation of the individual sectors and their key interdependencies under a range of unified scenarios of future developments spanning natural sciences, demography, and economics. Demands for infrastructure services are derived from these scenarios of key demand drivers [49]. For example, demand for transport services, such as car passenger travel, is derived from future scenarios of population, GVA, and endogenously computed travel time and cost (an example of adaptive dynamic behaviour). Long-term dynamics are explored through narratives of technological change and consumer acceptance that affect the attributes of infrastructure assets and demand for infrastructure services. The infrastructure sectors are represented by detailed engineering simulation models that are linked with one another, and while a comprehensive description of each model is beyond the theoretical focus of this paper, they are available for energy [50], transport [51], digital communications [52, 53], solid waste [54, 55], and water [56, 57]. The linkages between these models represent the critical dependencies between sectors (see Figure 1) including flows ranging from resources to information.

For example, the energy supply model simulates the operation of the UK's portfolio of current and potential future electric power stations, the electricity transmission and distribution networks, gas pipeline, pumps, and storage facilities. Electricity and gas are thus supplied to meet demand for energy-related infrastructure services. The simulation models enable analysts to test the implications of *strategies* within the infrastructure system. Crucially, the simulation models produce quantitative performance metrics which allow analysts to evaluate the performance of the infrastructure system under different conditions. By comparing the performance metrics of multiple model runs across a wide range of scenarios and combinations of planning strategies, analysts can explore robust policy options across the infrastructure system-of-systems.

5.4. Critically Reviewing a System-of-Systems Approach to Infrastructure Public Policy Decision-Making. In this section we evaluate the added-value provided by utilising a system-of-systems approach for infrastructure decision-making. We discuss the existing limitations, as seen from the perspective of complex adaptive systems theory, and whether new insights can be provided into the properties of the national infrastructure system.

We illustrate a mapping in Figure 2, from the distinct properties of infrastructure as a complex adaptive system to the implemented methodology, with infrastructure being modelled as a system-of-systems using NISMOD. This firstly includes adaptive agents, whereby operators of critical national infrastructure deploy different long-term planning strategies to meet future demand under a range of exogenous scenarios and conditions. Secondly, diverse agents are represented by different infrastructure decision-makers across the various sectors in the system-of-systems simulation framework. Diverse agents are also represented on the demand side, where demands for infrastructure services are segmented by socioeconomic attributes using a set of spatially disaggregated household demographic profiles and commercial and industrial productivity statistics. Thirdly, the modelling approach captures short-term dynamics of interdependencies between systems; as decisions are made by each individual sector, this changes the system-level conditions, with ramifications for investment and operational decisions elsewhere in national infrastructure. By simulating the operation of the system, we capture the supply dynamics to meet the diverse demands for infrastructure services. Fourthly, as in reality, the decision to invest in a sequence of irreversible interventions locks the system structure into a long-term trajectory. Finally, because of these properties, a spatially explicit national infrastructure system structure emerges, which is assessed using a set of performance criteria metrics, such as capacity, coverage, cost, and emissions.

However, while developing and applying new theories can be a useful intellectual academic exercise, there is still the question as to whether this *improves* the existing understanding of infrastructure. This case study demonstrates that complex adaptive systems theory and system-of-systems methodologies can be combined predicated on the

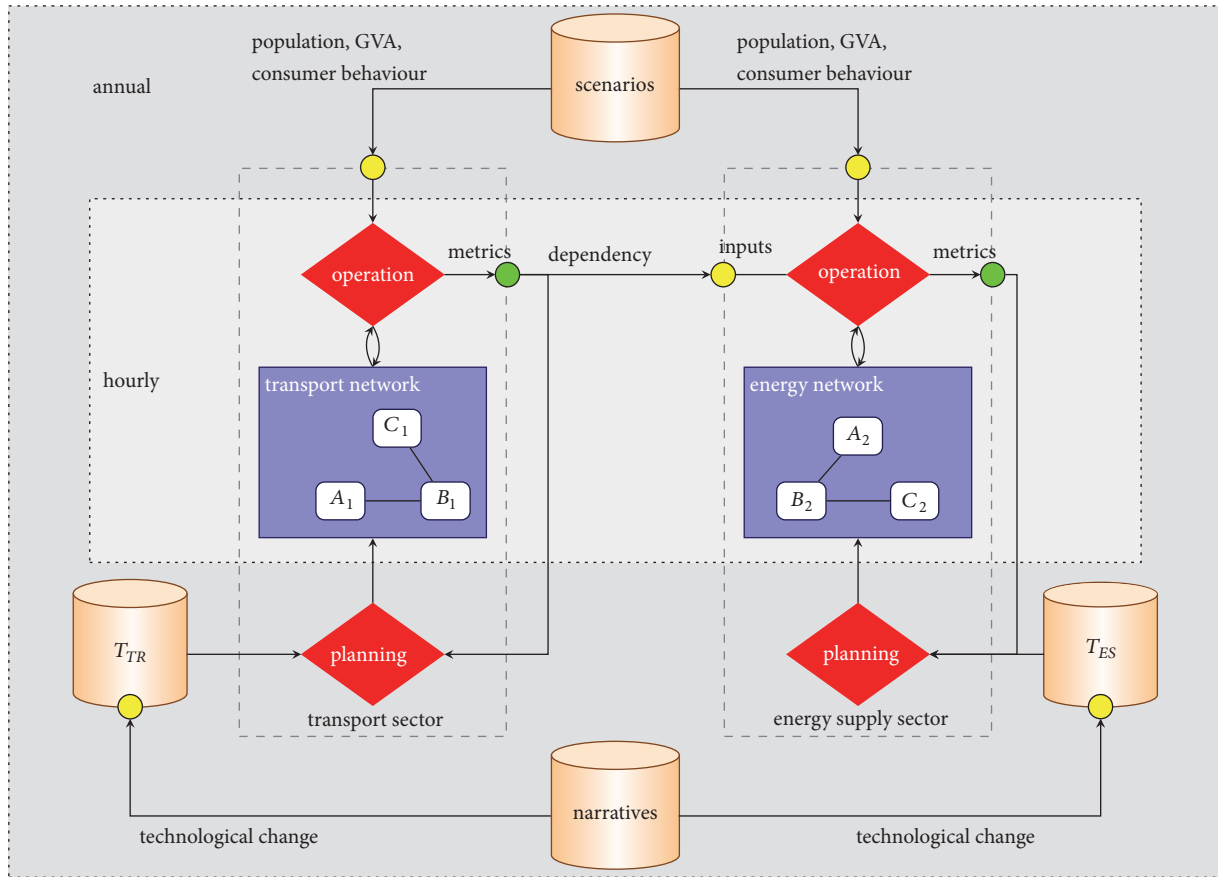


FIGURE 1: A dependency shown between just two infrastructure sectors contained in the ITRC's National Infrastructure System Model. The cylinders labelled T_{tr} and T_{es} represent the stock of available technologies for the transport and energy sectors. Narratives hold the collection of assumptions exogenous to the modelled system about long-term technological changes and modify the attributes of available technologies. Scenarios capture changes in socioeconomic drivers of infrastructure service demands. The network structure that underpins the hourly operation of the sector is altered over annual planning timescales as technology changes, and long-term planning investments result in the turnover of the infrastructure stock. Performance metrics produced from the operation of the system simulation feed back into the planning strategies governing future investments and provide the results of a model run.

properties outlined in Table 2, enabling developments beyond traditional systems-based analysis. Given there is growing dissatisfaction assuming that reality can be modelled as static, deterministic, and containing homogenous, rational agents, this is to be welcomed.

While there have been relatively few examples of complexity-based approaches supporting public policy, in this application to long-term infrastructure decision-making we have detailed a methodology addressing five properties of complex adaptive systems (adaptive agents, diverse agents, dynamics, irreversibility, and emergence), across three hierarchical levels ranging from agents, to networks, to systems. The main contribution of this application of the national infrastructure system model is that we capture the emergence of a whole national infrastructure system, driven by agent-level decisions and explicitly modelled interdependencies across the sectors of energy, transport, digital, water, and waste. The breaching of individual infrastructure sector system boundaries creates new opportunities for understanding trade-offs and synergies across sectors, not only

within individual systems, with cumulative potential to make more effective policy decisions, while reducing the likelihood of unintended consequences. Adopting these methods will require a change in mindset by both model developers and policy decision-makers, as it requires increased use of system-of-systems-based thinking and associated modelling methodologies. In doing so, this could further unshackle approaches that view reality as something that is predictable and linear, towards increased recognition that the world is highly dynamic, diverse, and evolving: in essence, *complex*.

6. Conclusion

In this article we have sought to build on the core properties identified by Arthur [10], Delorme [16], and Lei et al. [12], to assess whether a CAS approach might help to provide a better understanding of the forces underpinning change in national infrastructure systems. We find that properties of a complex adaptive system characterise the workings of infrastructure systems well and subsequently articulate a system-of-systems

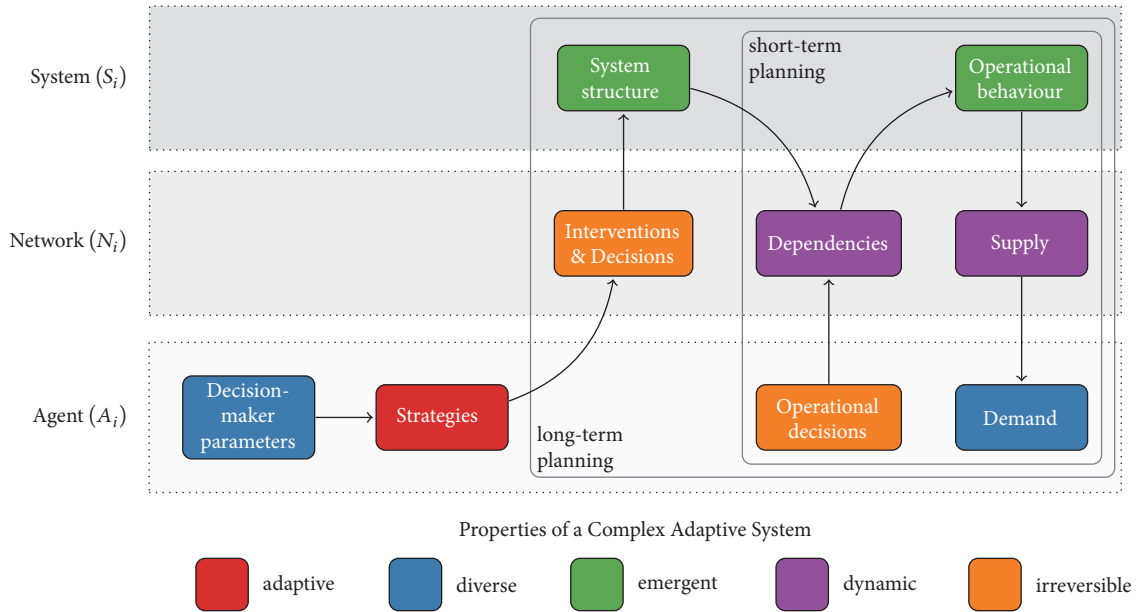


FIGURE 2: Mapping the properties of a complex adaptive system to a system-of-systems approach.

method grounded in this theory. The novel contribution of the paper is the articulation of the case study describing a decade of research which applies complex adaptive systems properties to the development of a national infrastructure system-of-systems model. This enables decision-makers to explore the trade-offs and properties of an emergent national infrastructure system, driven by agent-level decisions and explicitly modelled interdependencies between energy, transport, digital communications, waste, and water. Subsequently, the approach has been used by the UK National Infrastructure Commission to produce a National Infrastructure Assessment which is capable of coordinating infrastructure policy across a historically fragmented governance landscape spanning eight government departments. The application will continue to be pertinent moving forward due to the continuing complexity of interdependent infrastructure systems, particularly from increased electrification and the proliferation of the Internet of Things.

Data Availability

In this article we theoretically review the use of complexity methods and provide a case study based on a particular application. We reference the models developed and used for this process but do not report results from them. Data used by these models can be traced via the references provided in the paper.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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