Editorial: Infrastructures, sustainability and models

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Abstract: Infrastructure and society are intertwined in an unsustainable reinforcing feedback loop of expansion and growth. Modelling and simulation of infrastructures as large-scale sociotechnical systems are suggested to underpin decision making on public policy, corporate strategy and research and support decoupling or reversing this loop. The background, foundations and requirements for infrastructure modelling to foster sustainability are explored in this special issue. Despite the complex system of infrastructure and the chaotic character of society, the authors of the contributed papers, which are introduced here, give proof that the next generation of infrastructure models can emerge to help us address the challenge of improving decision making on infrastructure development for sustainability.

Keywords: infrastructure; sociotechnical system; agent; sustainable development; evolution; transition.

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1 Introduction

Infrastructures are the backbones of our industrial society. At the beginning of the 21st century, however, it is becoming clear to anyone that our industrial society is not sustainable. We are threatened by energy and resource depletion and by regional food and water scarcity. Through the dramatic loss of topsoil, biodiversity and global climate changes, Earth may lose much of its capacity to sustain humans. Since society shapes infrastructures and infrastructures shape society, to avoid a systemic crisis, to reinvent and reshape society calls for a transformation of its infrastructure backbones.

This is a formidable challenge as:

> "the structure, scale and scope of infrastructures and industrial networks evolve through a never-ending series of decisions on (dis)investment, expansion, modification, regulation and innovation. In the private and public sector alike, there exists a need for informed, 'no-regret' decision-making, to effect corporate strategy or public policy. Underpinning actors' decisions in response to changes in their external world requires models and simulations that span years to several decades." (Lukszo and Dijkema, 2009)

Infrastructure, sustainability and modelling tie together the papers in this special issue which were developed from a selection of papers presented at the international conference on infrastructure systems 'Building Networks for a Brighter Future' (Rotterdam, the Netherlands, 10–12 November 2008) organised by the Next Generation Infrastructures Foundation. Whereas the previous issue (Lukszo and Dijkema, 2009) focused on infrastructure operation, this special issue contains the papers addressing infrastructure evolution and transformation.

Prior to introducing the papers in this special issue and presenting some conclusions, we explore the challenge of infrastructure transformation by:

- addressing the relation between infrastructure and society
- reflecting on infrastructure development
- touching upon sustainability
- introducing infrastructure modelling.

2 Infrastructures and society

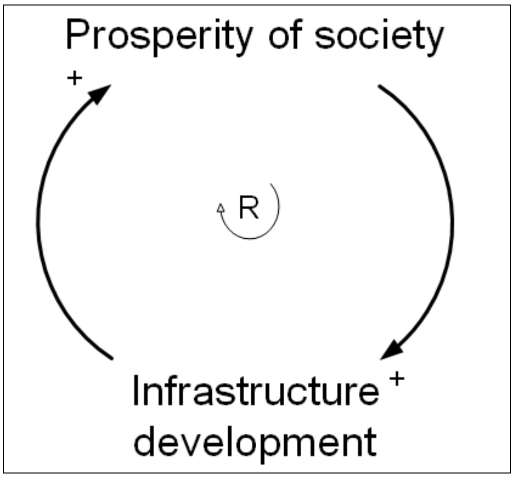
Around the globe, citizens and companies have come to rely on uninterrupted availability of electricity. Global industrial supply chains have been shaped by container transport which relies on ports, road and railroad infrastructures and logistics fuel infrastructure. Waste water and water infrastructures are crucial to maintain a healthy urban environment and to enable intensive agriculture and industrial operations. Information and Communications Technology (ICT) is pervasive in all industrial sectors, enabling financial markets and novel services and redefining the economics of products and production.

Human societies appear always to have benefited from infrastructures whereas hunter-gatherer societies only loosely depended on trails to move between hunting grounds, camp sites and hide-outs. As soon as sedentary agricultural societies were formed, transport and water infrastructure developed. The Inca and Roman empires were sustained by extensive road networks and waterworks; the importance of logistics was already recognised by Julius Caesar. The fortifications of ancient Babylon, Troy, Greece, Rome and other medieval cities as common defence to human enemies can also be considered infrastructure. Moreover, in early medieval Europe, the Dutch started building dikes as their common defence against flooding.

Infrastructure is one of the many factors that allow a society to prosper, population to grow and trading to flourish. For centuries, building infrastructures occurred in an endless space of 'wilderness' while energy supply was limited and work could only be done by people, domesticated animals, water or windmills. Communication was largely by transmitting spoken, written or coded messages via the road or water transport networks.

In general, a prospering society leads to growing infrastructure networks with their geographical scope, the capacity of their links and their density increasing. Therefore, this mutual influence may be seen as a reinforcing feedback loop (*e.g.*, Sterman, 2000) between infrastructure and society (Figure 1).

Figure 1 Reinforcing feedback loop between infrastructure and society



During the industrial revolution, this feedback loop intensified dramatically. Critical factors included the dramatic increase of energy resources available to human kind, the invention of the steam engine to convert them into work and the arrival of new organisation principles. Allenby (2009) makes a case out of the pervasive impact the advent and expanse of the American railroad system has had. He argues that railroads created industrial time, coevolved with communication infrastructure (telegraph), shaped managerial capitalism, capital and financial markets and transformed landscapes, economic and power structures and even the dominant American worldview.

Developments in the second half of the 19th century and the early 20th century led to a second acceleration of infrastructure-society coevolution. Among others, these included the discovery of crude oil, the invention of the light bulb, the internal combustion engine and mass production pioneered by Ford and the recognition of the importance of hygiene to human health. These led to the recognition that sewers and safe drinking water are crucial for city dwellers, to the rapid development of electricity networks and to the expansion and improvement of roads and road networks.

In the 20th century, infrastructure networks continued to coevolve with society. Regional electricity networks have grown into grids that span country if not continents. In the second half of the century, natural gas infrastructure networks evolved that today span the globe. The explosive development of the internet following the invention of the worldwide web enabled by html has no precedent. In his seminal book, Friedman (2005) signals the similar pervasive, shaping and transforming impact ICT will have in the 21st century as the railroads had in the early 19th century.

3 Infrastructure development

Many infrastructure networks we use today have not been planned for or designed as a single system. Rather, present network structure and system content are the result of an evolutionary process characterised by path dependency and lock-in; past decisions on technology and standards, to a large extent, determine which system, technology and innovations are technically and economically feasible later. The Dutch natural gas infrastructure offers a perfect illustration. After the discovery of the gigantic Slochteren field in the northeastern Netherlands in 1959, a national gas infrastructure was rolled out in less than a decade to connect each and every home. If another strategy had been implemented by the Dutch government, district-heating connected to cogeneration facilities could have been the dominant infrastructure today. With the dense gas grid in place, however, district-heating often is not competitive; natural gas offers economy-of-scale through the size of the network. Other lock-ins are standardisation and the collective mindset on natural gas. The rapid realisation of ubiquitous availability and access to the gas grid was accompanied by the development of reliable equipment that was safe to use within homes. Thus, today, in Dutch homes, gas use for central heating and hot tap water is the *de facto* standard. Natural gas use is considered to be safe, accepted and institutionalised.

With deregulation, liberalisation and, sometimes, privatisation, one important lock-in of many infrastructure sectors has been removed, *i.e.*, government dominance and monopoly. By unbundling production, transport and retail, the number of players increased dramatically. Previously, vertically integrated monopolist state-controlled companies had to adapt to a new playing field and rules of the game and decide how to best pursue their interests in the short and long terms. Governments and governmental agencies had to adapt to their new roles, to their changed span of control and to the instruments they have to influence the players. In the electricity sector, for example, these include production companies, national and regional grid operators, retailers, power exchange markets, traders, national and European competition authorities. There exists not a single player that completely controls the electricity infrastructure development. Consequently, instead of national planning of production capacity, companies determine when, where and how to invest in novel generation capacity. They must reckon with competition laws, environmental regulations, safety, and sector-specific legislation and so on. Thus, at any given time, the system is the collective result of past distributed decision making.

This, of course, does not imply that the people, companies or governments have no influence on the development of any infrastructure system. The case is quite the contrary. Transforming infrastructure sectors from state-owned monopolies into market economies, transactions replaced planning as the key coordination mechanism. Governments can influence what transactions may occur through policy and legislation, whereas public information, science and market can influence consumers, governments and corporate decision makers alike. It does imply that technology development alone will not transform infrastructures; infrastructures are large-scale sociotechnical systems (or so-called λ-systems) (Nikolić *et al.*, 2009) that coevolve with society (Dijkema and Basson, 2009; Thissen and Herder, 2008).

4 Infrastructures and sustainability

The term sustainable development' was coined with the publication of 'Our common future' in 1987 and defined as (economic) development and consumption that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Economic Development, 1987). Arguably, the best-known and most widely spread definition of sustainable development is largely only a guiding principle for the ongoing process of economic and social development.

Using a systems perspective, sustainability can be an organising principle for the transformation of infrastructure systems.

> "Sustainability pertains to a balanced interaction between a population and the carrying capacity of an environment such that the population develops to express its full potential without adversely and irreversibly affecting the carrying capacity of the environment upon which it depends." (Ben-Eli, 2004; 2006)

It is an emergent property of a system (Allenby, 1999; Ehrenfeld, 2007).

Adhering to the definition of Ben-Eli, however, we cannot label a particular infrastructure as being sustainable *per se* because infrastructures are an integral part of society. By determining the physical, economic and ecological impact of an infrastructure in isolation, we would neglect its impact on society. Taking sustainability as an emergent property of society, we not only must establish the effect of a particular infrastructure on the current balance among economy, ecology and society but also on the character and intensity of the dynamic feedback loop between infrastructure and society.

Infrastructure systems in society can be delineated at multiple scales. For example, in electricity grids, we can discern a regional, national and continental geographical scope where each level sets limits for other levels. The demography and geography of a particular region or country limit the scope for a feasible design of electricity production and network typology and for the inclusion of renewable energy sources. In Europe, legislative and regulatory coordination has shifted to the European Union (EU). Through national policies and regulation, however, member states can stimulate system innovation. A prime example is the German feed-in tariff system which has led to the development of a large renewable energy sector.

"What is [than] to be designed or steered to foster sustainability?" (Dijkema and Basson, 2009, p.160). We conjecture that systemic infrastructure research must address transformation of infrastructure, *e.g.*, from carbon intensive into carbon neutral. The main problem to be addressed is "What policies or actions can be expected to foster a timely transition?" Underlying questions are "How do we assess transition policy?", "What conditions will lead to the transformation of the infrastructure functions, asset base and operation?" and "How do we quantify and predict the physical, social, economic and environmental impact?"

5 Infrastructure modelling

An infrastructure can be represented as a sociotechnical system that develops over time subject to investment, disinvestment, policy, regulation and external developments. Asbjørnsen (1992) defines a system as "a structured assemblage of elements and subsystems, which interact through interfaces. The interaction occurs between system elements and between the system and its environment." Thus, a modelling paradigm is called for to model a system consisting of technical objects and social actors which interact internally and across the system boundary. The concept of agent-based systems that are composed of multiple interacting decision makers and physical elements is such a paradigm. An agent has been defined as "an encapsulated computer system that is situated in some environment, and that is capable of flexible, autonomous action in that environment in order to meet its design objectives" (Jennings, 2000). Thus, the term 'agent' can represent actors in the social network as well as a control mechanism of a component or a subsystem in the physical network. They interact by exchanging materials or goods, energy, information and decisions over interfaces.

Agent-based models were successfully set up to reflect the evolution of sociotechnical systems such as an electricity infrastructure or industrial network (Nikolić, 2009; Chappin *et al.*, 2009). Therein, as in natural ecosystems, the agents must survive interacting, competing and cooperating with other agents, subject to conditions imposed from an external world. In a simulation, possible external changes take the form of scenarios. Using this approach, the question "Does emission trading or carbon taxation stipulate a change in the behaviour of the actors involved and does this materialise in reduced carbon emission from the sector and the society?" has been addressed concerning carbon policies in the long run (Chappin *et al.*, 2009).

To increase our understanding of how such large-scale systems behave, we must not only elucidate and incorporate in the models the causal relations and laws of nature that determine the behaviour of the physical network but also the intentional, social and institutionalised relations that represent the behaviour of the multiactor network. To change the technology and structure of the physical network and to shape infrastructure transformation, an adequate incentive structure for the players is required. This structure can be induced by using simulation models including competition with knowledge and skills, by innovation and investment decisions of financiers, owners and operators of subsystems and, finally, by the society which benefits from the products or services delivered through the infrastructure.

6 Modelling the evolution of infrastructure systems

> "The purpose of the special track at the conference 'Building Networks for a Brighter Future' was to bring together researchers involved in agent-based technologies for modeling, control, decision-making, policy development and management of infrastructure networks." (Lukszo and Dijkema, 2009)

Reflecting on the state-of-the-art in diverse research communities, papers included in the previous special issue of this journal focused on modelling infrastructure operation. The papers included in this volume, however, address the long-term transition and evolution of the infrastructure systems.

Chappin and Dijkema present how the management of transitions in energy infrastructure systems can be underpinned by a framework using agent-based simulation models for the assessment of transition assemblage design alternatives. The models for three cases are reviewed, namely:

1 carbon policies and electricity production
2 transformation of global Liquefied Natural Gas (LNG) infrastructure
3 introduction of Light Emitting Diode (LED)-based lighting system.

Xie and Ilić define an approach providing a systematic means for analysing the dynamics of electricity grids with increasing penetration of distributed renewable energy resources such as wind and solar. Allowing transformation of electricity infrastructure is a crucial issue as the occurrence of network instability and service breakdown related to the feed-in of electricity from renewable sources to the existing grid will seriously impact social acceptance and, thereby, affecting the pace of adoption of these technologies.

Nikolic and Dijkema introduce an evolutionary modelling approach that consists of a social process for model development, *i.e.*, learning from model development, implementation and case study. In each iteration step, more and more encompassing infrastructure models are created. Thus, with each extended model, a greater share of the sociotechnical complexity of these systems is captured. The approach is succinctly illustrated by the model genealogy of a series of agent-based models developed to study industry-infrastructure coevolution.

Davis *et al.* focus on the problem of how to suitably visualise economic and ecologic system parameters to decision makers as they change during infrastructure development and over decades of system evolution. After illustrating this in the case of evolving bioelectricity networks, they explore the possibilities offered by the rapidly evolving internet and Semantic Web 2.0 to collaboratively build infrastructure models and acquire massive datasets by smartly connecting databases available on the web.

In the final paper, AlAbdulkarim and Lukszo address designing new added value services related to the operation of critical infrastructures such as smart metering in the energy sector. Based on this case, analysing information security threats and their consequences, the authors emphasise the importance of incorporating information security as nonfunctional requirements in the early stages of system development rather than as an afterthought to system implementation and deployment.

7 Conclusion

In this editorial, we have argued that infrastructure and society are intertwined in a reinforcing feedback loop of expansion and growth which is unsustainable to some extent. Similar to society, infrastructures are the emerging result of the interaction between players engaged in an endless process of distributed decision making. Any infrastructure is a complex sociotechnical subsystem of society, and from the coevolution of infrastructures and society, sustainability must emerge somehow. This, then, leads to the question, what changes to infrastructure systems are to be explored and what impact are to be visualised to help develop and design infrastructures for sustainability?

Exploring this question requires a systems approach. Transforming infrastructures to foster sustainable development requires adequate decision support underpinned by models and simulations of large-scale sociotechnical systems.

With the contributions to this special issue, the authors have begun to address the formidable challenges involved in infrastructures, sustainability and modelling. Decomposing earth systems and societal systems enables us to elucidate structure, content and relations, and provides a starting point for modelling. Exploring the infrastructures using agent-based modelling enables us to underpin directions for research and decision making by simulation. This not only requires adequate system boundary selection and detail in technical object and agent representation but also a novel modelling process to include and integrate the following:

- knowledge from multiple domains
- massive and reliable datasets
- correct and relevant representation of and linkage to policy and other transition instruments
- adequate visualisation, validation and representation of results.

A variety of challenges in modelling the evolution of infrastructures in this special issue demonstrates that a next generation of infrastructure models can emerge and help us improve decision making on infrastructure development for sustainability.

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