Guest editorial (17.2)

Complexity and sustainable utility services

June 30, 2015 · Editorial

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Varga L. Guest editorial (17.2): Complexity and sustainable utility services. Emergence: Complexity and Organization. 2015Jun 30 [last modified: 2015 Oct 6]. Edition 1. doi: 10.emerg/10.17357.6840d0f84446501f1c991932737d69b6.

Abstract

This special issue is inspired by a range of challenges in complex infrastructure system-of-systems which drive an interest in research and practice towards the delivery of sustainable utility services from integrated, smart infrastructure systems.

Aging and fully used capacity in utility infrastructure systems, which generate, transport, store and transform resources, such as coal and rainwater, into utility products, such as electricity and potable water respectively, are creating a dilemma for investment. On the one hand, the low carbon society is demanding alternatives to traditional non-renewable pathways but on the other hand, investment in infrastructure demands certainty, scale, security, return on investment, and economic growth. What does the new infrastructure look like? Does it need to become more local or regional? How do current actors including utility companies, infrastructure providers, network operators, the government, and so on, need to change to put a focus on meeting utility service demand (rather than measuring the quantity of utility product delivered) within the age of the digital economy, smart technology autonomy and human-technology interaction? How do consumer behavior, automated demand response, and other socio-technical dependencies influence the effectiveness of this approach?

We propose it is necessary to move beyond considering each utility as a distinct silo providing a single utility product. This siloed approach has created a utility product centric industry in which the *supply* of infrastructure (roads, water mains, sewers, telecommunications networks, transmission lines, etc.) and products (gas, electricity, potable water, etc.) is paramount, and ignores the patterns of *demand* for the services (mobility, flexible working, ambient cooling, hygiene, etc.). This product supply focus acts to create lock-in to existing regimes which are still largely fossil-fuel dependent. This siloed approach persists despite the complex infrastructure system-of-systems exhibiting high levels of inter-dependency and feedback, and where overlapping vulnerabilities, investment and operational challenges, are poorly understood.

Furthermore technological innovation, in devices using both non-renewable sources (such as photovoltaics) and renewable sources of energy (such as carbon capture storage), is creating competition and lack of clarity as to which infrastructure investment to make. A broad palette of technologies is emerging particularly to address the variability of renewable energy supply. Otherwise, globalization has been the driving force of the digital economy creating opportunities via the open internet for small to medium scale businesses to trade with very low overheads. These businesses are able to meet (and reduce) local demand for utility products through the provision of smart devices, and services to improve the efficiency of local equipment and goods such as boilers, insulation and double glazing. However uncertainties concerning business models for more intense and macro utility service provision together with risks in areas of regulation, contracting, security, ownership, and so on, are preventing larger scale roll-out. Barriers need to be liberated to allow service innovation to emerge, but this is not without the need for investment in increasing skills and accreditation to ensure safe and secure supply of integrated utility services.

These multiple challenges arise at a time when the UK population is growing and there appears no stopping the positive feedback in demand for more utility services arising from improved wealth, greater knowledge and inter-connectivity through social networks, increased mobility, and so on. Meanwhile, in response to the predictions of climate change models the Kyoto agreement imposes very strong reductions in carbon emissions for the nations of the world. In particular the UK is signed up to reduce carbon emissions to 20% of their 1990 value by 2050. At the same time there is a need to increase water efficiency and water savings in the upcoming decades. The European Water Framework Directive 2000/60 integrates economics into water management and policy making; for example it promotes the use of water charging to act as an incentive for the sustainable use of water resources.

Recognition of integrated utility services co-evolving in the digital economy with complex infrastructure systems of various scales represents a great opportunity to gain important insights into the nature of complex systems. Dynamic, spatially distributed patterns of generation, transport, storage and consumption are being studied using multi-agent models, with learning agents at different levels of the system. Modelling using a complex systems approach has the potential to test our assumptions and to gain insights into risks, opportunities and futures unimaginable. These models are beginning to demonstrate the emergence of new structures in complex infrastructure systems, and are needed to explore long-term horizons, focusing on normative ends which are low in carbon, sustainability, economically viable, and socially desirable.

Given this context, together with colleagues, a satellite conference was established at the prestigious European Conference on Complex Systems (ECCS) held in Barcelona in 2013. I acknowledge the kind contributions of the satellite co-organizers, Dr Enrique Kremers, from the European Institute for Energy Research and Prof Bogumil Ulanicki, from the Center for Engineering Science and Advanced Systems. We accepted seven papers which have since been developed and are presented here. Given the significance of energy needs in all infrastructure systems, it is not surprising that the papers in this issue have a focus on energy systems.

Strzelecka *et al.* examine utility-service provision as an example of a complex system. They represent the utility–service provision system as a directed hyper-graph in which products and services are represented with nodes whilst devices are hyper-edges spanning between them. Devices usually connect more than two nodes, thus standard graphs cannot fully describe the utility–service provision problem. Analysis of the hyper-graph metrics, including the prediction of the performance of the graph when there is a failure to deliver a product, enables the creation of an optimal transformation graph which meets the service demands of a particular domestic dwelling. The optimal transformation graph emerges via an iterative approach which uses a master graph (also a hyper-graph) that contains all possible devices and products. The transformation graph is a standard graph where nodes are devices, storages for products or services, while edges are product or service carriers, and so it can be implemented as a practical solution.

Oliver *et al.* provide a method of configuring an electrical power network with distributed generation by multi-objective optimization with evolutionary computing. They propose that technical and economic improvements to electrical power networks are possible through the optimal deployment of distributed generator units which may use renewable energy sources. They analyze the multi-dimensional results of the evolutionary computation component in order to reveal relationships between the network's design vector elements, by means of most influential nodes and type of technology, as well as tipping points in the behavior of the system. Using a case study, the paper demonstrates how the method assists in answering questions such as how might a new infrastructure be composed in terms of distributed generator units, how its components are geographically distributed, and how many of each type would be most appropriate given cost constraints. It also addresses the essential problems of power flow and optimal power flow calculations of alternating current in electrical power networks.

Viejo *et al.* take a concrete example to examine criticality in a complex socio-technical energy system. Complexity theory suggests that criticality occurs at the edge of chaos, between order and disorder, and provides highly interesting phenomena, such as emergence, which are important for the evolution of the system. The energy system is composed of multiple networks and levels, usually described by their voltage, and is undergoing a paradigm shift from a centralized hierarchical structure to one which is more distributed and in which locally generated energy flow may become bi-directional (going both up and down the levels). An exemplary case of a refrigeration system is simulated where different types of variables are adjusted. Phase shifts from order to partial order to oscillation (undesirable due to its potential for damage) are detected. Using distributed smart grid measures which are supposed to improve grid stability, oscillating problems were detected, as the system is driven towards the edge of chaos.

Varga *et al.* examine the notion of Multi-Utility Service Companies (MUSCos) who use a novel business model that competes with traditional utility product providers whereby customers' services increase and resource efficiency is improved. The model shows how Multi-Utility Service Companies (MUSCos) could invade the market, changing it from markets focused on selling, for example, energy to customers, to markets aimed at selling efficiency. The output of our modelling is the extent to which the resource efficiency of UK homes can be significantly improved, and we show this in 10 centile categories. The output shows a major shift in the energy resource efficiency over 40 years. The real advantage for the MUSCo customer is that there is a discount on both the house improvements offered and the price of future supplies of energy and water. MUSCos are able to offer reduced cost of house insulation, appliances which reduce consumption and waste from multiple utilities, and they can also achieve marginal profits from financing of these appliances.

Gonzalez de Durana *et al.* demonstrate how local energy networks are instances of complex infrastructure systems integrated by generation, distribution, storage and consumption subsystems. They provide an agent based model which addresses the crucial issues of energy efficiency, by considering all energy carriers, such as gas (chemical), heat (thermal), and electricity together with an information network constituting a local multi-carrier energy network. The model implementation was developed from the previous work of the authors for describing smart grids where a two layer structure, for electrical power flow and communication, was used. The multi-carrier model is a step towards delivering a model to address the utilities conversion ontology which enables representation of any infrastructure component and activity (extract, transform, store and deliver). The scope of the multi-carrier model covers system transition in large scale socio-technical systems, co-evolutionary processes, and the use of scenarios to enable impact assessment.

Oldenburg *et al.* carry out model-based analysis of urban energy systems, on the basis of a city's energy Master Plan which outlines the city's long-term vision for its energy infrastructure and targets for energy outcomes, such as CO_2 emission reductions, and heating . This work takes a bottom-up perspective to assess the feasibility and bottlenecks of an energy master plan. A combination of system dynamics and an agent-based simulation model of the city's energy system are applied resulting in both a high spatial and temporal granularity. The model simulates a city's energy system and analyses the effects of the measures which are outlined in the master plans. The measures are an increase in photovoltaic electricity production and solar thermal panels. The effects of these two measures can be seen at both qualitative and quantitative levels. In order to achieve expected energy demand reductions through building refurbishment, the transition presented in the model highlights the need to discriminate investment into different districts of the city.

Pablo-Martí *et al.* present an agent-based model of population dynamics for the European regions. This paper underlines the importance of changing populations which have a bearing on the destination and demand for utility services. The paper extends previous work by using an agent based approach which produces models with greater explanatory capacity and to generate plausible scenarios more flexibly. The database has been developed on the basis of the population census, and the input data is used then to obtain a model that helps to understand the dynamics of population at the NUTS3 spatial level of resolution. Each agent in the model passes sequentially through the five implemented modules: aging and death, education, pairing, labor market and migration. The model forecasts the population dynamics of European regions in the period 2001-2021 demonstrating how agent-based modelling can contribute to integrate demographics and economics to forecast accurately migration patterns as a result of labor and income differences between socioeconomic integrated areas as the European Union.

The seven papers provide a rich contribution towards improving our understanding of integrated utility services.