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# **International Symposium for Next Generation Infrastructure Conference Proceedings**

Future infrastructure in all countries needs to be fit for purpose in order to support societal development in a changing world. Present assumptions about how infrastructure systems respond to changing societal needs and factors such as extreme events, security of energy, water and food supply, impact on the economy and exploitation of innovative technology have been challenged and found wanting.

The International Symposium for Next Generation Infrastructure (ISNGI) vision is to provide leadership and support for the development and growth of a coherent, world class, infrastructure research community, which engages academia, industry and citizens in a joint venture that drives innovation and value creation. In response to this vision and to the grand challenge

"Can we imagine resilient infrastructure systems that can meet the needs of twice today's population with half today's resources while providing better liveability for all?"

ISNGI 2014 was designed to support the rapidly expanding international research community in seeking to understand the interactions between infrastructure, the population it serves, the environment in which it functions, technology and the economy.

In total ISNGI 2014 brought together 40 international research contributions and 100 delegates, including a number of distinguished key note speakers, to create the opportunity for those involved in infrastructure research to meet their peers, engage in cutting edge discussion and ensure that their activities are informed by the best research and thinking in this vital field of endeavour.

We are delighted to present this collection of peer reviewed extended abstracts in response to the ISNGI 2014 themes of: Resilience and Reliability of Infrastructures; Infrastructure Resilience and Performance; Infrastructure and the City; Infrastructure Financing and Economics; Infrastructure Interdependence; Infrastructure Provision and Social Needs; Infrastructure and Extreme Events; Multi-Level and Transnational Governance Issues. The contribution made by these proceedings is totally in accord with the ISNGI vision and moves the state of knowledge forward to a significant extent.

**Professor Brian Collins**

**Dr Tom Dolan**

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# **Resilience and Reliability of Infrastructures**





# Enhancing Infrastructure Resilience Under Conditions of Incomplete Knowledge of Interdependencies

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## ABSTRACT

Today's infrastructures — such as road, rail, gas, electricity and ICT — are highly interdependent, and may best be viewed as multi-infrastructure systems. A key challenge in seeking to enhance the resilience of multi-infrastructure systems in practice relates to the fact that many interdependencies may be unknown to the operators of these infrastructures.

How can we foster infrastructure resilience lacking complete knowledge of interdependencies? In addressing this question, we conceptualize the situation of a hypothetical infrastructure operator faced with incomplete knowledge of the interdependencies to which his infrastructure is exposed. Using a computer model which explicitly represents failure propagations and cascades within a multi-infrastructure system, we seek to identify robust investment strategies on the part of the operator to enhance infrastructure resilience.

Our results show that a strategy of constructing redundant interdependencies may be the most robust option for a financially constrained infrastructure operator. These results are specific to the infrastructure configuration tested. However, the developed model may be tailored to the conditions of real-world infrastructure operators faced with a similar dilemma, ultimately helping to foster resilient infrastructures in an uncertain world.

**Keywords:** Interdependencies, Resilience, Networks, Electricity Infrastructures, Incomplete Knowledge, Modeling and Simulation

## INTRODUCTION

Hurricane Sandy, which struck the Northeast coast of the U.S. on 29 October, 2012, was the second costliest Atlantic hurricane in history and the largest Atlantic hurricane ever<sup>1</sup>. The infrastructure impacts of Hurricane Sandy were immense — 8.7 million customers lost power; 25% of customers lost mobile, landline, Internet and cable television service; New York City's subway services were completely shut down; and multiple oil and gas refineries/pipelines were disabled<sup>2</sup>. These impacts were not only a direct consequence of meteorological conditions. They were also a result of the (inter)dependencies between infrastructures, which allowed failures to cascade from one infrastructure to another — e.g. from the electricity infrastructure to the gas and oil infrastructures, and from the gas and oil infrastructures to the road infrastructure — as well as beyond the geographical scope of the hurricane itself.

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1 NOAA. NOAA's National Weather Service Newport/Morehead City, NC event summaries / case studies. Web site, October 2012. URL <http://www.erh.noaa.gov/mhx/EventReviews/20121029/20121029.php>. Accessed May 2014.

2 Comes, T. and van de Walle, B. Measuring disaster resilience: The impact of Hurricane Sandy on critical infrastructure systems. In *Proceedings of the 11th International ISCRAM Conference*, 2014.

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Due to the many (inter)dependencies between different types of infrastructures and the potential for disruptions to cascade between infrastructures, it is of limited use to assess the resilience of different infrastructures independently. Often, it is more productive to view infrastructures as *multi-infrastructure systems* – interacting networks of infrastructure components featuring various (types of) dependencies. However, a key challenge in seeking to enhance the resilience of multi-infrastructure systems in practice relates to the fact that many interdependencies may be unknown to the actors responsible for operating and safeguarding these infrastructures<sup>3</sup>. Part of this challenge may be attributed to the organizationally fragmented nature of multi-infrastructure systems, which limits the control and knowledge of individual actors<sup>4</sup>.

Actions by infrastructure operators to identify and catalogue infrastructure interdependencies can be an important step to enhancing resilience. However, complete knowledge of infrastructure interdependencies is an elusive goal, as interdependencies are inherently “dynamic and situational”<sup>5</sup>. Infrastructures are constantly changing and co-evolving<sup>6</sup>, meaning that new (hard and soft) interdependencies may continuously arise. Moreover, precisely what constitutes an interdependency may depend on the situation. These realities limit our capacity to develop accurate models of multi-infrastructure systems, thus restricting our ability to effectively foster resilient infrastructures.

*How can we foster infrastructure resilience lacking precise knowledge of interdependencies?* In addressing this question, we conceptualize the situation of a hypothetical operator of an electricity network faced with incomplete knowledge of the interdependencies between his infrastructure and other infrastructures. Using a computer model which explicitly represents failure propagations and cascades within a multi-infrastructure system, we explore the effectiveness of different investment strategies on the part of the infrastructure operator to enhance the resilience of his infrastructure.

## BACKGROUND – MODELING INTERDEPENDENT INFRASTRUCTURES

Due both to the socio-technical complexity of multi-infrastructure systems and the impracticality of experimenting with massive infrastructure failures in the real world, modeling and simulation can play an important role in helping to untangle the potential consequences of disruptions in multi-infrastructure systems. Ouyang<sup>7</sup> differentiates between four different approaches within this body of work – empirical approaches, agent-based approaches, system dynamics approaches and network-based approaches. *Network-based approaches* normally involve the representation of infrastructure components as nodes and the links or interdependencies between them as edges. An example of this type of analysis is introduced by Lam et al.<sup>8</sup>, who use a systematic set of experiments to identify critical nodes in a generic multi-infrastructure network based on the giant component size.

The model introduced in this paper follows a network-based approach. However, rather than assuming complete knowledge of the multi-infrastructure network, we test different strategies for dealing with the problem of incomplete network knowledge. This problem has also been addressed by Tai, et al.<sup>9</sup>, who suggests that, rather than seeking to determine the effects of possible failures in a network, we should solve the inverse problem – to identify those networks that may result in “the most extreme disruptions”. These networks may then be used to identify scenarios in the real world that could potentially lead to the realization of such disruptions<sup>9</sup>.

We adopt a different approach. We begin by conceptualizing the situation of a boundedly rational operator of a hypothetical electricity infrastructure. We assume that this operator lacks complete knowledge of the interdependencies between his infrastructure and a connected infrastructure, over which he has no control.

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3 Robert, B. and Morabito, L. An approach to identifying geographic interdependencies among critical infrastructures. *International Journal of Critical Infrastructures*, 6(1):17–30, 2010.

4 De Bruijne, M. and van Eten, M. Systems that should have failed: Critical infrastructure protection in an institutionally fragmented environment. *Journal of Contingencies and Crisis Management*, 15(1):18–29, 2007.

5 U.S. DOE. Overview of response to Hurricane Sandy nor’easter and recommendations for improvement. Technical report, February 2013.

6 Nikolic, I. *Co-evolutionary Method for Modeling Large-scale Socio-technical Systems Evolution*. PhD thesis, TU Delft, 2009.

7 Ouyang, M. Review on modeling and simulation of interdependent critical infrastructure systems. *Reliability Engineering & System Safety*, 121:4360, 2014.

8 Lam, C.Y., Lin, J., Sim, M.S. and Tai, K. C. Y. Identifying vulnerabilities in critical infrastructures by network analysis. *International Journal of Critical Infrastructures*, 9:190–210, 2013.

9 Tai, K., Kizhakkedath, A., Lin, J., Tiong, R. and Sim, M. Identifying extreme risks in critical infrastructure interdependencies. In *International Symposium for Next Generation Infrastructure*, 2013.

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Additionally, we assume that the operator faces significant uncertainty concerning the severity and frequency of future disruptive events to which his infrastructure may be exposed. Given the massive uncertainties surrounding looming threats such as climate change and (cyber-)terrorism, this is a very real challenge facing today's infrastructure operators.

Starting from this basis, we ask the following question: *How should an infrastructure operator ideally invest to ensure a resilient network in the face of these uncertainties?* In addressing this question, we draw from Lempert, et al<sup>10</sup>, who suggest that, in dealing with such situations, decision makers should not seek optimal strategies but rather robust strategies – “strategies that that perform ‘well enough’ by meeting or exceeding selected criteria across a broad range of plausible futures”. With this in mind, we place our hypothetical infrastructure operator in a simulated environment consisting of a (known) electricity network and an (unknown) interdependent second network, both of which may be subjected to a range of disturbances. We assign the operator four possible strategies for enhancing the resilience of his electricity network, and examine how these strategies perform under different conditions.

## MODEL DESIGN

The starting point for the model is a network representation of a generic electricity infrastructure (infrastructure A). The setup of infrastructure A is based on the *IEEE 118 bus power system test case*<sup>11</sup>, which represents an archetypal electricity transmission infrastructure. Infrastructure A includes three types of nodes – representing electrical substations, power generation facilities and power consuming facilities, or loads – and one type of link – representing power lines or electrical transformers. Infrastructure A is augmented with links to a second infrastructure network of a different unspecified type (infrastructure B). Infrastructure B could be conceptualized to represent a road infrastructure, natural gas infrastructure, IT infrastructure, etc. Infrastructure B is composed of a set of randomly connected nodes and edges, and features only a single type of node and a single type of edge. Infrastructures A and B feature a number of common links in the form of interdependencies. For the sake of simplicity, we assume that all of these interdependencies are bi-directional – that is, each represents a dependency of infrastructure A on infrastructure B and vice versa.

Each run of the simulation consists of 100 timesteps, each representing a timespan of one year. Every timestep during the course of a simulation, we introduce a set of failures, which correspond to the disabling of a set of links in the multi-infrastructure network. It is assumed that all of the failures within a given year occur simultaneously – that is, each year a single set of concurrent failures occur. These failures may affect links of infrastructure A or infrastructure B, or the interdependencies between them. The number of failures occurring each timestep is randomly determined according to a power law size-frequency distribution. Approximate power law size-frequency distributions are typical of many types of natural disasters<sup>12</sup>, as well as electricity blackouts<sup>13</sup>. Precisely which links are affected by a failure is randomly determined, and all links are returned to working order at the start of the next timestep.

The failure of a single link may affect not only that link, but may also result in a cascade of failures through the multi-infrastructure network. Failure cascades through the electricity network (infrastructure A) are determined by an iterative power flow algorithm. Following a set of initial failures, the algorithm calculates anticipated power flows through the network. If the calculated power flow across any line exceeds its capacity, the line is assumed to fail due to overload. This results in an altered distribution of power flows, which may cause additional lines to fail. This process is repeated until no more power lines are overloaded. Failure cascades in infrastructure B are determined in a simpler manner – if a link fails, there is a 10% chance that each of its neighboring links will fail that timestep.

Via interdependency links, failure cascades may cross from infrastructure A to infrastructure B, and vice versa. Each time a failure cascades from one infrastructure to the other, it induces (a) failure(s) in the latter. This may cause the failure to cascade (via another route) back to the first infrastructure, and so on. In this manner, we represent not only the propagation of failures within a particular infrastructure, but also the potential for first, second, third and higher order interdependency effects.

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10 Lempert, R., Popper, S. and Bankes, S. Shaping the next one hundred years: New methods for quantitative, long-term policy analysis. Technical report, RAND Pardee Center, 2003.

11 Christie, R. Power systems test case archive. Web site, May 1993. URL [http://www.ee.washington.edu/research/pstca/pf118/pg\\_tca118bus.htm](http://www.ee.washington.edu/research/pstca/pf118/pg_tca118bus.htm). Accessed May 2014.

12 Barton, C. and Nishenko, S. Natural disasters - forecasting economic and life losses. Web site, 2013. URL <http://pubs.usgs.gov/fs/natural-disasters/>. Accessed November 2013.

13 Dobson, I. Carreras, B.A., Lynch, V.E. and Newman, D.E.. Complex systems analysis of series of blackouts: Cascading failure, critical points, and self-organization. *Chaos*, 17:1–13, 2007.

The model is implemented in the agent-based modeling platform *Netlogo*<sup>14</sup>, and uses the MATLAB-based power system simulation package *Matpower*<sup>15</sup>. Runtime communication between these pieces of software is enabled via a custom-developed Netlogo extension, the *MatpowerConnect* extension.

## REPRESENTATION OF INVESTMENT STRATEGIES

A hypothetical operator of infrastructure A seeks to ensure the infrastructure's resilience in the face of (unknown) future failures. However, the operator's task is complicated by several factors. First, he does not know exactly how severe future failure scenarios may be, so he does not know precisely how robust his network must be to withstand these failures. Second, the operator does not know where or how many interdependencies exist between his infrastructure (infrastructure A) and infrastructure B. Third, the operator has no control over and limited knowledge of infrastructure B – that is, he cannot influence the design of that network nor can he predict possible failures within it.

The operator of infrastructure A is given a set of four possible strategies to enhance the resilience of his electricity network. The strategies are as follows:

- **Focus on the critical links:** Each time a link of the electricity infrastructure fails due to capacity overload, the operator increases the link's capacity by the magnitude of the overload.
- **Focus on the interdependencies:** Each time an unknown interdependency is revealed (due to the failure of an interdependency link), the operator constructs a redundant interdependency link, essentially obviating the possibility for future failure of that link.
- **Pre-emptively increase capacities:** The operator increases the capacity of all power lines by 50% at the start of the simulation.
- **Combination:** Combination of strategies 1 and 2.

In addition to these four strategies, we include a null strategy (strategy 0), corresponding to no action on the part of the infrastructure operator. Each investment made by the infrastructure operator is assumed to entail a certain cost. The cost of one additional redundant interdependency link or power line is assumed to be 1 monetary unit. The cost of one unit of additional power line capacity is assumed to be 1 monetary unit, divided by the mean capacity of power lines in the system.

## EXPERIMENTS

We have carried out a set of 60 experiments with the developed model. The purpose of these experiments is to identify robust strategies for enhancing infrastructure resilience – strategies that perform sufficiently well across a range of possible futures. The performance of the different strategies is evaluated using two metrics – resilience and cost. *Resilience* is defined as the mean performance of infrastructure A across all timesteps of all simulations employing that particular strategy, with performance quantified in terms of the fraction of demand served – the mean fraction of power received by customers vs. that which was demanded. *Cost* is defined as the sum of all expenditures of the infrastructure operator in making upgrades to his network, again averaged across all simulations employing the respective strategy. In the course of experimentation, we vary the values of three key parameters: (1) the strategy employed by the infrastructure operator, (2) the number of interdependencies between the electricity infrastructure and the second infrastructure, and (3) the severity of failure scenarios.

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14 Wilensky, U.. Netlogo. Web site, 2012. URL <http://ccl.northwestern.edu/netlogo/>. Accessed February 2013.

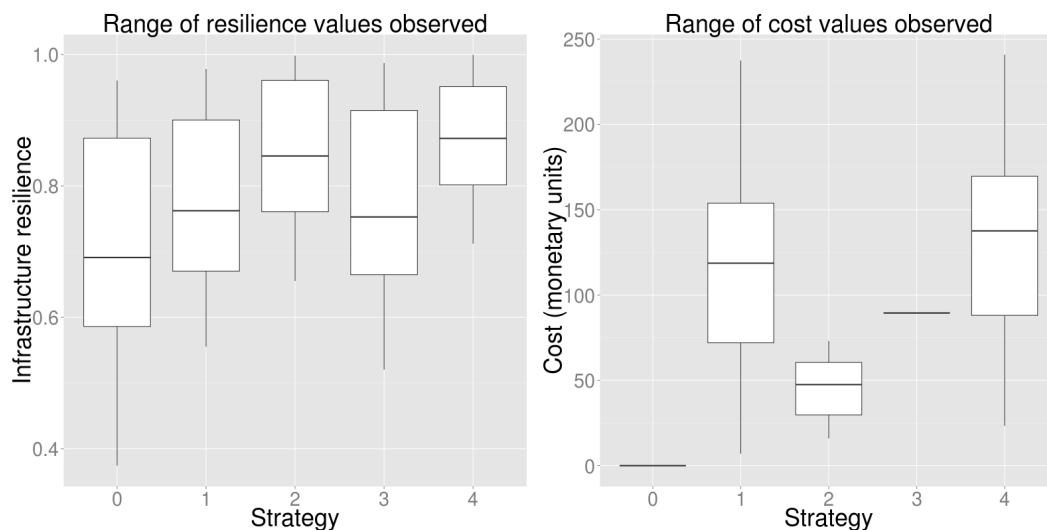
15 Zimmerman, R., Murillo-Sanchez, C., and Gan, D. Matpower: A MATLAB power system simulation package. Web site, 2011. URL <http://www.pserc.cornell.edu/matpower/>. Accessed February 2013.

## RESULTS AND ANALYSIS

Figure 1 illustrates key results from the developed model. These plots show the spread of observed resilience and cost values observed across each of the tested strategies. In terms of resilience, the top performing strategies are strategies 4 and 2, corresponding to mean resilience values of 0.87 and 0.85, respectively. Both of these strategies involve focusing on constructing redundant interdependency links between infrastructure A and B, suggesting that failure cascades between infrastructures A and B play an important role in affecting the performance of infrastructure A. It is important to note, however, that – under certain circumstances – a strategy of focusing exclusively on the construction of redundant interdependency links (strategy 2) can still result in relatively low resilience values – as low as 0.66. A strategy combining the construction of redundant interdependencies with the construction of additional capacity for the critical links of infrastructure A (strategy 4) has the effect of increasing the minimum observed resilience value from 0.66 to 0.71.

As illustrated in Figure 1, the best performing strategy in terms of cost (excluding strategy 0) is strategy 2, which corresponds to a mean investment of approximately 46 monetary units. On average, strategy 1 is significantly more expensive, featuring a mean investment of approximately 114 units. However, it is interesting to note that, under certain conditions, strategy 1 can result in lower costs than strategy 2 – as low as 7 monetary units. A closer look at the results reveals that these conditions occur only in situations with a very low severity of failure scenarios. Thus, if the infrastructure operator is relatively confident in the limited severity of future failure scenarios, this may be an attractive strategy.

Which strategy is most robust depends on the priorities of the infrastructure operator and which values for the different metrics may be considered “good enough”. If the operator prioritizes resilience and prefers minimum resilience values above 0.7, the most robust option would be to follow a strategy combining the construction of redundant interdependencies with the construction of additional capacity for the critical links of infrastructure A (strategy 4). If the operator seeks to minimize investment costs while still maintaining relatively high resilience values, the most robust option would be to follow strategy 2, and focus exclusively on constructing redundant interdependencies.



**Figure 1: Results of the developed model: box plots showing the range of observed resilience values (left pane) and cost values (right pane). The ends of the box indicate the 25th and 75th percentiles.**

## CONCLUSIONS

Uncertainty concerning both the locations/types of infrastructure interdependencies and the severity/frequency of future failure scenarios are very real problems faced by today's infrastructure operators. In this paper, we have introduced a model exploring different long-term strategies for an infrastructure operator to invest in light of these uncertainties. The results from the developed model show that a strategy focusing on the construction of redundant interdependencies may be the most robust option for a financially constrained infrastructure operator. It must be kept in mind that these results are specific to the infrastructure configuration tested and rely on a set of assumptions that may not hold in the real world. However, the approach used and the developed model may be useful insofar as they can be tailored to the specific conditions of real-world infrastructure operators faced with a similar dilemma. For instance, the generic network structures used in the current model can be replaced by real-world networks of different types (e.g. ICT, transport, water), and a broader array of investment strategies may be assessed. In this manner, the developed model can be a stepping stone towards fostering resilient infrastructures in an uncertain world.

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# Resilience of Hierarchical Critical Infrastructure Networks

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## ABSTRACT

Concern over the resilience of critical infrastructure networks has increased dramatically over the last decade due to a number of well documented failures and the significant disruption associated with these. This has led to a large body of research that has adopted graph-theoretic based analysis in order to try and improve our understanding of infrastructure network resilience. Many studies have asserted that infrastructure networks possess a scale-free topology which is robust to random failures but sensitive to targeted attacks at highly connected hubs. However, many studies have ignored that many networks in addition to their topological connectivity may be organised either logically or spatially in a hierarchical system which may significantly change their response to perturbations. In this paper we explore if hierarchical network models exhibit significantly different higher-order topological characteristics compared to other network structures and how this impacts on their resilience to a number of different failure types. This is achieved by investigating a suite of synthetic networks as well as a suite of 'real world' spatial infrastructure networks.

**Keywords:** Critical Infrastructures, Hierarchical Networks, Infrastructure Resilience

## INTRODUCTION

The well documented failures of infrastructure systems, such as large scale electricity blackouts across Europe and the US in 2003, along with more recent extreme weather and cyber-attack disruption, has driven significant interest in gaining a better understanding of how different types of infrastructure network responded to a range of perturbations. To this end a wealth of research has investigated the resilience of infrastructure networks using graph-theory, where graph metrics (e.g., node degree, average path length, betweenness etc.) have been used to quantify the resilience of infrastructure networks with respect to theoretical graph-models (e.g., random, small-world and scale-free)<sup>1</sup>. In many cases, results have suggested that infrastructure networks exhibit a scale-free structure which is robust to random failures but much more vulnerable to targeted attacks.

However, such studies have often just investigated an individual type of infrastructure system and often only a single network instance within this. This has the potential limitation that the spectrum of infrastructure network topologies may be insufficiently analysed and understood. In particular, it is now recognised that a number of infrastructure networks may be organised logically and/or spatially over multiple levels forming a potential family of hierarchical networks that may exhibit a different behaviour/response to perturbations<sup>2</sup>. In this work we present the results of

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1 Albert, R. and Barabasi, A.-L. (2002) 'Statistical mechanics of complex networks', *Reviews of Modern Physics*, 74, pp. 47-97.

2 Svendsen, N.K. and Wolthusen, S.D. (2007) 'Analysis and Statistical Properties of Critical Infrastructure Interdependency Multiflow Models', *IEEE Workshop on Information Assurance*. pp. 247-254.

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a comprehensive analysis of the resilience of infrastructure networks to different forms of failure. On the basis of a detailed analysis of a synthetically generated suite of network models along with a subsequent analysis of real world infrastructure network systems, we show that a number of infrastructure systems exhibit a clear hierarchical organisation which results in a notably different response to failures compared to the established scale-free model.

## INFRASTRUCTURE NETWORK MODEL SUITES

In order to provide a theoretical baseline and comparison for this study a suite of synthetic networks was created. This comprised of a number of common graph models to create a full spectrum of networks; from those with a random topology through to those with a hierarchical organisation. Network models were generated for random (Erdos-Renyi and GNM)<sup>3</sup>, scale-free<sup>4</sup>, small-world<sup>5</sup> and hierarchical community<sup>6,7</sup> models. These were augmented with a tree model and two modified hierarchical models (hierarchical-random and hierarchical-random+) developed during this study. For six of the graph families, where there is a parameterised exponent to the model, 1,000 realisations with a maximum of 2,000 nodes were created for each. In the case of the tree and hierarchical community models only 45 and 9 realisations were generated respectively due to the rigid structure of these.

Spatial networks for different critical infrastructure sectors (energy, transport, water, telecommunications etc.) were compiled from a variety of sources including the UK ITRC (Infrastructure Transitions Research Consortium) database<sup>8</sup>, Ordnance Survey UK products and Open Street Map data. In total 31 different networks were constructed (6 air route networks, 2 energy networks, 13 rail networks, 5 road networks, 4 river networks and 1 communication network) ranging in scale from national through to local spatial infrastructure systems. In order to create valid topological and spatial network models, the data-sets describing node and edge assets were processed and networks built using a suite of open source network processing software built around the Networkx package<sup>9</sup>.

## METRIC ANALYSIS AND FAILURE MODELLING

In order to compare the synthetic network models and also the real infrastructure network models a graph-metric analysis was undertaken. In our work we have employed two key metrics to characterise the structure of the topology of a network under investigation; maximum betweenness centrality and the assortativity coefficient. Maximum betweenness centrality characterises the propensity of a network to be able to efficiently carry a load or flow via its topological structure, while the assortativity coefficient is essentially a measure of how correlated overall the degree of nodes are with respect to their topological neighbours. Both measures were selected due to their ability to characterise high-order topological characteristics of a network compared to traditional measures such as degree distribution and average path length<sup>10,11</sup>. In order to statistically evaluate the resulting metrics in terms of whether they are different for different types of synthetic and real world networks a transformed divergence analysis was undertaken.

In addition to the graph-metric analysis, both the synthetic and real infrastructure networks were subjected to failure modelling. The implemented failure models remove a chosen node at each epoch, along with their corresponding edges. This process continues iteratively until all nodes are removed from the network (at any epoch nodes that become isolated due the removal of another node are also removed). Three approaches were used for the node

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3 Erdos, P. and Renyi, A. (1959) 'On random graphs I.', *Publ. Math. Debrecen*, 6, pp. 290-297.

4 Barabasi, A.-L. and Albert, R. (1999) 'Emergence of Scaling in Random Networks', *Science*, 286, pp. 509-512.

5 Watts, D.J. and Strogatz, S.H. (1998) 'Collective dynamics of 'small-world' networks.', *Nature*, 393, pp. 440-2.

6 Ravasz, E., Somera, A.L., Mongru, D.A., Oltvai, Z.N. and Barabasi, A.-L. (2002) 'Hierarchical organization of modularity in metabolic networks.', *Science (New York, N.Y.)*, 297, pp. 1551-5.

7 Ravasz, E. and Barabasi, A.-L. (2003) 'Hierarchical organization in complex networks', *Physical Review E*, 67.

8 Barr, S.L., Alderson, D., Robson, C., Otto, A., Hall, J., Thacker, S. and Pant, R. (2013) 'A National Scale Infrastructure Database and Modelling Environment for the UK', *International Symposium for Next Generation Infrastructure*. Wollongong, New South Wales, Australia.

9 Ibid.

10 Albert, R. and Barabasi, A.-L. (2002) 'Statistical mechanics of complex networks', *Reviews of Modern Physics*, 74, pp. 47-97.

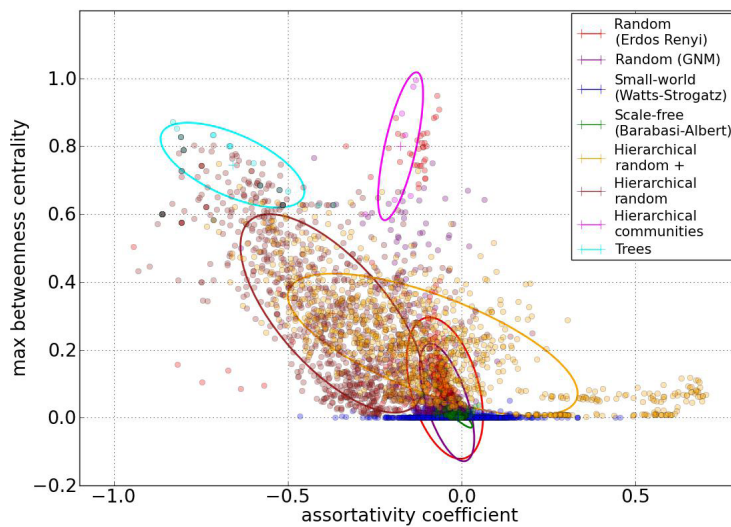
11 Newman, M.E.J. (2003) 'The Structure and function of complex networks', *Physics*, p. 58.

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selection; (i) random, (ii) targeted by maximum node degree and (iii) targeted by maximum node betweenness<sup>12,13</sup>. At each epoch graph metrics on the number and average size of components, size of the largest component, and the average path length were calculated to capture the behaviour of the network during failure modelling. This allows comparisons to be made in how a network fragments and the performance changes as the number of nodes removed increases. For the synthetic network models 100 from each 1,000 realisations (where possible) were randomly analysed.

## RESULTS

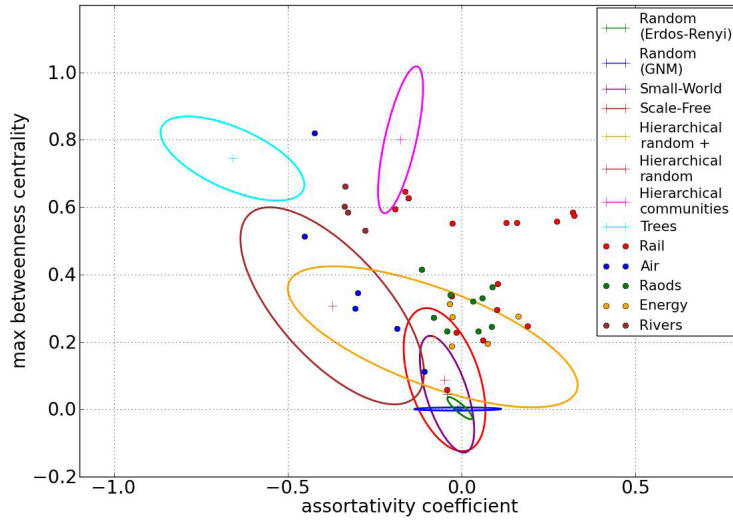
Figure 1 shows the calculated metric values of maximum betweenness centrality and assortativity coefficient for all the realisations of the eight different types of synthetic network model investigated, along with their corresponding standard deviational ellipses. Noticeable overlap occurs between the traditional network models employed in infrastructure analysis (random, small-world and scale-free) while the family of hierarchical models seem to exhibit a distinctly different structure in terms of these metrics. The average transformed divergence from the hierarchical communities and tree model compared to the 4 non-hierarchical models (two random, scale-free and small-world) was 99.28, contrasting with intra hierarchical and intra non-hierarchical values of 83.2 and 84.9 respectively. In the case of the actual infrastructure networks investigated, a number of these were found to exhibit similar characteristics to the synthetic hierarchical models, as illustrated in Figure 2. The plot shows that two air networks (routes for the USA and British Airways), the four UK river networks (Tyne, Eden, Dee and Severn) and three rail networks (Tyne and Wear metro, rail for Greater London and the Paris RER) returned metric values with a strong association to the hierarchical synthetic networks. These all lie in closer proximity to the ellipse and the mean centres of hierarchical models than non-hierarchical models, suggesting a hierarchical organisation similar to the model in question.



**Figure 1: Metric values for the synthetic networks along with mean and single standard deviation ellipse of each model.**

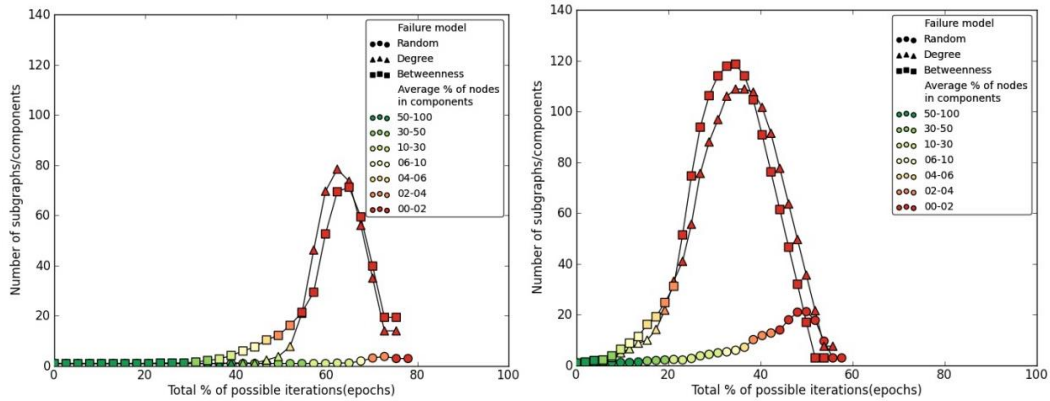
<sup>12</sup> Ibid.

<sup>13</sup> Dueñas-Osorio, L.A., Craig, J.I., Goodno, B.J. and Bostrom, A. (2007) 'Interdependent Responce of Networked Systems', *Journal of Infrastructure Systems*, 13, pp. 185-194.



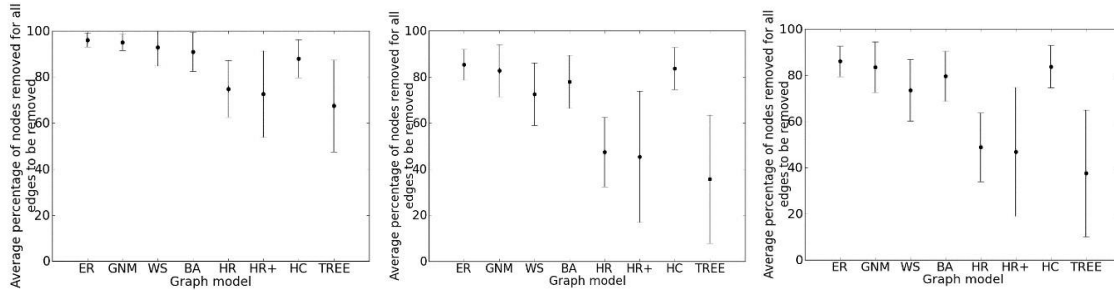
**Figure 2: Metric values for the infrastructure networks along with the synthetic standard deviation ellipses.**

Failure analysis focused on comparing the failure characteristics of the synthetic non-hierarchical networks with that of the synthetic hierarchal networks, and then an analysis of the failure characteristics of the real infrastructure networks that may be hierarchal. Figure 3 shows the model results for two synthetic network models; a scale-free model and a hierarchical model (a hierarchical random+ network). It is clear that the hierarchical model shows a more dramatic response to the three failure types both in terms of when the network becomes disconnected and also in terms of the number of separate components and their respective size. It is also evident that overall the hierarchical network fails quicker, with less than 60% of the total number of potential epochs required compared to nearly 80% for the scale-free network. This indicates that the hierarchal network is less resilient to all types of perturbation.



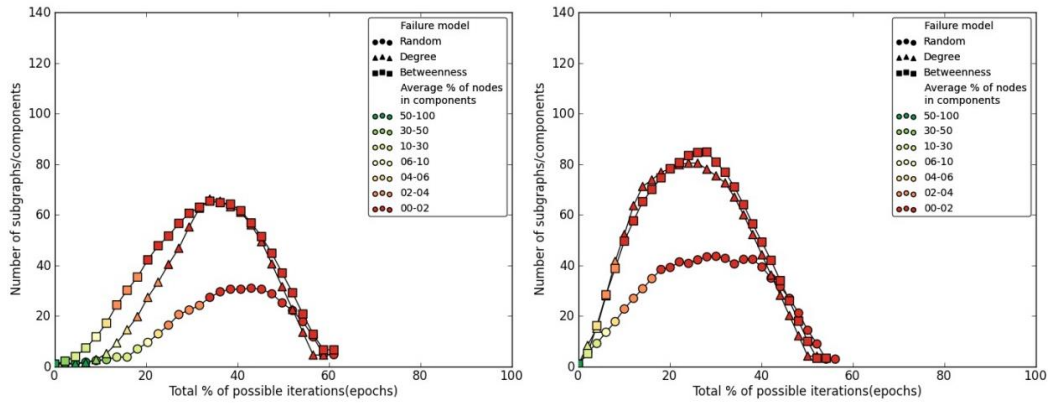
**Figure 3: Response of a scale-free network (left) and a hierarchical network (right) to all three failure models.**

Results similar to Figure 3 were consistently found across the range of synthetic network models investigated (Figure 4), with three of the hierarchical models being consistently less resilient to the three failure models with, for the two targeted failure models, complete failure occurring at around 40% of the total number of possible epochs for the tree model, and 50% for the HR and HR+ models. In the case of the random failure model the hierarchical response is around 15-20% better compared to the targeted models.



**Figure 4: The average and standard deviation of the percentage of nodes that needed to be removed for the total failure of each synthetic network model for the three failure models; random(left), degree(centre) and betweenness(right).**

Figure 5 shows the response of applying the failure models to the road network for the Tyne and Wear region of the UK (around Newcastle-upon-Tyne) which was indicative of a scale-free network and the rail network for Greater London which exhibited a hierarchical structure in terms of the metrics. The hierarchical rail network is noticeably less resilient to all forms of failure compared to the scale-free road network. While both show a relatively high-sensitivity to the targeted attacks (degree and maximum betweenness), the rail network also shows a noticeable sensitivity to random attack. Indeed, for even a relatively small number of epochs the hierarchical rail network shows a dramatic level of fragmentation with the number of components at 10 epochs ranging between 20-55 compared to 5-8 for the scale-free road network. Similar results were found for the other infrastructure networks that exhibited a hierarchical structure, with the average response to the failure models around 10% worse in terms of the number of nodes required to generate a null graph in terms of the network edges removed (Table 1).



**Figure 5: Response to the failure models of (left) road network for the Tyne and Wear region and (right) rail for Greater London.**

**Table 1: Failure comparison of the hierarchical infrastructure networks and the non-hierarchical.**

	Average percentage of nodes removed for network to fail and the standard deviation ( $\sigma$ )		
Network	Random	Degree	Betweenness
Hierarchical infrastructures (as found through the metrics)	58.5 (10.7)	41.6 (13.2)	42.7 (13.3)
Non-hierarchical infrastructures	66.2 (6.7)	51.4 (7.5)	52.0 (7.2)

## CONCLUSION

Through the use of a suite of synthetic networks and critical spatial infrastructures this research has shown that networks with a hierarchical organisation exhibit a greater vulnerability to failures when compared to non-hierarchical models (including the scale-free model), with a number of infrastructure networks shown to share this organisation and the associated failure characteristics. Networks with a hierarchical organisation show a much greater rate of fragmentation with subgraphs forming at a quicker rate as well as becoming empty graphs much sooner during failure analysis. The greater vulnerability of those infrastructures which are hierarchically organised as shown in this work highlights that by understanding the underlying structure of networks we can begin to improve how we model their characteristics and behaviour. This can help to develop infrastructure networks with improved levels of resilience to perturbations through policies and management strategies which are founded on a greater level of understanding of network structure and behaviour.

# Modelling Interdependent Cascading Failures in Real World Complex Networks using a Functional Dependency Model

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## ABSTRACT

Infrastructure systems are becoming increasingly complex and interdependent. As a result our ability to predict the likelihood of large-scale failure of these systems has significantly diminished and the consequence of this is that we now have a greatly increased risk of devastating impacts to society.

Traditionally these systems have been analysed using physically-based models. However, this approach can only provide information for a specific network and is limited by the number of scenarios that can be tested. In an attempt to overcome this shortcoming, many studies have used network graph theory to provide an alternative analysis approach. This approach has tended to consider infrastructure systems in isolation, but has recently considered the analysis of interdependent networks through combination with percolation theory. However, these studies have focused on the analysis of synthetic networks and tend to only consider the topology of the system.

In this paper we develop a new analysis approach, based upon network theory, but accounting for the hierarchical structure and functional dependency observed in real world infrastructure networks. We apply this method to two real world networks, to show that it can be used to quantify the impact that failures within an electricity network have upon a dependent water network.

**Keywords:** Resilience, Interdependency, Network Graph Theory, Hazard

## MODELLING INTERDEPENDENT INFRASTRUCTURE SYSTEMS

Network theory is an area of graph theory that concerns the study of graphs, which are mathematical structures used to model relationships between discrete objects. In this context a 'graph', or network, consists of nodes and connecting edges. The study of networks is a relatively young area of research and has been largely driven by the desire to study real world networks, such as social and biological networks. One of the main contributions of this area of research is the discovery and classification of underlying patterns in many real world networks. There are four main classes of network, into which the many real world networks (including infrastructure systems) can be placed. Each of these classes are distinguished by a degree distribution, where the degree of a node is the number of connections it has with other nodes and the degree distribution of a network is the probability distribution of these degrees for the whole network.

The first documented network class was the random graph<sup>1</sup>, which has since been shown to be a poor

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<sup>1</sup> Erdos, P. & Renyi, A. On The Evolution of Random Graphs. *Publication of the Mathematical Institute of the Hungarian Academy of Sciences* **5**, 17-61 (1960).

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representation of real world networks. However, this network class formed the basis for the small-world network class, developed by Watts and Strogatz<sup>2</sup>, which has been shown to replicate a range of real world networks including subway systems<sup>3</sup>. These two classes of network are characterised by a Poisson degree distribution; however, Barabasi and Albert discovered that real world networks tend to form a power law degree distribution<sup>4</sup>. Networks that follow this power law are more commonly known as scale-free networks and include the Internet and the World-Wide-Web.<sup>5</sup> Other real world networks, including power grids, have been found to have an exponential degree distribution and are termed 'exponential networks'.<sup>6,7,8</sup>

The main advantage of classifying a real world network into a network class is that it gives an insight into the inherent hazard tolerance of a network. For example, infrastructure systems have been shown to fall into either the scale-free or exponential network class<sup>9,10</sup> and these networks consist of a small number of highly connected nodes and a large number of weakly connected nodes. As such they have been shown to be vulnerable to targeted attack, as this will tend to remove one of the highly connected nodes to cause the maximum disruption, and also resilient to random hazard, as this will tend to remove one of the many weakly connected components<sup>11</sup>.

In this paper, we are considering the hazard tolerance of two real world networks and whether we can use this approach to gain an insight into their resilience to different attack strategies. We have constructed a network model of both networks using data obtained from a real electricity distribution network and a real water network that is, in reality, connected to the electricity network. The electricity network consists of 883 nodes (representing the Grid Supply Points, Bulk Supply Points, Primary Substations and Distribution Substations) and 3039 connecting links; whilst the water network consists of 144 nodes (representing the Source Nodes, Pumping Stations, Water Treatment Works, Service Reservoirs and Demand Nodes) and 305 connecting links. For a detailed explanation of the process used to model real world networks using network graph theory, the reader is directed to Dunn et al.<sup>12</sup> The degree distributions for these two networks have been shown in Figure 1. From this figure, it can be seen that the water network clearly follows an exponential distribution (forming a straight line when the results are plotted on a log-linear axis). However, it is more difficult to classify the electricity network, as it does not appear to fit exactly into one network class. This is due to the presence of a large number of small degree nodes. As the water network can be classed as exponential, it should be resilient to random hazard and vulnerable to targeted attack. However, classifying these networks does not necessarily give an insight into the hazard tolerance of the water network when the electricity network is disrupted, as the dependent links between these networks are not considered. To establish this relationship, an additional analysis approach is needed.

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2 Watts, D. J. & Strogatz, S. H. Collective dynamics of 'small-world' networks. *Nature* **393**, 440-442 (1998).

3 Latora, V. & Marchiori, M. Is the Boston subway a small-world network? *Physica a-Statistical Mechanics and Its Applications* **314**, 109-113 (2002).

4 Barabasi, A. L. & Albert, R. Emergence of scaling in random networks. *Science* **286**, 509-512 (1999).

5 Barabasi, A. L., Albert, R. & Jeong, H. Scale-free characteristics of random networks: the topology of the World-Wide Web. *Physica A* **281**, 69-77 (2000).

6 Amaral, L. A. N., Scala, A., Barthélemy, M. & Stanley, H. E. Classes of small-world networks. *Proceedings of the National Academy of Sciences of the United States of America* **97**, 11149-11152 (2000).

7 Liu, J. Z. & Tang, Y. F. An exponential distribution network. *Chinese Physics* **14**, 643-645 (2005).

8 Wilkinson, S. M. & Henderson, N. A. in *14th World Conference on Earthquake Engineering* (Beijing, China, 2008).

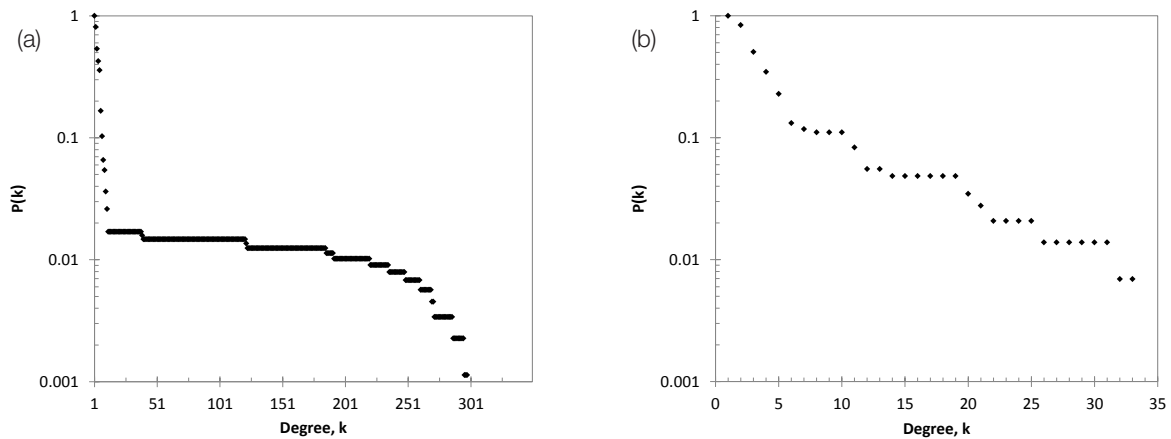
9 Crucitti, P., Latora, V. & Marchiori, M. A topological analysis of the Italian electric power grid. *Physica a-Statistical Mechanics and Its Applications* **338**, 92-97, doi:10.1016/j.physa.2004.02.029 (2004).

10 Wilkinson, S., Dunn, S. & Ma, S. The vulnerability of the European air traffic network to spatial hazards. *Natural Hazards* **60**, 1027-1036, doi:10.1007/s11069-011-9885-6 (2012).

11 Albert, R., Jeong, H. & Barabasi, A. L. Error and Attack Tolerance of Complex Networks. *Nature* **406**, 378-382 (2000).

12 Dunn, S., Fu, G., Wilkinson, S. & Dawson, R. Network theory for infrastructure systems modelling. *Proceedings of the ICE - Engineering Sustainability* **166**, 281-292 (2013).

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**Figure 1: The degree distributions for the (a) energy and (b) water networks.**

Previous studies have modelled the interdependency between two coupled networks by using additional links, which are usually directed, to represent the dependence of components in one network upon those in another. One study by Buldyrev et al.<sup>13</sup> assessed impact of failure within Internet infrastructure as a result of disruption to electricity infrastructure. In their study, they identified the dependent links between the two networks by coupling each Internet server to the geographically nearest power station. They then removed power stations, at random, and observed the resulting impact to the Internet network, following an iterative process to fail connected nodes. Nodes were deemed to have failed if (1) all of their connected nodes were failed and/or (2) their dependent node in the other network was failed. They showed that these networks were extremely sensitive to random failures and that the removal of a small fraction of nodes in one network was sufficient to produce an iterative cascade of failures in the interdependent network.

Further studies have attempted to identify a critical threshold (or proportion of failed nodes) which induces this cascade of failures in the dependent network, by combining network theory with percolation theory. One notable study by Gao et al.<sup>14</sup>, developed this approach and used it to study the failures between two partially interdependent random networks. In their study, they ‘fail’ a proportion of nodes in one network and observe how the failure propagates to the connected network, by defining two conditions for failure: (1) nodes fail if they do not belong to the largest cluster of nodes, and (2) nodes also fail if they depend on the failed nodes in the other network.

However, this percolation theory approach only considers the topology of the network and does not consider the direction of flow in these networks or their hierarchical structure. For example, in electricity infrastructure a Primary Substation can only operate if it is connected to, at least one, Bulk Supply Point and this is not captured in a purely topological model. Therefore, we develop a new approach which recognises that nodes are used to represent a range of components and that flow between these components is not always bi-directional.

## DEVELOPMENT OF FUNCTIONAL DEPENDENCY MODEL

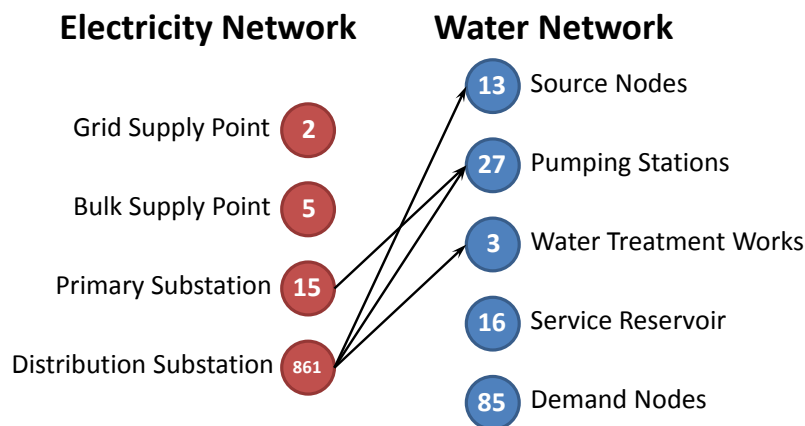
We develop what we term a ‘functional dependency’ model which incorporates the hierarchical structure of real world infrastructure networks and the direction of flow through the use of directed links. Following traditional network theory models, we use nodes to represent the different components in both networks, however, unlike traditional models we record the type of component that the node represents. Figure 2 shows the type, and number, of each component in both the electricity (red) and water (blue) networks.

By recording the different types of nodes we can ensure that the hierarchical structure, observed in real world networks, is maintained (e.g. electricity can flow from a Grid Supply Point to a Bulk Supply Point, but not vice versa). We could simulate the flow of service in these networks using a flow model, such as that presented by Dunn and

13 Buldyrev, S. V., Parshani, R., Paul, G., Stanley, H. E. & Havlin, S. Catastrophic cascade of failures in interdependent networks. *Nature* **464**, 1025-1028, doi:10.1038/nature08932 (2010).

14 Gao, J. X., Buldyrev, S. V., Stanley, H. E. & Havlin, S. Networks formed from interdependent networks. *Nat. Phys.* **8**, 40-48 (2012).

Wilkinson<sup>15</sup>; however, we deem a detailed study of flow and capacity outside the scope of this paper and therefore use the hierarchical structure to make an assumption regarding the capacity of each of the ‘supply’ components (e.g. Grid Supply Points and Service Reservoirs). The intention is not to replicate the extant network precisely, but rather to develop a plausible model that captures the essential failure characteristics of the real network.



**Figure 2: Showing the number of each individual component in the energy (red) and water (blue) networks and the interconnectivity of these components (black lines).**

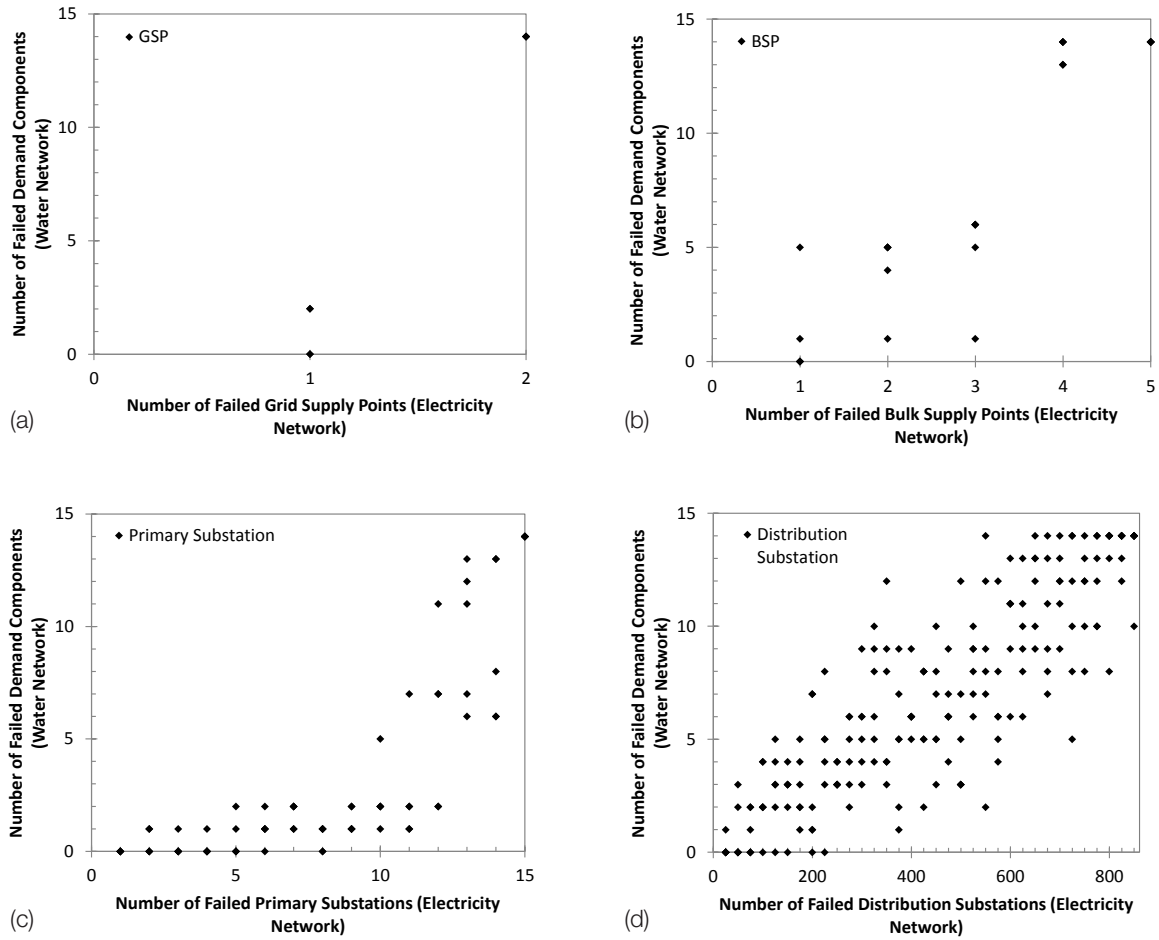
In the electricity network we achieve this by using Dijkstra’s algorithm to calculate the length, in terms of the number of nodes traversed, of the shortest route from each Distribution Substation to each Primary Substation. It is assumed that the closest Primary Substation supplies the Distribution Substation under normal operational conditions. Based on discussions with local experts, we also define the limit to the area a primary substation might supply in an emergency as 50% greater than its supply boundary in its typical configuration.

In the water network, the dependencies of the different components in the raw water sections of the network are easily understood, they take the shape of dendritic patterns feeding into the three water treatment works which then feed directly into service reservoirs. The downstream network requires more interpretation. In addition to the connectivity of the network, the ability of a service reservoir to feed a demand node is based upon their respective elevations. If the reservoir level was more than 20 metres above the highest property in the demand node then it can be supplied (the 20 meter difference accounts for the need to deliver a minimum level of pressure to a consumer’s property). It is assumed that pumping stations can provide a pressure equivalent to the level of the highest point they supply.

The identification of dependent links between the networks is simplified because, as major consumers, the water components generally have named substations. The proximal substation was used for the two components where this was not the case. Between these networks we identified 31 dependent links and the components they connect have been shown in Figure 2 (black arrows).

In a similar manner to previous studies, we randomly fail a proportion of nodes in the electricity network and observe how this failure propagates to the dependent water network, by defining two conditions of failure. Nodes in the water network are deemed to have failed if they are (1) no longer connected to at least one functional ‘parent’ node (e.g. a node that is directly above them in the hierarchical structure), or (2) are connected to a dependent node in the other network which has been failed. However, unlike previous studies, we observe how the failure of components at different levels in the electricity network impacts the water network. We initially fail a proportion of nodes of different components (termed *primary failure*) and observe how this failure cascades throughout the network (removing further nodes, termed *secondary failure*), before considering how this failure propagates to the water network. The results of this analysis are shown in Figure 3.

<sup>15</sup> Dunn, S. & Wilkinson, S. Identifying Critical Components in Infrastructure Networks Using Network Topology. *Journal of Infrastructure Systems* **19**, 157-165, doi:10.1061/(ASCE)IS.1943-555X.0000120 (2013).



**Figure 3: Showing the number of failed demand nodes in the water network, due to the failure of (a) the grid supply points, (b) bulk supply points, (c) primary substations and (d) distribution substations in the electricity network.**

From Figure 3, it can be seen that the removal of different components in the electricity network have different impacts upon the water network. This is expected; removing a distribution substation is unlikely to affect other nodes but the effect of a lost bulk supply point will cascade through the system. However, it is interesting to note the different patterns of impacts caused by the failures at different levels in the hierarchy. For example, it can be seen that the correlation between primary substations failures and failed demand components is non-linear, and appears to increase exponentially (Figure 3(c)). By contrast the correlation between the number of failed distribution substations and the number of demand components (Figure 3(d)) is linear, although there is a large amount of scatter in the results.

It is also evident that the complete failure of the electricity network (shown on the extreme right of the graphs in Figure 3) does not result in the complete failure of the water network. This is due to the presence of the service reservoirs (which do not require a supply of electricity to function) meaning that approximately 80% of the demand components network remain functional. It should be noted that we only perform a static analysis, and therefore do not capture the depletion of these resources; however, these components typically have sufficient capacity to last longer than the power companies' expected return to service time.

## CONCLUSIONS

In this paper we have presented a new approach to the analysis of interdependent failures between two coupled networks. Our approach is based upon traditional network theory, modelling the networks as a series of nodes and connecting links, but maintains the hierarchical structure of real world infrastructure networks and also makes an assumption of the supply capacity of each of the ‘supply’ nodes through the use of directed links. We have applied this approach to analyse two real world networks, an electricity network and a dependent water network, to assess how failures within the electricity network propagate to the water network. Through this analysis it was shown that the failure of different components in the electricity network can have vastly different impacts to the water network. This approach could be used in future studies to increase the validity of using network theory models to assess the impacts of cascading failures between two coupled networks.

## ACKNOWLEDGEMENTS

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# Designing a Solid Waste Infrastructure Management Model for Integration into a National Infrastructure System-of Systems

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<http://discovery.ucl.ac.uk/1469077/>

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## ABSTRACT

Solid waste management is arguably one of the most important municipal services provided by government<sup>1</sup>. Given the rapid socio-economic changes that are projected to take place in the UK<sup>2</sup> it is important that we plan our future waste management capacity to ensure the continuance of this valuable service. The Solid Waste Infrastructure Management System (SWIMS) model was designed to model the current solid waste infrastructure requirements (from collection through treatment and disposal) for an area based on its solid waste arisings. SWIMS allows an area's waste treatment capacity requirements to be forecast against future socio-economic change to help decision-makers choose the right solid waste infrastructure given their goals, constraints and ideas about future conditions. The modelling of solid waste management systems has been carried out since the 1970s<sup>3</sup> and such modelling exercises have been undertaken for numerous different geographical areas around the world<sup>4</sup>. However, the SWIMS model is unique in that it was designed to also operate within a larger national infrastructure system-of-systems model, including interdependencies with other infrastructure sectors including energy, water and waste water. To achieve such flexibility the SWIMS model was carefully designed using object-oriented programming (OOP) principles. In documenting this model's design methodology we hope to demonstrate how applying OOP principles enables such models to not only be more flexible and more easily integrated with other modelling efforts, but also more easily understood by system experts and end-users.

**Keywords:** Solid Waste Infrastructure Modelling, Object Oriented Programming, Model Design, Model Re-use

## INTRODUCTION

The SWIMS model was born out of the requirements of the Infrastructure Transitions Research Consortium (ITRC) national infrastructure system-of-systems modelling project<sup>5</sup>. The key aim of the ITRC project is to inform decisions regarding planning and investment in national infrastructure systems (i.e. Energy, Transport, Water, Waste, and

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2 ONS. "National population projections, 2010-based statistical bulletin", Office for National Statistics (2010).

3 Morrissey, A. J. & Browne, J. Waste management models and their application to sustainable waste management. Waste Management 24, 297-308, doi:<http://dx.doi.org/10.1016/j.wasman.2003.09.005> (2004).

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Information & Communications Technology) by evaluating the performance of national infrastructure strategies in providing infrastructure services under a wide range of future conditions. To achieve this aim the project required the development of a system-of-systems model, known as NISMOD-LP, which enabled the analysis of each of the individual systems, their interdependences and their performance in a wide range of possible future socio-economic and climatic scenarios and management strategies.

The SWIMS model was designed from the beginning to become the solid waste infrastructure component of this larger NISMOD-LP system-of-systems model<sup>1</sup>. SWIMS was also designed to operate as a stand-alone solid waste infrastructure modelling tool, enabling decision-makers from any area or country to analyse their future solid waste infrastructure capacity requirements.

In order to meet these dual aims the model had to meet several key requirements. Firstly, it had to be capable of modelling the capacity requirements of a given area, either autonomously or under instruction. Secondly, the system had to track the infrastructure capacity requirements of an area's waste streams through time from generation to collection, treatment and final disposal as either an exported waste, a new product or as landfilled waste. Thirdly, the system had to be able to model any area of any geographic scale made up of smaller modular areas. It could thus be made to represent a city, a county, or a state including all the regions within a state. Fourthly, the system had to be able to explore the many alternative ways in which waste can flow through the system and analyse the environmental and financial costs and benefits of these alternative options under a range of future conditions (scenarios). It must therefore be capable of providing information on the relative worth of alternative infrastructure strategies in achieving area-specific goals (such as maximising materials recovery or minimising costs), given a set of management constraints (such as EU Landfill Directive<sup>6</sup>), and given a host of possible future scenarios (such as demographic and economic changes). Finally, in order to function effectively as a component within a larger UK national infrastructure system-of-systems the SWIMS model needed to be open to manipulation by NISMOD-LP for the assessment of system-wide management strategies, and interdependencies with other infrastructure sectors (such as energy, transport and waste water). Thus, the SWIMS model needed to be capable of operating both as a stand-alone model of solid waste capacity management and as an integrated component within the NISMOD-LP system-of-systems.

## SYSTEM DESIGN

As a stand-alone modelling system, SWIMS model the flows of heterogeneous waste material streams (and their associated material properties) through a waste management system from the point of generation through collection, treatment and disposal based on the principle of mass balance. Potential environmental impacts associated with the management of these waste flows are quantified using Life Cycle Assessment with system expansion (to account for the recovery of materials and energy), whilst financial costs are calculated using Cost-Revenue Analysis. Figure 1 displays a high-level view of the main processes in the model by which the waste that is generated by various waste producer groups is collected, treated and disposed of by a 'waste manager' within the system.

Waste is generated in the model based on a Household Waste Function<sup>7</sup> that relates population and economic growth to arisings of waste types. This waste is then collected via a range of possible collection methods and converted into waste streams based on their means of collection (household kerbside collected residual waste, dry recyclables and organic wastes, etc). Each of these waste streams is treated and converted to either commercial products (energy, metals, and plastics) or another waste stream that is treated until the residual is sent for final disposal. A 'waste manager' agent manages this entire process using the available infrastructure and their costs and capacities to fulfil these waste management requirements within certain specific economic and environmental goals and constraints. The model also forecasts possible changes in demand and capacity utilisation under different socio-economic scenarios and makes decisions regarding new investment using a range of alternative management strategies. Such a system allows decision makers to test these alternative management strategies against future uncertainties allowing them to gain insights into the conditions and strategies that could lead to regional capacity shortfalls or where over-capacity can lead to the phenomena of stranded assets.

In order to best achieve the aims of this project, the SWIMS model was constructed based on real- world solid waste management components and processes through the application of object-oriented programming (OOP) principles.

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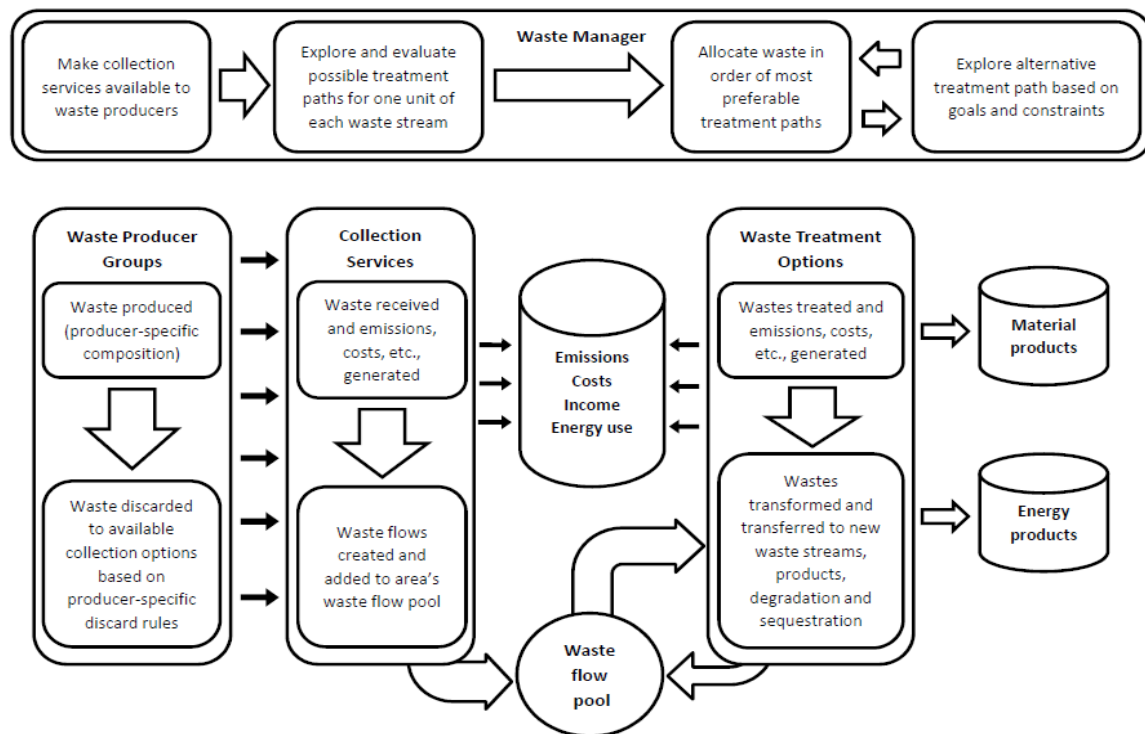
6 The Landfill Directive (Council Directive 1999/31/EC) <http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31999L0031>

7 Beigl, P., Lebersorger, S. & Salhofer, S. Modelling municipal solid waste generation: A review. *Waste Management* 28, 200-214, (2008).

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In simple terms, this meant that the model design contains objects based on the actual objects in the waste management system being modelled - those same processes and components that appear in the process map in Figure 1, such as waste collection decisions, incinerators and landfill sites.



**Figure 1: A process map outlining the management of the production, collection, treatment and disposal of waste**

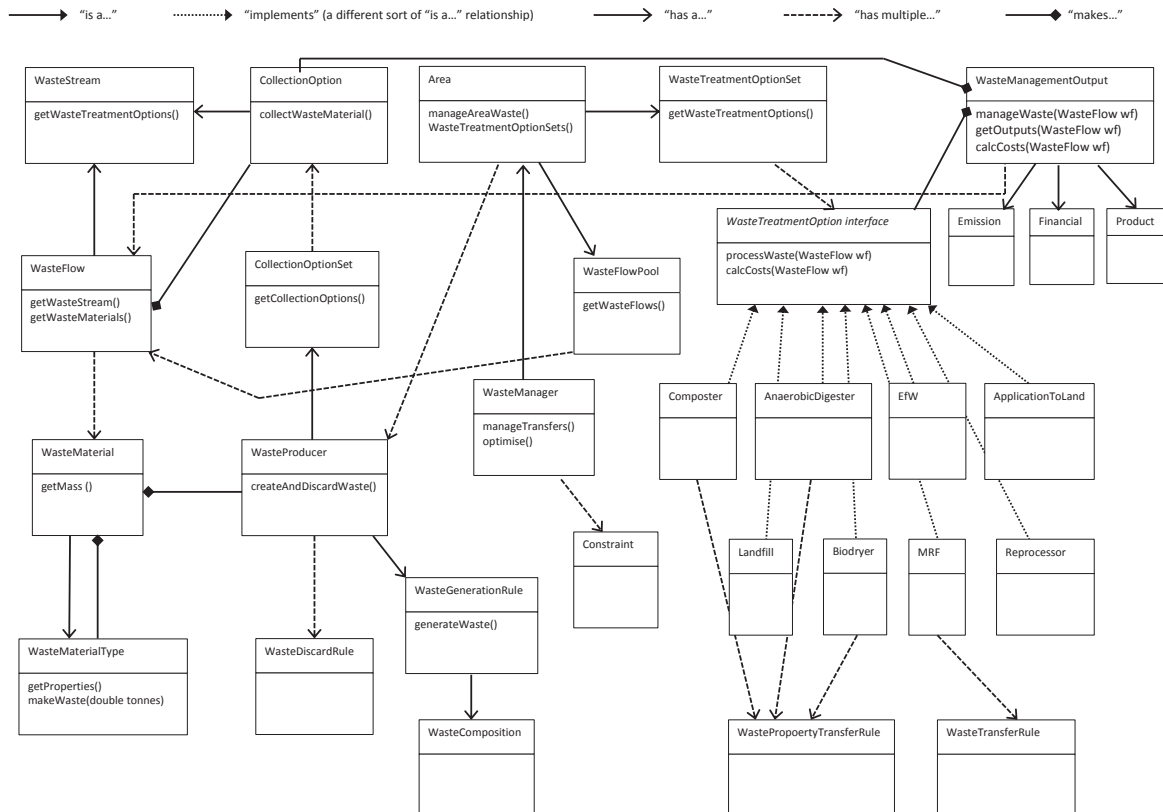
Designing the SWIMS system involved the application of the three key OOP principles of *abstraction*, *encapsulation* and *inheritance*. The concept of *abstraction* refers to the style of programming that uses objects and classes that are abstractions or representations of actual objects in the real world. An object can be a physical object, such as a tonne of waste or a landfill site, or it can be intangible, such as a management decision or the price of a commodity. A *class* is the set of rules that define an object. An object is therefore a particular instance of a class. For example, if we had a class that broadly defined all incinerators then each particular incinerator plant would be an object of the incinerator class.

As shown in the class diagram of the SWIMS model (Figure 2) the objects that make up the model are based on actual waste treatment process objects, such as Materials Recovery Facilities and Anaerobic Digesters, that have real world properties and perform functions (methods) such as processing waste and incurring costs. Although these objects only ever manipulate data within the model they still operate on this data using the same principles observed in their real world counterparts. Thus, the modelled system within SWIMS can mimic the functioning of its real-world equivalent using objects and processes that have a direct correlation to objects and processes in the real world.

*Encapsulation* is an OOP concept that describes a way of organising the many types of information and processes that help the individual objects to be used as efficiently and securely as possible. Encapsulation involves splitting an object up into its public interface - or what is needed to “drive” the object - and its private interface - or what makes the object work “under the hood”. For instance, to ensure that the NISMOD-LP system-of-systems model does not ‘break’ the inner workings or logic of the SWIMS model, only those methods and properties of the objects that are required by NISMOD-LP are exposed in the model’s interface.

Finally, object *inheritance* or generalisation is the process of organising the features of different types of objects that share the same purpose. For instance, the **WasteTreatmentOption** class shown in Figure 2 is a parent class from which a number of specialised child classes are derived, such as an **MFR** (Materials Recovery Facility) or an **AnaerobicDigester** class. The **WasteTreatmentOption** class contains properties such as *name* and *annualCapacity* and methods such as *processWaste* or *calcCosts* that would be common properties and methods for all child classes derived from this parent class. A derived **AnaerobicDigester** child class would therefore inherit all the **WasteTreatmentOption** class’s properties and methods as well as its own set of unique properties and

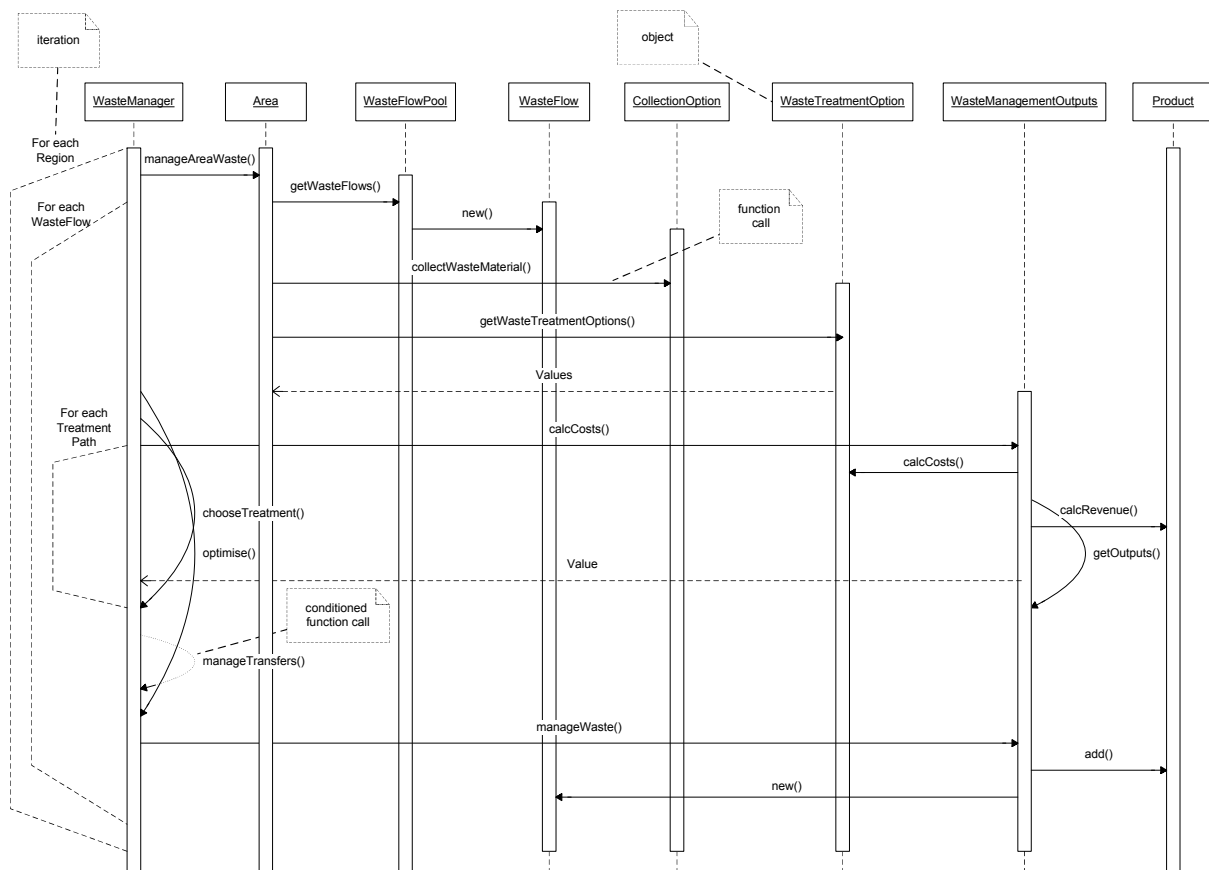
methods that are particular to the **AnaerobicDigester** class (such as *biogasProduction*).



**Figure 2: A class diagram for the SWIMS model. Note that to avoid unnecessary cluttering only a subset of the SWIMS model's objects, properties and methods are shown. Note that in order to avoid unnecessary clutter this class diagram does not contain all of the classes, attributes and methods present in the final design of the model.**

Object inheritance is one of the key reasons for using the OOP approach. Inheritance provides reusability and a mechanism for adding features to existing classes without the need extensive modifications to the model. This is achieved by deriving a child class from an existing parent class. The new child class then has the combined features of both the inherited interface (properties and methods) of the parent class as well as its own unique properties and methods. The child class can also operate using the codebase within the methods of the parent class or it can override these processes with its own codebase. This not only provides a way of ordering and organising objects, but more importantly allows methods that are common to each child class to be coded within the parent class. This reduces the amount of code that needs to be written, as well as the amount of code that must be debugged – an important time-saving benefit. It also allows for huge flexibility in examining alternative configurations of child objects that can be slotted in and out of the model as required, because other code components that interact with this class within the model can be confident that every child class has the same interface components of the parent class.

When designing such a system using OOP it is very important to understand how the various objects work together and how they will combine to run the necessary system processes. It is therefore necessary to map out the communication and functioning of the various model objects. A number of design methods are available for this task, including writing pseudo-code or building sequence diagrams. Figure 3 shows an example of a sequence diagram for the SWIMS system, showing the process of managing the waste flows that have been generated - including waste collection, treatment and disposal. Note that as waste disposal processes act in much the same way as other treatment options it has been included as a **WasteTreatmentOption**, similar to other intermediate treatment options, such as 'mechanical biological treatment' or 'windrow composting'.



**Figure 3: A sequence diagram showing the interaction between the various model classes involved in the process of treating a waste flows in the SWIMS model.**

The process of mapping out the classes and functions through a sequence class diagram, or an equivalent method, provides the designers with the information necessary to build an outlay of the classes required in the model. The classes designed for the SWIMS model (shown in Figure 2) were developed through an iterative process of hypothesising the necessary objects and then modelling their communications through sequence diagramming. This can be a laborious process, but one that should greatly increase the speed with which the model code can be written once the designs are completed.

## CONCLUSIONS

Building a system that is capable of modelling the management of an area's waste infrastructure is not a trivial task. Adding the ability to tightly integrate this model with a larger, more complex system-of-systems vastly increases the difficulty. Applying OOP design principles was integral to enabling the SWIMS modelling project to meet such demanding, multi-layered objectives. Through abstraction and encapsulation the same objects used to manage an area's waste are provided as objects for manipulation by the larger more complex system-of-systems. As the objects with the SWIMS model represent objects that exist in the real system their functions and attributes are more likely to reflect what the larger system needs in order to integrate it into its structure. By exposing objects, such as the **CollectionOption** object, alternative collection options can be examined for their financial or downstream implications. Allowing any child classes that have been derived from the **WasteTreatmentOptions** object to be dynamically interchanged allows the larger system to examine highly complex alternative management strategies, including those that might only be considered within the context of a larger system-of-system - such as comparing the benefits of reducing fossil fuel use by increasing energy from waste to alternative options for reducing the production of CO<sub>2</sub> within other infrastructure sectors such as energy and transport.

One obvious limitation of the SWIMS model is that it assumes that all future options and decision criteria have already been identified and thus the problem of solid waste management becomes a process of evaluation of

these limited set of alternatives<sup>8</sup>. This limitation exists for all such systems that attempt to model the management of future conditions. However, through its OOP design the inclusion of any future waste management advances into the SWIMS model is made easier as any such new option can be accommodated as child classes of the **WasteTreatmentOptions** parent class, thereby reducing the amount of code that needs to be written.

A key benefit of the OOP methodology that does not necessarily get enough recognition is its ability to facilitate communications between all parties involved in the design, development and application of the model. Building a model based on real world objects facilitates communication between all parties involved in the model development, allowing the model architects to talk to the domain knowledge experts and end-users with reference to objects and processes that are familiar to them. Clearer communications can result in a model that is much more likely to operate as expected and it facilitates the handover of the model, increasing its life and usability.

Many physical systems models are built as single-use models, particularly those used for smaller projects. This trend is partly a reflection of the fact that smaller projects tend to require models for only a very specific problem in a particular context<sup>9</sup>. However, in many cases models are built in a single-use format because the model developers do not have sufficient experience or training in such advanced software development methodologies. Although re-use was a requirement of this project it is our hope that this manuscript demonstrates how, through the application of object-oriented programming principles, physical system models can be built in such a way that not only makes them re-useable but also makes them easier to use. Given the advantages of the OOP methodology, it would be wise for those modelling physical systems to make the effort to learn how to apply this methodology, even if they do not have such complex, multi-layered requirements. OOP is a methodology that has been developed through decades of experience and it is for very good reasons that it is now standard within all mainstream software development languages.

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8 Morrissey, A. J. & Browne, J. Waste management models and their application to sustainable waste management. *Waste Management* 24, 297-308, doi:<http://dx.doi.org/10.1016/j.wasman.2003.09.005> (2004).

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# Infrastructure and the City



# I-11: Sustainable Supercorridor

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## ABSTRACT

Recently enacted Federal transportation legislation known as MAP-21 — Moving Ahead for Progress in the 21st Century — has brought renewed attention to a proposed interstate corridor connecting Las Vegas, Phoenix and Tucson, Arizona. Part of the much larger Interstate 11 proposal linking Mexico and Canada (otherwise known as the CANAMEX or Intermountain West Corridor), a new type of corridor has the potential to signal a break from the 1950s model of road building and the start of a new, technologically advanced and sustainably minded network of smart infrastructure. Using I-11 as a case study, the intent of this larger research effort is to explore three key ways otherwise status quo infrastructure can be transformed into innovative sustainable solutions: by intervening in the design and planning process, by transforming the existing mono-functional freeway prototype, and by evolving the freeway paradigm from an “engineering only” to a “sustainability first” model. In collaboration with partner schools along the route (University of Arizona, Arizona State University, and University of Nevada, Las Vegas), researchers and design affiliates from architecture, planning, landscape architecture, engineering, and environmental studies are co-investigating the possibilities of transforming the proposed I-11 freeway from a limited use, auto-dominant roadway into a sustainable, multi-functional, ecologically and socio-economically focused Supercorridor. This presentation will focus on seven sites selected between Casa Grande and Nogales, Arizona and the next generation infrastructure prototype design proposals developed in the 2014 interdisciplinary urban design studio.

**Keywords:** Supercorridor, Interdisciplinary, Grand Challenge, Interstate 11, Next Generation Infrastructure

## INTRODUCTION

Recently enacted Federal transportation legislation known as MAP-21 – Moving Ahead for Progress in the 21<sup>st</sup> Century – has brought renewed attention to a proposed interstate corridor connecting Las Vegas, Phoenix and Tucson, Arizona. Part of the much larger Interstate 11 proposal linking Mexico and Canada (otherwise known as the CANAMEX or Intermountain West Corridor), a new type of corridor has the potential to signal a break from the 1950s model of road building and the start of a new, technologically advanced and sustainably minded network of smart infrastructure. Using I-11 as a case study, the intent of this larger research effort is to explore three key ways otherwise status quo infrastructure can be transformed into innovative sustainable solutions: by intervening in the design and planning *process*, by transforming the existing mono-functional freeway *prototype*, and by evolving the freeway *paradigm* from an “engineering only” to a “sustainability first” model. In collaboration with partner schools along the route (University of Arizona, Arizona State University, and University of Nevada, Las Vegas), researchers and design affiliates from architecture, planning, landscape architecture, and engineering are co-investigating the possibilities of transforming the proposed I-11 freeway from a limited use, auto-dominant roadway into a sustainable, multi-functional, ecologically and socio-economically focused Supercorridor.

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What this Supercorridor concept means specifically and how this might happen, however, remain relatively uncharted territory for freeway projects and the agencies that design and build them. In light of the scope of the work, the first two research questions are in ongoing and are briefly summarized below; the third is the primary focus of our presentation and includes research and design proposals from our recently completed interdisciplinary urban design studio.

1. How to broaden the freeway design *process*. Though outside experts are often consulted in the alignment selection or road design impact assessment studies to mitigate community demands or satisfy environmental regulations, they are rarely if ever included in the conceptualization and inchoate development of the corridor itself. Inevitably, traffic management rather than human or environmental needs tends to dictate the shape and use of much of our landscape. The broadening of the process could either reflect the consideration of a broader range of amenities as part of the programming up front (multimodal transportation, water harvesting and distribution, renewable energy, data, animal habitats, public space and open space), or it could reflect a broadening of the process through the inclusion of a broader range of experts not typically included early in the freeway planning process (architects, landscape architects, urban designers, ecologists, hydrologists, renewable energy experts, sustainably-focused transportation researchers). Both have the potential to alter the infrastructural product through greater inclusivity and broader objectives.

The hypothesis of the research to date is that any intervention must happen at the very earliest stages of the planning process, beginning with a top down position (likely armed with a powerful planning document and a committed and charismatic project champion) that sets an agenda very different from those based on the singular, historical priority of autonomous vehicle efficiency. The motivation behind Interstate 11 is particularly interesting as it is driven not from traffic capacity needs but from a vested interest in increased economic development opportunities in the southwest region. In light of that, a multi-functional, technologically savvy agenda for the corridor which is developed collaboratively with energy, environmental, planning and design professionals as a way to introduce more innovative and symbiotic networks of use could transform both the economy and the identity of the region.

2. How to *transform the freeway prototype*. Virtually unchanged since the first modern-era freeways were constructed in the 1940s and 50s, current freeway design standards are focused nearly exclusively on traffic flow and traffic safety. Though roads are one of our single largest public investments, road innovation has advanced minimally in the last half century. “Failure to Act” studies published by the ASCE show a necessary investment of \$1.7 trillion towards surface infrastructure, \$736 billion towards electricity, and \$126 billion towards drinking water and wastewater to avoid economic penalties, reduction in standard of living, and loss of jobs.<sup>1</sup> With these large investment needs in mind, this research question assesses infrastructural bundling, the combining of multiple transportation and communication conduits in a shared right of way.

Bundling strategies, used informally for centuries in small, localized ways, became less prevalent with the modern era’s attraction to large-scale master planning and efficiency as a guiding metric. They are returning now, however, as fewer resources are available to solve more and more complex problems, particularly those resulting from climate change, risk, and population growth. Texas’s proposed \$175 billion Trans-Texas Corridor is the largest case to date. The 4,000 mile long, quarter-mile wide route proposed combining cars, trucks and trains with underground space for water, electric, gas, and oil lines. The advantages include long-term economic efficiency, streamlined procurement and construction processes, an overall reduced environmental footprint, and a dedicated long-range route to reduce localized traffic congestion. The disadvantages, though, are numerous, primarily the up-front costs, wide swath of land impacts, security vulnerabilities, and, in this case, resident outcry against tolls brought on by the public-private financing model.

Our evaluation indicates that one of the Trans-Texas Corridor’s critical faults was its model of infrastructural adjacency rather than infrastructural symbiosis. Lining up infrastructural needs, though potentially more efficient than not, takes vast amounts of space and does little to capitalize on their potential interactivity or provide new amenities. Alternatively, infrastructural symbiosis intentionally mimics an ecosystem by co-locating systems to shared advantage. This may be as integrated as waste products from one system providing fuel or heat for another (see NL Architects’ WOS8 transfer station), or as simple as designing multi-functionality into all components (such as transit structure supporting solar panels and serving as conduits for renewable energy distribution). Following the same ecological logic, a related strategy attempts to supplement the costs (both economic and environmental) of hard infrastructure

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<sup>1</sup> American Society for Civil Engineers (ASCE), Failure to Act Economic Studies: The Impact of Current Infrastructure Investment on America’s Economic Future, 2013. retrieved 2 October 2013 <http://www.asce.org/economicstudy/>.

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by substituting it in part for green infrastructure systems, allowing nature to take back over some of the functions we have for decades superseded with technology (water purification in particular).

Interstate 11 has the potential to incorporate renewable energy, water harvesting and distribution, and multi-modal transportation as well as added public amenities and concentrated land use planning. Its potential route traverses territory that has some of the highest capacity for renewable energy in the country. The potential to co-locate renewable energy production and water capture along with transit, freight and auto traffic is an unprecedented and environmentally-critical opportunity. Designing their relationships symbiotically means the supercorridor has the potential for a net-positive contribution.

3. How to *transform the infrastructure paradigm*. Bundled or not, freeways have significant impacts on surrounding land uses, local and regional environments, human and animal habitats, and issues of economics and equity. Interstate 11 runs the risk of exacerbating the decentralized, low-density development patterns typical of Tucson, Phoenix, and Las Vegas if built in the traditional form. Instead, this third question focuses on reconceptualizing infrastructure as the largest public space component of a twenty-first century networked city. An integrated, “design first” look at the supercorridor holistically considers transportation, housing, economic development, jobs, recreation, energy, water, food, and access as key integrated ecologies of project design and planning. At the nexus of architecture, landscape architecture, and urban design, infrastructure becomes the civic core of the twenty-first century sustainable city. Designing this infrastructural civic core was the objective of the spring 2014 interdisciplinary urban design studio.

#### IUDS14: I-11 SUSTAINABLE SUPERCORRIDOR DESIGN STUDIO

A corridor justification report on the I-11 for the Arizona and Nevada Departments of Transportation (ADOT and NDOT respectively) was completed in August of 2013. References in that report suggest that an enhanced corridor is possible and desirable both by government agencies and community stakeholders and that further study of the concept is supported and likely. From the report:

“There is considerable support for the study of a multi-functional Corridor that not only provides multimodal transportation opportunities but also houses assets that require similar rights-of-way. Utility (including transmission lines and telecommunications) and energy (including liquid/natural gas, fiber/dark fiber, wind, and solar) options and other emerging future opportunities were offered as potential candidates for shared or combined rights-of-way or easements... The Corridor could be the opportunity to build a smart or ‘green’ corridor of the future, serving as a new model for the movement of goods and people by learning from the best practices of previous corridor development.”<sup>2</sup>

Capitalizing on a promising degree of agency interest, our team has been working directly with state and county agencies and engaged non-profits to broaden the vision of this infrastructural opportunity. With billions of federal, state, and local dollars at stake, we see the Supercorridor concept not only (and perhaps not even primarily) about improving the transportation model for the movement of goods and people, but about seeking innovative, high-tech and high-design, multi-disciplinary solutions that leverage this immense investment in the built environment for a range of social, economic, and environmental benefits.

The goal of this past semester’s interdisciplinary urban design studio (IUDS14) was to use I-11 as a case study for the design of next generation infrastructure. The studio worked alternatively in interdisciplinary and disciplinary-specific teams. Tasks alternated between the macro (network) and micro (node) scales of the I11 route. Following introductory research on the demographics, environmental concerns, cultural assets, and current conditions of the expected route (or route alternatives, where appropriate), opportunistic yet somewhat prototypical (rural, urban, suburban) sites were selected. Fourteen interdisciplinary teams (seven from the University of Arizona, four from Arizona State University, and three from University of Nevada, Las Vegas) developed site specific proposals, while additional teams of planning students investigated questions specific to route alternatives or macro concerns. Representatives from ADOT, the Sonoran Institute, Pima County, Maricopa County, as well as professionals from the three disciplines participated as real stakeholders throughout the course of the semester.

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2 I-11 and Intermountain West Corridor Study, Corridor Justification Report. CH2Mhill and AECOM for Arizona Department of Transportation (ADOT) and Nevada Department of Transportation (NDOT). August 21, 2013. p84. Report can be found on line at: [http://i11study.com/wp/wp-content/uploads/2012/09/I11\\_CJR\\_08\\_21\\_13\\_FINAL.pdf](http://i11study.com/wp/wp-content/uploads/2012/09/I11_CJR_08_21_13_FINAL.pdf). retrieved 2 October 2013.

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Project success was gauged by each team's ability to achieve next generation infrastructure criteria. Derived from previous research by the author, next generation infrastructure incorporates eight criteria that transform limited use conduits into part of a productive civic network.<sup>3</sup>

Next Generation Infrastructure is:

- 1. **multi-functional** – It capitalizes on overlapping spatial and economic investment to accomplish many things at once; it is a hybrid of multiple activities or uses.
- 2. **public** – It is the new civic realm, where public life happens, not just where tax dollars are spent.
- 3. **visible** – In next gen infrastructure, resource consumption and infrastructural processes are made visible to promote accountability and acknowledge responsibility for collective needs and personal consumption.
- 4. **productive** – Next gen infrastructure is socially productive; it increases rather than decreases equity by providing amenities, opportunities, and environmental enhancements while reducing negative impacts.
- 5. **locally specific, flexible and adaptable** – Unlike last gen infrastructure, next gen infrastructure recognizes the need to change over time and place, to adapt to people and technology, to be community specific, and to work at micro as well as macro scales.
- 6. **sensitive to the eco-economy** – Next gen infrastructure is environmentally as well as economically conscientious. It prioritizes strategies of reuse, recycle, revitalize or reinvent to expand the life of latent investment and preserve historical value.
- 7. **design prototypes or demonstration projects** – It recognizes infrastructure as public space for human occupation, considering qualities such as scale, materiality, use and aesthetics. Model projects show how next gen infrastructure succeeds beyond increased functionality.
- 8. **technologically-advanced and innovative** – Next gen infrastructure is smart. It uses new technology to increase efficiencies, human experience, environmental response, and networked capabilities.

Seven southern Arizona projects each tackled a different prototypical condition: border crossing, brownfield site, divided neighborhood, urban center, suburban sprawl, obsolete manufacturing, and wilderness. Two projects shown here, one for Marana, a bedroom community 25 miles north of Tucson, and one for Tucson's primary entrance into downtown, Congress Street and the proposed I-11, exhibit the different foci of the prototypes. The design for Marana responds to their emerging educational industry, their adjacency to water and their desire to grow independently of metro areas to the north and south. The Marana Supercorridor node is primarily a multimodal hub with expansive green infrastructure and densified residential connected to new corporate and educational development and public space. Tucson's intersection with the Supercorridor capitalizes on its position as the largest metro area in southern Arizona. Reinvented as "Energy City", the Tucson Supercorridor node captures solar and kinetic energy which charges a fleet of on-demand driverless cars and powers high-tech retail, residential and office space. The node also connects to the streetcar, commuter rail and future hyperloop. Dense development provides ample condensate and rainwater harvesting diverted to ground level living machines that ultimately recharge the Santa Cruz River and provide new recreational opportunities. The objective of these proposals is to illustrate the results of infrastructural opportunism, where leveraging major transportation investments with an innovation, design, and environmental emphasis can transform infrastructure from a string of detriments to a wealth of opportunities.

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3 The Next Generation Infrastructure criteria listed here were developed by the author in conjunction with cityLAB partners as a result of previous research that emerged from work on cityLAB's WPA 2.0 competition. More on that topic can be found in Samuels (2010) "Working Public Architecture," *Places: Forum of Design for the Public Realm*, <http://placesdesignobserver.com/entry.html?entry=12427>. And in Dana Cuff's article "WPA 2.0: Working Public Architecture" in *Harvard Design Magazine* 33, *Design Practices Now*, vol 2, Landscape Architecture and Urban Design. Fall/Winter 2010/2011.

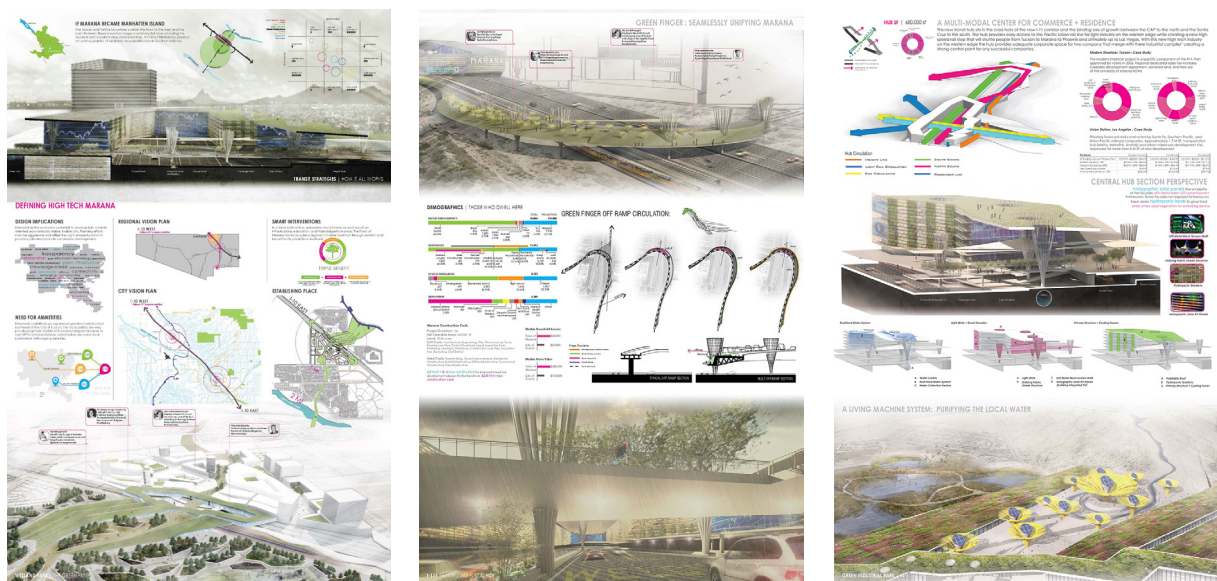
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## CONCLUSION

From Las Vegas to Nogales, the studio design proposals highlight a range of problems and opportunities inherent in a paradigmatic shift of this scale. The necessity of solving questions one and two – intervening in the process and inventing new prototypes – becomes even more evident as the design proposals clearly rely on radical reshaping of the status quo practices around infrastructure design and implementation. Our siloed thinking about use and distribution of resources is ineffective in solving the wicked problems of the coming century. For example, our collective and individual energy expenditure dedicated to car-centric living is obsolete, yet our commitment to mobility, consumption, and wealth has an inordinate impact on the mega-scale, multi-billion dollar projects that move goods and people. In this world of resource uncertainty, new infrastructure must express civic responsibility for the 21st century and be an agent of environmental, social, and economic change. The occasion to transform the legacy of sprawl into a new vision of sustainable design and planning is unprecedented.

Interstate 11 is a fortuitous opportunity intersecting the larger question of infrastructure reinvention for a new generation via interdisciplinary, collaborative thinking. The model for infrastructure design, planning, and construction lags far behind the logistically possible networked, responsive and productive possibilities. The three questions posed here with test projects developed in the design studio intend to instigate a larger conversation, beginning with the real stakeholders in the inchoate stages of large-scale infrastructure planning. This research and design will be instrumental in developing visionary solutions to some of our country's oldest and most stubborn problems – our love of mobility, our addiction to cheap energy, and our demand for easy accessibility. Simultaneously, we are building a new generation of student researchers and designers who recognize the value of cross-disciplinary collaboration, big thinking, and breaking out of the status quo.

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**[Re]formation: interdisciplinary student proposal for Marana, AZ. Students: Stratton Andrews, Daniel Aros, William Greenway, Alexandra Hines, Ying Yang.**



**Figure 1: Energy City: interdisciplinary student proposal for Tucson, AZ.**  
**Students: Steven Giang, Sally Harris, Kendra Hyson, Katherine Laughlin, Bernardo Teran.**

# Extended Definition of Capacity in Airport Systems

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## ABSTRACT

Nowadays the main airports throughout the world are suffering because their capacity are getting close to saturation due to the air traffic which is still increasing besides the economic crisis and oil prices. In addition, the forecasts predict an increase in air traffic of at least 3.6% until 2020. This situation makes very important to come up with solutions to alleviate capacity congestions in the main airports throughout the world. Capacity has been perceived traditionally as the factor to be addressed in airport systems and it is faced through a technical perspective. In this paper we propose to change the mind-set and view capacity of airport systems taking other factors than pure technical ones. The discussion is illustrated with the example of Schiphol Airport.

**Keywords:** Airport, Aviation, Capacity, Mismatch, System

## INTRODUCTION

Nowadays the main airports throughout the world are suffering because their capacity are getting close to saturation due to the air traffic which is still increasing besides the economic crisis and oil prices<sup>1</sup>. In addition, the forecasts predict an increase in air traffic of at least 3.6% until 2020<sup>2</sup>. Furthermore in the case of European Airports, it has been reported that around 60 European airports are at the edge of congestion. The latter statement is based on the declared capacity of the airports which most of the time calculate their number based on the technical characteristics present in airports. These levels of saturation will be perceived in the coming years as problems in different functional areas at the airport itself. At the airside more and more aircrafts will be put on holding, delays incurred due to lack of gates after landings, congestions in the terminals and in general queues everywhere at different levels.

Traditionally capacity problems have been seen and addressed from the technical stand point. Assuming that the operations within an airport are a mixture of parallel and sequential operations the practical capacity can be defined in terms on the most restricted element of the airport<sup>3</sup>. Furthermore, depending of the airport system under study, the bottleneck can change and will direct in most of the time the actions to be taken in order to cope with the current demand. If the airport is not able to handle in the proper way the passengers then an expansion of the terminal will be planned; on the other hand if the schedule flights incur in more delays that a particular threshold then it would suggest that the problem is on the capacity of the runway system, thus a new runway could be the solution for the

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1 EUROCONTROL, 2008, "Challenges of Growth", <<http://www.eurocontrol.int/articles/challenges-growth>

2 Airport Council International, 2004, "Study on the Use of Airport Capacity", ACI EUROPE, pp. 1-15, Brussels, Belgium

3 Janic, M., 2008, "Airport Analysis, Planning and Design", NOVA, New York

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capacity constraint and so on. Adding a new runway is a long-lasting process; therefore various studies indicate that in most of the cases runway capacity (defined in number of hourly movements) is the limiting factor for airport capacity<sup>4 5</sup>. Other studies indicate that airport capacity is a more complex matter that involves various different factors. Suau-Sanchez<sup>6</sup> et al. mention that the total airport capacity is the aggregate of infrastructure capacity, air space capacity and environmental capacity. Wei et al.<sup>7</sup> argue that congested hub capacity will have up- and downstream effects on spoke capacity as well. These studies show that there is no single definition of airport capacity and that various factors play a role.

Defining airport capacity by maximum hourly runway movements does not cover all the limiting elements. Other factors that also play a role in the capacity must be taken into account such as societal restrictions and airline business models on hub and spokes. These restrictions are sometimes subjective but it does not mean that must be neglected under a decision-making process. Elements like noise, emissions but also limited runway slots all influence the possible solutions to deal with constraint airports on how to allocate airport capacity amongst airport users or what measures will add capacity to the airport on the long run.

In order to better understand the elements that influence the airport capacity and study the possible solutions on how to deal with constraints airports an extended airport capacity definition is needed.

In the following sections the different factors that must be taken into account are presented and discussed, and an extended definition of capacity is addressed.

## THE CAPACITY EQUATION

As it has been mentioned before, the capacity has been traditionally defined based on the technical elements that allow the flow of entities within the airports such as time slots, runways, facilities to handle the incoming traffic and passengers. This paradigm of analysing the system is the correct one under the assumption that the system depends on these solely factors and on the interrelationships among them. However it is important to keep in mind that airports have different roles and functions. The main function of an airport is not only to transport people and goods (or to connect air- and land transportation); nowadays the functions of the airport have evolved to more complex airport cities. They can have a strategic role for the development of regions; they provide connection at regional and at global level that in turn impact the development of society. The allocation of airport capacity amongst airlines is important for the role and contribution of the airport for the region. In some studies this is referred to as the bringing airport demand management measures in the allocation of scarce airport slots<sup>8</sup>. In addition to these functions, there is a close interaction between the airline business model (i.e. how to operate the hub and spoke model) and the use of airport capacity in the hub-and-spoke system.

Besides the economic roles the aviation is playing within a region, it has been perceived that in developed countries people are actively involved in the operation of airports (directly or indirectly). Society not only appreciate airport benefits, but can also be annoyed by airport hindrances (noise, emission, etc.); thus society in turn can have a preponderant role in the operation limits of an airport. This role can be more or less important depending on the development of the country and the society itself. Noise is not a technical issue but requires a societal response and community participation to handle. If this is not done properly society can have a large influence on limiting the airports capacity. Suau-Sanchez et al.<sup>9</sup> define therefore environmental capacity as: 'the level of airport operational ability that can be reached after airport activity is limited due to socio-environmental factors.'

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4 Desart, B., Gillingwater D., Janic, M., 2010, "Capacity dynamics and the formulation of the airport capacity/stability paradox: A European perspective", *Journal of Air transport Management* Volume 16, Issue 2, pp. 81-85

5 Wilken, D., Berster, P., Gelhausen, M., 2011, "New empirical evidence on airport capacity utilisation: Relationship between hourly and annual traffic volumes. Research in Transportation Business & Management", Vol.1, Issue 1, pp. 188-127

6 Suau-Sanchez, P., Pallares-Barbera, M., Paül, V. 2011, "Incorporating annoyance in airport environmental policy: noise, societal response and community participation", *Journal of Transport Geography*, Vol.19, Issue 2, pp. 275-284

7 Wei, W., Hansen, M., 2006, "An aggregate demand model for air passenger traffic in the hub-and-spoke-network", *Transportation Research Part A: Policy and Practice*, Volume 40 Issue 10, pp. 841-851

8 Madas, M., Zografos, K., 2010, "Airport slot allocation: a time for change? Transport Policy", Vol. 17, Issue 4, pp. 274-285

9 Suau-Sanchez, P., Pallares-Barbera, M., Paül, V. 2011, "Incorporating annoyance in airport environmental policy: noise, societal response and community participation", *Journal of Transport Geography*, Vol.19, Issue 2, pp. 275-284

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The extended role of the airport in case of constraint capacity requires not only the efficient use of the existing capacity by the current users. The society demands an optimal balance of the airport added value for the region and the hinder caused by the airport operations. Any unbalance will in future further hamper the development of airport capacity.

The purpose of this article is come up with an extended equation of airport capacity that includes the various elements that together define the airport capacity. Each of these elements can have a different set of variables to define the impact on the airport capacity and to manage the possible solutions to extend the capacity in future.

## PARAMETERS OF THE EQUATION

The different elements of the capacity equation (1) must be discussed in order to understand the role they play in the system.

### **CAPACITY: F(Business Model , infrastructure, airspace, societal conditions) (1)**

**Business model.** The business model determines how the airlines serve the different markets of interest. Traditionally the business model has influenced the operation of airports in different regions of the world basically through the development of their networks<sup>10</sup>. The airports adapt their operation and facilities in accordance with the business model of the airlines that are the direct client of the airports. In some airports the operations are strongly influenced by the legacy carrier within the region of the airport which is the leader in the local market. Thus the airport operation is directly influenced by the relationships between the most influential actors and the airport itself.

**Infrastructure.** Infrastructure is the most known and studied of the parameters that choke capacity in airports. As it has been discussed, the scientific community pays a lot of attention in ways of managing in a more efficient way the resources at hand in order to cope with the traffic demand<sup>11 12 13 14 15</sup>. Technical capacity put restrictions in the available facilities but on the other hand capacity restrictions can be the driver for developing novel techniques that force the evolution of the industry e.g. optimization techniques, more efficient engines etc.

**Airspace.** The airspace is the region (3D) in the air in which the airplanes are flown. This space is basically controlled by humans with the support of technology such as radars, GPS, satellites. Since the activity of monitoring and controlling the flying entities is performed by humans, there are inherent risks and limits to the control operations. Due to the increase in traffic the international community is looking for innovative ways to manage the flow of aircraft within the airspace in order to reduce conflicts and improve the flight plans<sup>16 17</sup>.

**Societal Conditions.** This parameter of the equation might have been not important some years ago; but with the evolution of societies this factor is getting more importance since society is having more influence in the developments needed to cope with the demand of the coming years. There are some interesting examples that give evidence of the role that this factor is having nowadays<sup>18</sup>.

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10 Airport Council International, 2004, "Study on the Use of Airport Capacity", ACI EUROPE, pp. 1-15, Brussels, Belgium

11 Arias, P., Guimarans, D., Mujica, M., Boosten G., 2013, "A methodology combining optimization and simulation for real applications of the Stochastic Aircraft Recovery Problem", in Proc. of EUROSIM 2013, Cardiff, UK.

12 Mujica, M., Zuniga, C., 2013, "A Simulation-Evolutionary Approach for the allocation of Check-In Desks in Airport Terminals", in Proc. of ATOS 2013, Toulouse, France

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14 Madas, M., Zografos, K., 2010, "Airport slot allocation: a time for change? Transport Policy", Vol. 17, Issue 4, pp. 274-285

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16 SESAR JU, <[http://ec.europa.eu/transport/modes/air/sesar/index\\_en.htm](http://ec.europa.eu/transport/modes/air/sesar/index_en.htm)>

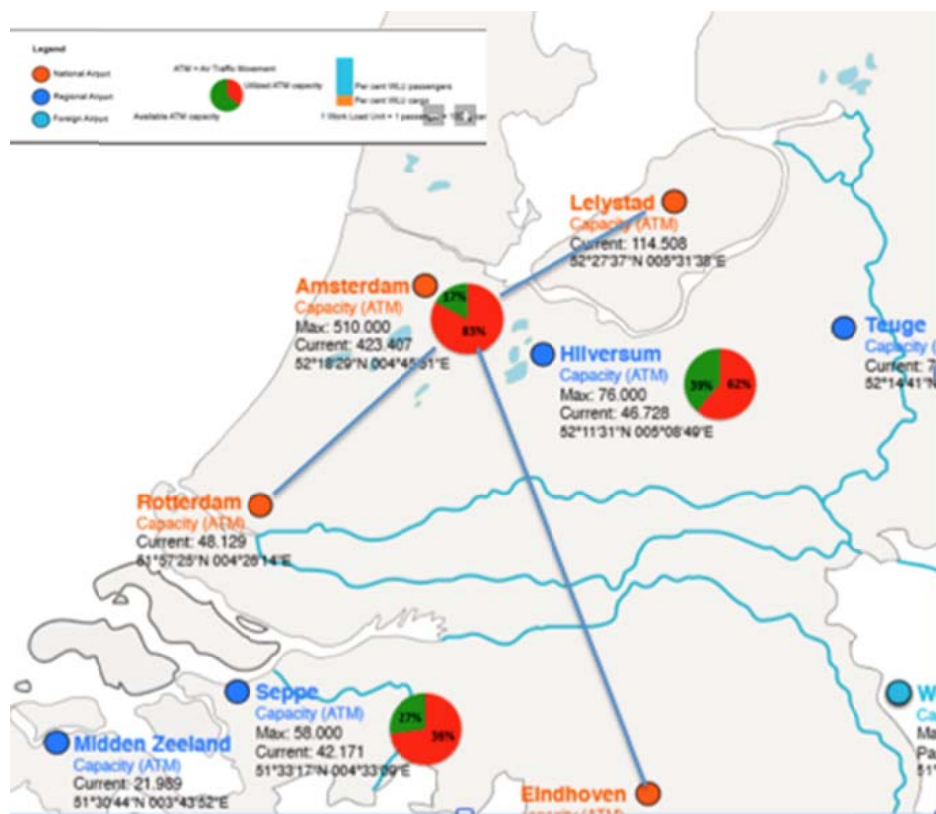
17 NextGen, [www.faa.gov/nextgen/.../NextGen\\_Implementation\\_Plan\\_2013.pdf](http://www.faa.gov/nextgen/.../NextGen_Implementation_Plan_2013.pdf)

18 Suau-Sanchez, P., Pallares-Barbera, M., Paül, V. 2011, "Incorporating annoyance in airport environmental policy: noise, societal response and community participation", Journal of Transport Geography, Vol. 19, Issue 2, pp. 275-284

## SCHIPHOL AIRPORT CASE

Schiphol is a good case to illustrate both the extended importance of the airport for the region (the so-called mainport impact) as well as that fact that the airport is constraint by both runway limitations (maximum hourly movements) and societal constraints in terms of noise. Finding the balance between added value (mainport and hinder) is a key issue for Schiphol and therefore understanding the building blocks of capacity in order to manage the balancing act.

Schiphol currently performs 425,000 operations which corresponds to an 83.3% of saturation considering the declared capacity of 510,000 ATM<sup>19</sup>. For all these reasons the national government is interested in developing a system of airports that serve for the purpose of the region. Fig. 1 illustrates the region in which the new system is planned to operate. The local government is concerned about the capacity levels that Schiphol has reached thus they propose to develop an airport system in which some traffic will be diverted from Schiphol to regional airports. Currently local and regional actors are struggling to devise what will be the best way and which traffic to divert and the implications and consequences for the region under those decisions.



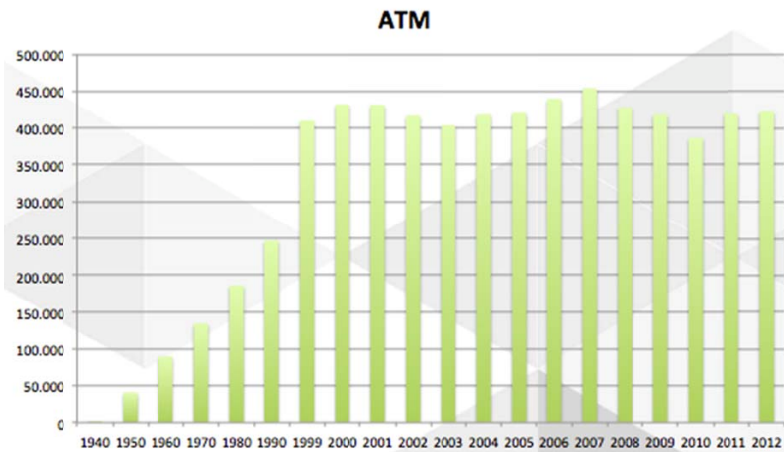
**Figure. 1. The situation of North Holland**

Schiphol airport has a declared capacity of 510,000 ATM/year<sup>20</sup>. On 2012 the number of ATM reached 423,407 which corresponded to a level of saturation of 83%. This numbers represent an increase compared to the previous year in which the ATM numbers reached 420,349 ATM as Fig. 2 illustrates.

19 Schiphol Airport, 2011, "Feiten en Cijfers", <<http://Schiphol.nl/SchipholGroup1>>

20 Ministry of Infrastructure and Environment, 2009, "BIJlage1 Luchvaartnota", <<http://www.rijksoverheid.nl/>>





**Figure. 2. Traffic evolution in Schiphol**

According to what has been investigated by different authors <sup>21 22</sup> with these numbers one would be expected to perceive high queues or more delays in the airport. On the contrary Schiphol has been improved in terms of delay figures. During 2012 according to EUROCONTROL average delay per flight was reduced in 10% compared to 2011 <sup>23</sup>. The previous numbers indicate that at least in the case of Schiphol there is a mismatch between technical capacity and the actual capacity.

### The Capacity Equation for Schiphol

The different elements will be discussed in this subsection to illustrate that the capacity equation should be investigated in order to come up with a more elaborated definition of capacity that can be applied to different airports.

### Business Model

Schiphol is strongly influenced by the legacy carrier KLM with his partner AF. The main hub of KLM-AF is Schiphol airport. They belong to the Skyteam alliance. The business model operated by KLM has put a lot of pressure to the local government to keep the alliance partners inside Schiphol and those who are not considered of value be diverted to the secondary airports in the future system. Under these assumptions Schiphol must adapt to the type of traffic that will appear under this model and the necessary adaptations must be performed for that objective.

### Infrastructure

Schiphol is a large airport with 5 runways and huge terminal facilities. In terms of operations it has a good performance as it suggests their numbers in punctuality (measured as 15 min. tolerance). In the case of arrivals it went from 86.1% to 87.6% in punctuality and for departures it went from 81.2% to 81.9% both evaluated from 2012 to 2013 <sup>24</sup>; this numbers are surprising since during 2013 the traffic increased and one would expect that the delays would increase as well if it were the case of a congested airport.

### Airspace

The airspace indeed chokes capacity but in the case of Schiphol TMA has been improved as the delay figures suggest <sup>25</sup>. Besides that one of the main objectives of the SESAR is to increase airspace capacity through the so-

<sup>21</sup> Janic, M., 2008, "Airport Analysis, Planning and Design", NOVA, New York

<sup>22</sup> Solak, S., Clarke J.B., Johnson, E.L., 2009, "Airport terminal capacity planning", Transportation Research Part B, Elsevier

<sup>23</sup> EUROCONTROL, 2012, "Delays to Airtransport in Europe", CODA Digest ANNUAL <<http://www.eurocontrol.int/sites/default/files/content/documents/official-documents/>>

<sup>24</sup> Schiphol Group, 2013, "Facts and Figures" <<http://www.schiphol.nl/SchipholGroup/Company1/Statistics/FactsFigures.htm>>

<sup>25</sup> Schiphol Group, 2013, "Facts and Figures" <<http://www.schiphol.nl/SchipholGroup/Company1/Statistics/FactsFigures.htm>>

called 4D trajectories<sup>26</sup>.

### Societal Conditions

Netherlands is developed country in which the function of the airport is taken for granted and the region counts on the airport as another transport mode as efficient as the train or car. The efficiency of this transport mode must be achieved under a regulated environment. The airport must ensure not only the technical rules inherent to these kinds of systems such as (separation rules, crosswind rules, etc.) but also new restrictions imposed by the society. In the case of Schiphol these relationship with society is materialized in the Alders Platform which is “a consultative body in which the government, the aviation sector, local authorities and residents make agreements aimed at ensuring the aviation activities at Schiphol and the quality of life in the region remain in equilibrium”<sup>27</sup>. This Alders platform has the objective to put into play the interest of society when decisions concerned to the airport facility are being evaluated. During 2013 the Alders agreement influenced strongly the operation of the airport in such a way that the airport needed to adapt itself in order to avoid exceeding the noise limits in the vicinity of the airport measured with the noise enforcement points. This is just a small example of how society is acquiring more impact in the operation of such a facility and must be taken into account for the evaluation of capacity.

### CONCLUSIONS

Due to the increase in traffic worldwide, focus has been put in the capacity of air-ports throughout the world; in particular, in the case of Europe and the developed countries some factors have come into scene. These factors have been discussed in the paper and the case of Schiphol is presented to illustrate that there are different factors (some old but other new) that affect the actual capacity of a facility. The numbers presented contradict the expected performance when the traffic is increased thus suggesting that capacity is constrained by a different factors than the technical ones. The challenge for the scientific community is to investigate the different factors that influence nowadays modern aviation if good decisions are being taken for facing the future demand.

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26 SESAR JU, <[http://ec.europa.eu/transport/modes/air/sesar/index\\_en.htm](http://ec.europa.eu/transport/modes/air/sesar/index_en.htm)>

27 Schiphol Group, 2013, “Annual Report 2013”, <<http://www.annualreportschiphol.com/our-results/sustainable-performance/noise-and-the-local-community#>>

# Material Flow Analysis: Outcome Focus (MFA:OF) for Elucidating the Role of Infrastructure in the Development of a Liveable City

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<http://discovery.ucl.ac.uk/1469208/>

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## ABSTRACT

Engineered infrastructures (i.e., utilities, transport & digital) underpin modern society. Delivering services via these is especially challenging in cities where differing infrastructures form a web of interdependencies. There must be a step change in how infrastructures deliver services to cities, if those cities are to be liveable in the future (i.e., provide for citizen wellbeing, produce less CO<sub>2</sub> & ensure the security of the resources they use). Material Flow Analysis (MFA) is a useful methodology for understanding how infrastructures transfer resources to, within and from cities and contribute to the city's metabolism. Liveable Cities, a five-year research programme was established to identify & test radical engineering interventions leading to liveable cities of the future. In this paper, the authors propose an outcome-focussed variation on the MFA methodology (MFA: OF), evidenced through work on the resource flows of Birmingham, UK. These flows include water, energy, food & carbon-intensive materials (e.g., steel, paper, glass), as well as their associated waste. The contribution MFA: OF makes to elucidating the interactions & interdependencies between the flows is highlighted and suggestions are made for how it can contribute to the (radical) rethinking of the engineered infrastructure associated with such flows.

**Keywords:** Urban Metabolism, MFA, Liveable Cities, Resource Flows, Infrastructure

## INTRODUCTION

Engineered infrastructures (e.g., water, electricity, transport and digital) underpin modern society. Delivering services via such infrastructures is especially challenging in cities where different types of infrastructures are interlinked and intertwined, forming a complex web of (inter)dependencies. Yet this challenge must be addressed as the world becomes increasingly urbanised. Allied to this, cities are vast consumers of resources (e.g., water, energy and food), producers of waste and emitters of pollutants (including CO<sub>2</sub>). There must be a step change in how infrastructures deliver services to cities if those cities are to be liveable in the future (i.e., provide for the wellbeing of their citizens, operate in a low carbon manner and ensure the security of the resources they use).

Infrastructure is defined as “the basic physical and organizational structures and facilities (e.g. buildings, roads, power supplies) needed for the operation of a society or enterprise”<sup>1</sup>. However, this definition has expanded over recent years to encompass green infrastructure (a network of green and environmental features) as well as digital infrastructure (storage and exchange of data) and social infrastructure (facilities that contain health, education and public services). This paper considers all aspects of infrastructure related to the flows of water, energy, food, carbon-intensive materials (e.g., steel, paper, glass) and people, as well as associated waste, into, within and out

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1 Oxford English Dictionary. Definition of infrastructure in English, <<http://tinyurl.com/n5jp88z>> (2014).

of the city of Birmingham, UK. The authors employ a newly-devised variation of the Material Flow Analysis (MFA) methodology (Material Flow Analysis: Outcome Focus (MFA:OF)) for understanding the city's flows, their relationship with engineered infrastructures and their contribution to the city's metabolism. This work has been carried out as part of the *Liveable Cities* Programme, a five-year interdisciplinary research programme combining the Universities of Birmingham, Lancaster, Southampton and UCL. *Liveable Cities* aims to identify and test radical engineering interventions that will lead to liveable cities of the future. The Programme includes stakeholders from an array of backgrounds who are interested in city operations and who are able to provide useful insights and feedback to *Liveable Cities*. These stakeholders include architects, city councils, environmental consultancies and agencies, utilities, urban designers, and sustainable development consultancies. The contribution MFA:OF makes to elucidating the interactions and interdependencies between the flows is highlighted and suggestions for how MFA:OF can contribute to the (radical) rethinking of the engineered infrastructure associated with such flows are made.

## URBAN METABOLISM AND MATERIAL FLOW ANALYSIS: OUTCOME FOCUS

Urban Metabolism studies the resource flows in and out of a city system from a biological perspective<sup>2,3</sup>. This means that the city is seen as a living organism that is constantly evolving and reorganising. It largely extracts resources from beyond its boundaries, uses them within its boundaries to support city activities, and then deposits the resulting wastes back into the external environment. This is defined as linear metabolism<sup>4</sup>. This differs from the circular metabolism of a natural ecosystem, which produces no waste and survives off its immediate environment<sup>5</sup>. There have been numerous studies across the world using the methodology of urban metabolism focusing on the national and regional level<sup>6,7</sup>, but fewer at a city level and even fewer looking at cities in the UK. In the last 15 years there have been six previous UK city studies: Manchester<sup>8</sup>, Liverpool<sup>9</sup>, York<sup>10</sup> and London<sup>11,12,13</sup>. In addition, more recent work was carried out on the city of Birmingham by the Stockholm Environment Institute through their Resources and Energy Analysis Programme (REAP)<sup>14</sup>.

Material Flow Analysis (MFA) was a widely adopted approach used in the urban metabolism studies of UK cities. MFA has traditionally focussed on flows of materials, although such an object-focussed analysis risks oversimplifying the complex qualities of cities. The authors argue that an outcome-focussed analysis; for example, selecting flows and units of measure relevant to a desired outcome, provides a more nuanced picture and allows for the identification of infrastructure interactions, interdependencies and interrelationships, as well as incorporating economic, social, cultural and environmental priorities. Even so, additional information is required for a full city analysis (e.g., consideration of the temporal nature of the city's resource flows).

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14 Stockholm Environmental Institute (SEI). An Introduction to the Resources and Energy Analysis program, <<http://tinyurl.com/mnjbbnt>> (2007).

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## METHODOLOGY

The *Liveable Cities* Programme was established in 2012 to identify and test radical engineering interventions that would lead to liveable cities of the future. Such cities would be low carbon, resource-secure and provide a city environment in which societal wellbeing would be (at least) maintained and preferably enhanced. These are the programme's desired outcomes for cities. To identify how a city operates, three UK case study cities were selected to represent a range of locations and sizes: Birmingham, Lancaster and Southampton. Birmingham provided the original test bed, the learnings from which could then be applied to the other two cities having identified any gaps or shortcomings prior to applications further afield. MFA was selected as the most robust methodology for mapping resource flows at the city scale. Taking into account the programme's desired outcomes (low carbon, resource security, high wellbeing), six resource flows relevant to these outcomes and important to the operation of the city were identified: water, energy, food, carbon-intensive materials (steel; aluminium; cement; plastic; paper; glass; and sand, gravel & aggregates), people and waste. Importantly, the carbon associated with these flows was identified as well as raw movement data. Data sources and availability were also identified, with the intention that these sources were as accessible as possible.

The analysis had three primary objectives: (i) to establish a current baseline for Birmingham in terms of resource movement and carbon; (ii) to establish a desired state for Birmingham in 2050 in relation to these resources, and (iii) to inform radical re-thinking of the underpinning infrastructures and service provision mechanisms in order to develop a strategy for achieving the desired 2050 end state. The analysis was not intended to be a full MFA of the city.

## BIRMINGHAM: A SNAPSHOT

### Water

- Sources and related infrastructures: the vast majority of Birmingham's water is supplied to the city via a pipeline from the Elan Valley in Wales (some 73 miles away). This delivers around 345 MI/day to the city. This water is stored in a number of reservoirs around the city.
- Demand: 83,000 MI/yr.
- Waste: 182,500 MI/yr.
- Associated carbon emissions: 85 ktCO<sub>2</sub>/yr.
- These figures are calculated from Severn Trent Water data<sup>15</sup>.

### Energy

- Sources and related infrastructures: The National Grid supplies gas and electricity to the city via the "Big Six" energy companies. Diesel and petrol are sourced via oil refineries. In 2011, 26% of Birmingham's energy demand was supplied via domestic gas from the North Sea. Local energy (Combined Heat and Power, and District Heating) provides the city with 81 GWh per year along with 217 GWh from the Tyseley Energy from Waste Plant (2% of the city's energy consumption).
- Demand: There is a high demand for energy given that Birmingham is the second largest city in the UK and home to 1.07 million of people<sup>16</sup> (ONS, 2012). In 2011, the total energy consumed by the city was 1.66 Mtoe.
- Waste (Heat energy): 3.5 GW of heat.
- Associated carbon emissions in 2011: 2193 ktCO<sub>2</sub> (industry and commercial); 1891 ktCO<sub>2</sub> (domestic); 1405 ktCO<sub>2</sub> (transport).

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<sup>15</sup> Severn Trent Water. *Water Resources Management Plan Final Version. June 2010*, <<http://www.stwater.co.uk/about-us/our-business-and-strategy/water-resources-plan/>> (2010).

<sup>16</sup> Office for National Statistics (ONS). *2011 Census, Population and Household Estimates for the United Kingdom*, <<http://www.ons.gov.uk/ons/rel/census/2011-census/population-and-household-estimates-for-the-united-kingdom/index.html>> (2012).

## Food

- Sources and related infrastructures: The food supplies to the city are mostly imported from within the UK (just over 50%), with 28% from the EU and the remainder from the rest of the world<sup>17</sup>.
- Demand: The average Birmingham citizen consumes 3400 kcal a day, more than 1400 kcal above the average recommended Guideline Daily Amount for an adult. 25% of the population in the city is obese, the third highest rate in the UK, and that 40% of children aged 11 are overweight or obese<sup>18</sup>. Birmingham citizens buy 368 kt of food and 288 Ml of drink (excluding water) per year, spending £2.1 billion per year<sup>19</sup>.
- Waste: 155kt.
- Associated carbon footprint: 354 ktCO<sub>2</sub> (freight transport which includes food transfers).

## Carbon-intensive materials

- Sources and related infrastructures: The city produces nearly 8 Mt of manufactured goods. In addition, over two-thirds of the materials are imported (15 Mt). These imports consist of 11.6 Mt from within the UK (75%) and 3.7 Mt from the rest of the world (including 0.5 Mt of metals)<sup>20</sup>. Around half of the UK imports are from the paper and publishing industry together with the food, beverages and tobacco industry. Birmingham exports 11.8 million tonnes of manufactured goods, of which car exports make up around 8%<sup>21</sup>.
- Demand: Around 10 million tonnes of carbon intensive materials are consumed by the city<sup>19</sup>.
- Waste: (Industrial and commercial) 967 kt (2006/2007).
- Associated carbon footprint: 1891 ktCO<sub>2</sub>.

## People

- Sources and related infrastructures: There are 313,250 commuters coming into Birmingham every weekday; 62% of these live within the city boundaries, with 29% coming from local towns including Coventry, Tamworth and Wolverhampton. The remaining 11% come from further afield (extending as far as the Isle of Wight and Anglesey)<sup>22</sup>. Around 60% of commuters travel by car, while 18% travel by bus, 10% by walking, 5% travel by train, 2% cycle, with the remaining 5% using other means (including mopeds, scooters, motorbikes, taxi)<sup>23</sup>.
- Associated carbon emissions: 1405 ktCO<sub>2</sub>.

## CO<sub>2</sub> Emissions

- In 2012, Birmingham emitted 5.6 Mt CO<sub>2</sub> – about 42% came from the commercial sector which includes industry, 37% from domestic buildings and the remaining 21% from transport.

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19 Department for Environment Food and Rural Affairs (DEFRA). *Family Food 2012*, <<http://tinyurl.com/kfgfyw7>> (2012).

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21 HM Revenue and Customs. *UK overseas trade statistics and regional trade statistics*, <<http://tinyurl.com/oal2q8p>> (2014).

22 Office for National Statistics (ONS). *Annual Population Survey commuter flows, local authorities in Great Britain, 2010 and 2011*, <<http://tinyurl.com/lqypx3u>> (2013).

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## BIRMINGHAM: THE FUTURE

The *Liveable Cities* Vision prioritises a move towards a low carbon, resource secure city where the well-being of its citizens is enhanced or improved. Future city visions are being developed centred around the well-being of citizens. Such visions provide principles which cities can aim towards. When applied to a city, these principles inspire design concepts and ideas. Considering the principle of open public space, this requires designs that incorporate openness, availability and accessibility. Each of these has its own requirements. For example, accessibility requires geographical and temporal access for all people. Public transportation is one way of achieving this. Applied to Birmingham this might result in an extended city-centre tram system<sup>23</sup>, while applied to Medellin, Colombia this might result in cable cars<sup>24</sup>, the point here being that each city provides its own unique context and the resulting engineered solutions must reflect that context. Put another way, adopting a tram system as a universal solution to the problems of people movement would be a poor approach (and in fact, an unworkable solution in Medellin), whereas universal adoption of the guiding principle has merit. In all cases it is readily apparent that for visions to become reality, cities need to consider how existing flows might change, or how they could/should be modified (now and in the future) and what impact this would have on a city's liveability. MFA:OF provides part of the necessary evidence base; in the case of *Liveable Cities*, this involves selecting flows important for resource security and linking them to carbon if we are to meet the primary programme aims, and in parallel assessing them for a wider set of city performance parameters that encompass wellbeing, resource security, carbon, governance and economics. Inevitably, tensions will arise caused by interactions between flows. For example, in Birmingham if food waste is reduced this will impact on the amount of waste burnt by the incinerator in the energy from waste scheme and reduce energy production.

Designing to well-being principles cannot be done at the expense of a city's resource security or its carbon emissions, and many factors come into play. For instance, we might be forced to reduce the amount of allowable water usage per person, due to the combined effects of reduced availability and an expanding 'demand driven' population. If so, what impact might this have on our citizens and how can this be made more acceptable? What policies would be required? What would be the cost (to the economy and the environment) and what interventions in terms of solutions (existing or innovative) or transformative approaches might be required?

## CONCLUSION

Infrastructure is a vital part of our cities. Well-being is paramount for successful cities, but with increasing resource scarcity and the impacts of climate change it is time for cities to use such resources in the most efficient and lowest carbon way possible. Material Flow Analysis: Outcome Focus (MFA:OF) provides part of the required (and currently lacking) evidence capable of tying together these outcomes. By its nature, the implications for engineered infrastructures are made explicit and the opportunities for infrastructure to create liveable cities elucidated. The mechanisms for achieving a liveable city are necessarily varied, incorporating 'push' actions, such as higher energy costs, and 'pull' actions, such as aspirations for a better future. In addition, education, taxes, and incentives will contribute to behavioural change. In the UK, this will likely require funding and/or legislation from Government or the European Union to drive things forward. There is also a need to involve SMEs and industry. Good case studies and new methodologies, such as that of Birmingham and MFA:OF provided by the *Liveable Cities* team, will provide guidance and inspiration for cities to achieve the necessary carbon and waste reductions and resource efficiencies without compromising (and hopefully increasing) the wellbeing of its citizens. In turn, these city needs and aspirations of the future, which necessarily prioritise wellbeing, are embraced in *Liveable Cities*' guiding principles, which are then applied (engineered) to each individual, unique city context.

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23 Centro. *Midland Metro*, <<https://www.centro.org.uk/transport/metro/>> (2014).

24 Metro de Medellin. *Metro Cable*, <<http://tinyurl.com/pajawxa>> (2014).





# Building Progressive Confidence: the Transition from Project to Operational Opening in the Case of a Major New International Airport Terminal

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<http://discovery.ucl.ac.uk/1453394/>

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## ABSTRACT

The purpose of an infrastructure system is to deliver a variety of services to end users over long periods of time. One of the biggest challenges in the design and construction of new infrastructure facilities is the transition or handover from the project to operations. This is particularly the case for infrastructural assets that are complex in their operations such as energy generation plants, airports, ships and aircraft carriers, or hospitals. A variety of commissioning, testing, systems integration and operational readiness procedures have to be put in place to ensure a smooth handover to end users and operators. This paper presents an ongoing empirical study that investigates the challenge of delivering the operational outcomes of Heathrow Terminal 2 (T2), a major international airport hub terminal. The study consists of site observations, four preliminary and 15 in-depth interviews with highly knowledgeable informants in key positions concerning the delivery of the project and airport services to the end-users. Preliminary findings indicate that a specific form of high reliability focus which our participants called 'progressive confidence' is essential for the smooth transition from project to operations. The emergent findings suggest that this process comprises specific aspects of organisational learning, the notion of the "flip" between the project and operations and approaches for dealing with change. The findings suggest the importance of further research into the issues of operational readiness and transitioning towards the handover of complex infrastructure projects.

**Keywords:** Infrastructure Delivery Challenge, Airports, Reliability, Operational Readiness

## INTRODUCTION

Large-scale infrastructure is planned, designed, built, and delivered through temporary project organisations involving a large coalition of stakeholders. These projects may be required to maintain and upgrade existing facilities or build entirely new infrastructure systems. One of the most critical points in the lifecycle of any large-scale infrastructure is the transition and handover of the project to its end users and operators. This involves a shift in organisational structure, skills and culture from a temporary project to a permanent operator. It is at this stage that the organisation moves from design, construction, systems integration, testing and commissioning to operation and the provision of services to end users.

As a result, owners of complex infrastructure projects must pay particular attention to the handover from the project to operations. The primary purpose of handover is to enable a smooth transition between construction and operations. Even though the role of operational handover is relatively well investigated in the IT, defence, and aerospace industries, relatively little is known about key organisational routines and practices that lead to the successful transition from project to operational outcomes for infrastructure projects. This is surprising, given the key

role that the handover stage plays in the lifecycle such projects. It is clear that disruptions or failures in handover can create severe reputational damage and loss of revenues for the infrastructure owner and operator.

To address this gap, the purpose of this paper is to present a study that investigates *reliability* as a key feature of infrastructure handover. This will be accomplished through an empirical study focusing on the various organisations involved with the project-operations delivery phase of a major international airport hub terminal.

## NORMAL ACCIDENTS AND HIGH RELIABILITY ORGANISING

To investigate reliability aspects of the transition phase between the project and operations, we draw from organisation theory as a theoretical framework. The two most prominent strands of research that have tackled the organisational reliability issues are *normal accidents theory*<sup>1</sup> (NAT) and *high reliability theory*<sup>2</sup> (HRT). NAT argues that accidents are inevitable or *normal* in interactively-complex and tightly-coupled systems where localized incidents can quickly escalate and cause the entire system to fail. HRT, on the other hand, contends that there are certain organisations that manage to maintain a remarkably low occurrence of accidents in spite of the highly uncertain and changing conditions in which they operate. Examples of such organisations include nuclear power plants, aircraft carriers, submarines, and air traffic control systems. These organisations are referred to as *high reliability organizations* (HROs)<sup>3</sup>. Further research<sup>4</sup> has shown that, to maintain their remarkable safety performance, HROs operate by implementing the principles of: (1) Preoccupation with failure, (2) Reluctance to simplify interpretations, (3) Sensitivity to operations (4) Commitment to resilience, and (5) Deference of expertise.

Our intention in this paper is to speak to the existing debates in the field of organisational reliability and address the identified challenges of the systematic view<sup>5</sup> and the importance of the temporal dimension<sup>6</sup>. To this end, we employ an empirical research study that focuses on reliability in the project-operations transition stage of a large airport reconstruction project. After having elucidated the theoretical perspective and purpose of this study, we now turn to the research design and method. We also hope to contribute to the project studies and organisational literature by deepening our understanding of the often neglected transition to operations in the back-end of project life cycle.

## RESEARCH DESIGN AND DATA COLLECTION

We selected the project to operations transition stage in the setting of an airport terminal because prior research suggested that this is a difficult and poorly understood activity<sup>7</sup>. As experience with some major international airports has shown, problems that occur during the transition to airport operations can rapidly change the public perception of an otherwise successful project. One of the notable examples of such a situation is the hugely disrupted handover of Heathrow Terminal 5 in 2008 due to the poor coordination between BAA, the airport owner, and British Airways, the eventual occupier of the new building<sup>8</sup>.

The empirical research is designed as case study<sup>9</sup> of Heathrow Terminal 2 (T2), at the time of conducting the present study, an ongoing airport reconstruction project worth £2.5 billion (current price). Apart from its sheer scale, the complexity of the project was associated with creating a new terminal in a fully operational, extremely busy and

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1 Perrow, C. (2011). *Normal Accidents: Living with High Risk Technologies (Updated)*. Princeton University Press

2 Weick, K. E., and Sutcliffe, K. M. (2011). *Managing the Unexpected: Resilient Performance in an Age of Uncertainty*. Vol. 8, John Wiley & Sons

3 La Porte, T. R. (1996). "High Reliability Organizations: Unlikely, Demanding and at Risk." *Journal of contingencies and crisis management*, 4(2), 60-71.

4 Weick, K. E., and Sutcliffe, K. M. (2011). *Managing the Unexpected: Resilient Performance in an Age of Uncertainty*. Vol. 8, John Wiley & Sons.

5 Leveson, N., Dulac, N., Marais, K. and Carroll, J. (2009). "Moving Beyond Normal Accidents and High Reliability Organizations: A Systems Approach to Safety in Complex Systems." *Organization Studies*, 30(2-3), 227-249

6 Shrivastava, S., Sonpar, K. and Pazzaglia, F. (2009). "Normal Accident Theory Versus High Reliability Theory: A Resolution and Call for an Open Systems View of Accidents." *Human Relations*, 62(9), 1357-1390.

7 Davies, A., Gann, D. and Douglas, T. (2009). "Innovation in Megaprojects: Systems Integration at London Heathrow Terminal 5." *California Management Review*, 51(2).

8 Brady, T., and Davies, A. (2010). "From Hero to Hubris-Reconsidering the Project Management of Heathrow's Terminal 5." *International Journal of Project Management*, 28(2), 151-157.

9 Yin, R. K. (2011). *Applications of Case Study Research*. Sage

congested airport, where operations had to be maintained despite the ongoing works. Motivated by lessons learned from various airport openings worldwide, the transition from the project to operations played a major role in the project. Reliability and safety were expressly a key part of the organisational culture in this project which makes it a particularly relevant research setting to study aspects of reliability in the delivery of infrastructure operations to the end users. Moreover, the airport opening was publicly perceived as successful and various public media made recurrent references that attribute the successful opening to the carefully planned transition from construction to becoming operational. A number of organisations had to work interdependently during the handover including a new Operational Readiness (OR) team established to achieve a smooth opening.

This study aimed to answer the following research question: What the organisation responsible for creating the new airport terminal did to successfully manage the transition from project mode to operations mode? To address this research question, we designed a study that focuses on understanding the role, practices and interactions of the various organisations involved in delivering the new terminal building. The exploratory phase of the research comprised a one-day observational visit of the project, whereby we conducted preliminary conceptual interviews<sup>10</sup> with three highly-knowledgeable informants. The outcome of this preliminary phase was the formulation of the above research question and preliminary validation of the relevance of a study focusing on the transition towards operational delivery.

To explore the conditions required to ensure a reliable handover, we approached a number of key informants in Heathrow Airport Limited, the project client organisation, to interview them about key aspects of safety and reliability as part of their organisational culture in delivering this airport project. The key informants were selected from different levels of the organisation such as (1) leadership, (2) organisational units, and (3) technical systems teams (e.g., buildings, and information and communication systems).

## EMERGENT FINDINGS: BUILDING OF PROGRESSIVE CONFIDENCE

Preliminary findings from the interviews and secondary project data indicate that reliability was a key aspect of the organisational culture both in the transition towards operational delivery as well as at the point of the project handover. Overall, emergent findings suggest a narrative in which the handover reliability can be conceived as a process of *building progressive confidence* as the project moves towards full operations. This progressive confidence is characterised by establishing routines, tests and guarantees to ensure a predictable transition process, whilst being constantly vigilant to the possibility of potential disruptions. Whilst the emphasis in progressive confidence building is on providing stability, there was an ever present recognition that the organisation had to be able to quickly and effectively solve unexpected problems and events that might hamper the smooth transition to operations. We continue with summarising several streams of findings that are emerging from the ongoing data analysis.

### Organisational learning

The informants made frequent references to lessons learned from a previous project that was delivered within the client organisation. The experience on this project was the basis for designing the handover effort of the project. This previous project experience was the motivation to take a strategic focus on the delivery of services and prepare for the operations six months ahead of the go-live date and with the specific strategic focus on passenger experience. Similarly, on the basis of experiences from openings of other international airports, the overarching strategy for the operations was to implement a “soft” opening with sufficient buffers in the airport capacity to accommodate any unforeseen events and, as a result, to achieve a formal opening that was a “*non-event*” in journalistic headlines terms. The period subsequent to the opening was, moreover, planned as a gradual *ramp-up period* of 4 months where the airport’s operations would be scaled up to gradually reach their full operating capacity allowing for sufficient time to adapt the processes to the new setting. One of the results of the strong sense for organisational learning was to plan a specific moment in the project timeline when the organisational ownership of the project would be handed over from the construction and development team to the operational readiness team. This important milestone in the project was, in the data, referred to as *the flip* that is further described in more detail.

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10 Spradley, J. P. (1979). *The Ethnographic Interview*. Holt, Rinehart and Winston New York.

### The “flip” between project and operations

The informants indicated that a particular date in the project timeline marked a significant shift of the emphasis from the construction project to the transitional project. This so called *flip* was referred to on numerous occasions by the informants in the context of events that occurred before or subsequent to it. While before the flip the focus was on system testing, after the flip the construction site was being used primarily for the purpose of staged trials. As opposed to technical testing of devices, the trials involved people and were organised in a succession going from physical units to entire areas in a progressively complex effort. The project involved 192 trials with a familiarisation program involving 3000 people in the final trials that also included a dummy live flight before the opening.

The gradual progression in the trials was organised in a way similar to the “soft” opening and gradual ramp-up plan for the airport operations. The rationale behind it was very well aligned with the basic principles of high-reliability organisations. Systems were established to ensure the performance of different aspects of user and operator interactions in the way that each subsequent trial was designed with an increased complexity and scale of system interactions. In such a way, the organisations involved in the transition towards the handover were dealing with high levels of uncertainty such as the numerous change requests that were generated as the project proceeded. This aspect is further elaborated in the following subsection.

### Dealing with change

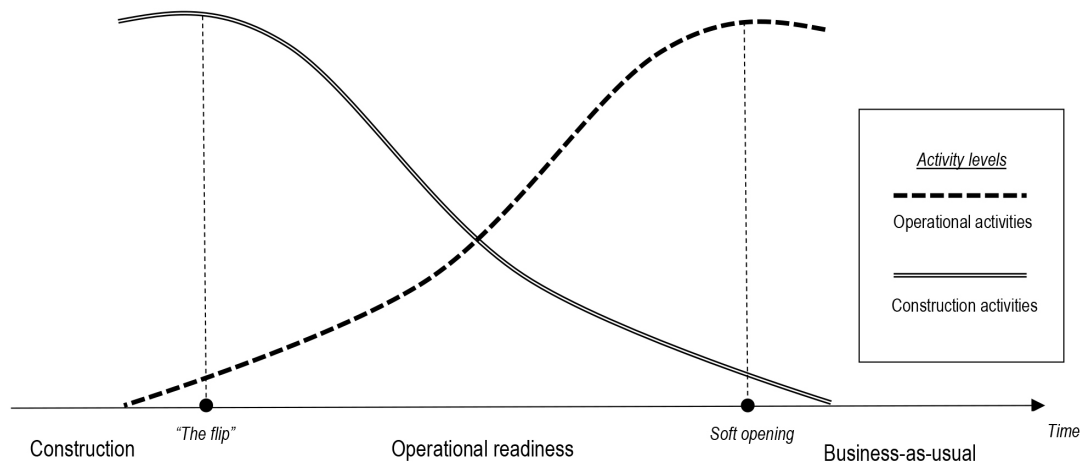
It was clear from the outset of the project that a combination of the complexity of the building and the rapidly changing aviation industry were likely to have an impact on the project as it unfolded with the requirement for changes. It is not surprising that this assumption proved to be true. Changes in scope, specification, and sequencing were a pervasive feature of the entire project, ranging from business changes of the airport tenant airlines, across policy-level changes in border control processes, towards the technological innovation of common check-in areas. As many of the changes were being implemented in the development and construction processes, they were particularly emphasised by the informants to have had a substantial impact on the trials and transition processes. As a result, the trials were often reporting difficulties as the changes were propagating throughout the airport project propelled by technical, business, social, as well as policy-level interdependencies that emerged but were unidentifiable from the outset of the project. One instance that describes the enactment of a chain of changes is the situation when an airline company expected to be a key tenant was taken over and, as a result, moved to another terminal in the airport. This caused a substantial reorganisation of the terminal building layout and processes because these were initially being developed to match the business model and processes of that particular airline company. As a consequence, the board of the client organisation negotiated a solution in which a major alliance (consisting of 23 international airlines) was chosen as the client of the airport development. This changed the project significantly because the various airlines did not necessarily share the same processes. As a result, a number of changes were instigated in the project at levels of technical support systems, layout of different parts of the facility, and design of the processes and passenger flows. This had a knock-on effect for the airlines themselves as not all of them had the processes in place to accommodate these changes. This awareness about the inevitability of change was ingrained in project practices and organisational culture. This translated into the level of organisational and business structure where the project used two separate contracts. Whereas one contract was specifying the requirements and defining the deliverables, a completely separate contract was in place to deal with all the incoming changes on the project. Summarising the emergent findings of the study, it can be said that the awareness of these changes and uncertainty led to a particular mind-set, characteristic for organisations that need to reliably operate in high-risk environments. We next discuss these findings in more detail.

## DISCUSSION AND CONCLUSIONS

Practices of high-reliable organisations include preoccupation with failure, reluctance to simplify, sensitivity to operations, commitment to resilience, and deference to expertise. Different interpretations and examples that can be reduced to these particular features are pervasive in the interview accounts. Drawing from these inferences, we refer to the various reliability practices as the *progressive building of confidence*. This term aptly summarises the emergent findings from the ongoing analysis of the case study data. The notion of progressive confidence teases out the emergent aspects of interdependency between project and operations that are normally not taken into account in discussions around the delivery of infrastructure assets and services. The emergent findings are summarised in the figure below (Fig 1).

This figure shows the relation between the activities of construction and operations. As opposed to the traditional project management body of knowledge that assumes projects entail discrete phases, our findings suggest that focusing on the discontinuities between these phases, in particular between construction and operations provides valuable insights into understanding the delivery of infrastructure services. Along the lines of this rationale, the handover of the project to the operators can be understood as a transitional phase that was labelled Operational Readiness in the case project. This transition can also be understood as a sub-project in its own right as:

- It is a temporary organisation with a specific purpose (i.e. to ensure a seamless delivery of infrastructure functionality to the users and operators),
- It is delivered in a limited timeframe (i.e. before the opening date)
- It requires substantial resources given its large scope (i.e. including technical tests and trials)



**Figure 1 – The transition between project and operations as the process of “progressive building of confidence”**

This transitional project is bounded by the construction activities on the one end and business-as-usual operations on the other end. In the T2 case study, it was characterised by a significant overlap between streams of construction and operation work. To be more specific, the operational activities were developed and delivered with a progressively increasing intensity, escalating from the construction phase to full capacity operations. At the same time, construction activities gradually decreased until the point the facility reaches full operational capacity. This transformation, understood as an interplay between construction and operational activities is, we argue, the distinguishing feature of a successful operational delivery.

The main practical contribution arising from this ongoing study is in the importance of the ex-ante strategy for the transition from a construction project towards a project to successfully deliver a fully functional operated environment. Although largely ignored by existing PM bodies of knowledge, we found that the broad awareness about the importance of achieving operational delivery in line with high reliability principles, was a key feature that pervaded both the interview accounts as well as secondary project documentation. This state of mind resulted in what this paper labels as the *progressive building of confidence*, an area that, we believe, deserves a lot more attention both from the perspective of practices as well as academic research.

## ACKNOWLEDGMENTS

The authors would like to express their gratitude to the informants of the study whose details will not be disclosed. In particular, we would like to thank Sally Blackwell for sponsoring this research on behalf of Heathrow Airport Limited. Without her support, this study would have been impossible. Finally, ideas incorporated into this article are developed during research funded by the EPSRC and ESRC through the *International Centre for Infrastructure Futures*, which was also used to assist in providing the staff resource required to conduct the research.



# Integrated Resource Planning for a Chinese Urban Development

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<http://discovery.ucl.ac.uk/1469209/>

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## ABSTRACT

Urban areas manage vast quantities of energy, water and waste resources. In order to minimise the cost and environmental impact, optimisation modelling is often used in the design and operation of these systems. However, traditional modelling approaches only consider the energy, water and waste sectors in isolation. This approach neglects the synergies possible between these systems whereby outputs from one system form an input to another, and hence sets an upper bound on economic and environmental impact minimisation. We formulate a mixed integer linear programming (MILP) model which takes a 'systems-of-infrastructure systems' approach to show how resource consumption can be reduced. The model takes as inputs possible resource conversion and transportation infrastructure and resources, and resource demands, and returns the optimal infrastructure choice and layout. The model is called PRaQ because it models 'processes, resources and qualities.' We apply the model to the design of a new urban development in China for three scenarios of various levels of resource integration. Results are still to be obtained.

**Keywords:** Infrastructure, Optimization, Modelling, Urban Resource Management, Industrial Symbiosis

## INTRODUCTION

Cities perform a vital socioeconomic role in human civilisation. Currently home to about half of the world's population, they generate around 80% of global GDP<sup>1</sup>, and are a proven means for improving quality of life as people seek health, economic, educational and other benefits. Accordingly, the globe's urban population is forecasted to rise to around 70% in 2050<sup>2</sup>. To achieve this level of urban growth, vast quantities of energy, water and waste must be consumed to support basic services and economic activity. This poses significant environmental challenges, including resource scarcity, poor water quality, air pollution<sup>3</sup>, water stress<sup>4</sup>, decreasing waste management capacity, and greenhouse gas emissions. Additionally, high levels of resource consumption pose an economic risk to an area, as a population outgrows its resource supply, imposing a limit on growth<sup>5</sup>.

The management of these energy, water and waste flows requires conversion, transport and storage infrastructures, and as such, efforts to reduce resource consumption are (in part) focused on better design and management of these systems. Traditionally, work in this area has tended to be siloed within individual infrastructure systems. However, in urban areas,

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1 United Nations. *World urbanization prospects*. (2011).

2 World Bank. *World development reports*. (2009).

3 Cao, S. & Li, C. The exploration of concepts and methods for low-carbon eco-city planning. *Procedia Environmental Sciences*. 5, 199-207 (2011).

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5 Bettencourt, L. M., Lobo, J., Helbing, D., Kühnert, C., & West, G. B. Growth, innovation, scaling, and the pace of life in cities. *Proc Natl Acad Sci U.S.A.* 104(17), 7301-7306 (2007).

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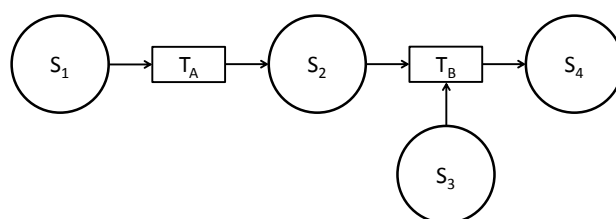


the co-location of infrastructure enables synergies between networks, whereby the output from one sector becomes an input to another. (Examples include waste-to-energy, biogas from sewage sludge, hydroelectric power, wastewater reuse<sup>6</sup>, and ‘industrial symbiosis’<sup>7</sup>.) Therefore, current approaches to urban resource management impose an upper-bound on the material and energy savings that are possible.

In this paper, we attempt to move beyond the traditional sector-specific focus on resource efficiency and examine integrated management of energy, water and waste infrastructures. Our objective is to develop an optimization model that can maximise opportunities for systems integration, and by applying it to a case study in urban China, to quantify the potential gains of such an approach under different development scenarios. We begin by discussing the current state of urban resource systems modelling and offer our proposed modelling framework. Next, we introduce a case study of a new urban development in China and describe how the model is applied. Finally, we present the results and summarise our conclusions.

## MODELLING URBAN RESOURCE SYSTEMS

The literature contains a wide variety of energy, water and waste planning models but lacks tools which meet demand for all three resource types simultaneously. To deal with multiple resource types in this manner, we require the model to have a very generic formulation. For this reason, we base our work on that of Samsatli and Jennings (2013)<sup>8</sup> (which is applied in Keirstead et al (2012)<sup>9</sup>). Thus it is based on a state-task network chemical engineering process model<sup>10</sup>, where ‘states’ represent any material with a given set of properties, and ‘tasks’ represent processes that convert a set of input states to a set of output states (Figure 1). Samsatli and Jennings apply this approach to urban energy systems, representing them as a network of resources (states) and technologies (tasks). A resource represents any material or energy streams involved in meeting energy demand.



**Figure 1. A state-task network. States denoted by ‘S’; tasks denoted by ‘T’.**

Here, we extend this formulation beyond energy resources to include water and waste, with demand for each of energy, water and waste management being met. Thus, gas, electricity, heat, water, wastewater, municipal solid waste and CO<sub>2</sub> can all be considered resources. Processes are used to represent any activity that can convert a set of input resources to a set of output resources. For example, Figure 1 could represent a power plant (T<sub>A</sub>), which takes coal (S<sub>1</sub>) as input, and produces electricity (S<sub>2</sub>); the electricity is fed into a wastewater-source heat pump (T<sub>B</sub>) along with wastewater (S<sub>3</sub>), from which heat (S<sub>4</sub>) is extracted. Processes also model the transport of resources using similar methods to evaluate the resource requirements and losses involved in transport networks (such as pipes and cables).

In addition to a broader range of resources, a further development to Samsatli and Jennings’ model is the incorporation of resource quality modelling. For example, when pumping water, pipe-wall friction will reduce the water’s energy head. In an integrated model, where the pumping energy will be a decision variable (together with the mass of water pumped), it is important to consider these energy losses, as this will impact the primary resources used in energy generating processes. Thus each resource must have at least one quality attribute corresponding to the resource properties we are concerned with. The model’s inclusion of processes, resources and qualities gives rise to its name ‘PRaQ’ (‘processes, resources and qualities’). To use the model, we must specify:

6 Kharrzi, A. & Masaru. Y. Quantifying the sustainability of integrated urban waste and energy networks: seeking an optimal balance between network efficiency and resilience. *Procedia Environmental Sciences*. 13, 1663-1667 (2012).

7 Eckelman, M. J. & Chertow, M. R. Life cycle energy and environmental benefits of a US industrial symbiosis. *Int J Life Cycle Assess*. 18(8), 1524-1532 (2013).

8 Samsatli, N. & Jennings, M.G. ‘Optimization and systems integration’ in Keirstead and Shah (eds) *Urban Energy Systems: An Integrated Approach*. Routledge (2013).

9 Keirstead, J., Samsatli, N., Pantaleo, A. M. & Shah, N. Evaluating biomass energy strategies for a UK eco-town with an MILP optimization model. *Biomass Bioenerg*. 39, 306-316 (2012).

10 Kondili, E., Pantelid, C. & Sargent, R. A general algorithm for short-term scheduling of batch operations I. MILP Formulation. *Comput Chem Eng*. 17(2), 211-227 (1993).



- resource demands for each zone of the study area, and time period;
- a set of allowable conversion and transport processes and their associated resources;
- coefficients to relate the input and output resource quantities and qualities for each process;
- the costs and emissions of resource imports;
- the cost for process capital, operation and maintenance;
- constraints on the minimum and maximum rate of process operation, and the location of imports, exports and processes;
- an objective function that minimises cost, emissions or some other indicator.

Given these inputs, the model will return an optimal resource-process network configuration, process operating rates, resource import/export schedules, and a summary of system performance metrics.

## A CASE STUDY: THE SHANNGU URBAN DEVELOPMENT

The intention of PRaQ is that it can be used as a strategic planning tool, to support engineers and architects at the early stages of urban planning, most ideally for the case where one decision maker is responsible for all the management of all resource types. This is the organisational structure for a new urban development managed by the ShaanGu Power Company Ltd<sup>11</sup>. Historically they manufacture machinery, but more recently they have expanded into utility service provision, managing the energy, water and waste for the redevelopment of an old industrial park in China.

## MODEL SCENARIOS

Three scenarios will be studied in order to evaluate the potential savings of alternative technology configurations. Each scenario will specify the same demands for heating, cooling, electricity, water, waste management and wastewater treatment. However they will vary in terms of the allowable set of input technologies:

- Grid case. This will meet demand by using technologies that require directly imported resources (for example a gas-fuelled domestic boiler). This represents a ‘business-as-usual’ scenario.
- Design case. This uses technologies which can reuse outputs from other processes. For example, a water-source heat pump (to provide heating) can be served by wastewater. This case is based on a design proposal by the ShaanGu Power Company.
- Wildcard case. This combines the above two technology sets.

For each scenario, the model is run to find the system that minimises the combined capital, operating and resource import costs.

## RESULTS, DISCUSSION AND CONCLUSIONS

By comparing the results of each scenario, we show that for a given level of utility service demand, cost savings can be made through integrated resource planning (Figure 1). A closer examination of the resource imports (Figure 2) shows that this is because the grid case relies on large import quantities of electricity (for cooling) and gas (for heating). The other scenarios (design and wildcard) integrate together the water and energy systems through the use of a water-source heat pump, with the result that the area is less reliant on resource imports.

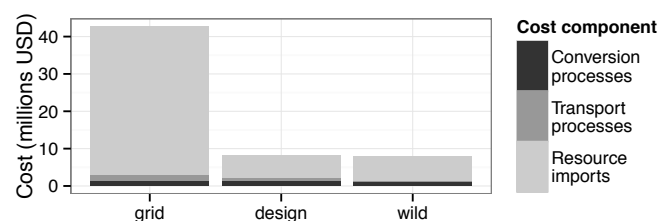
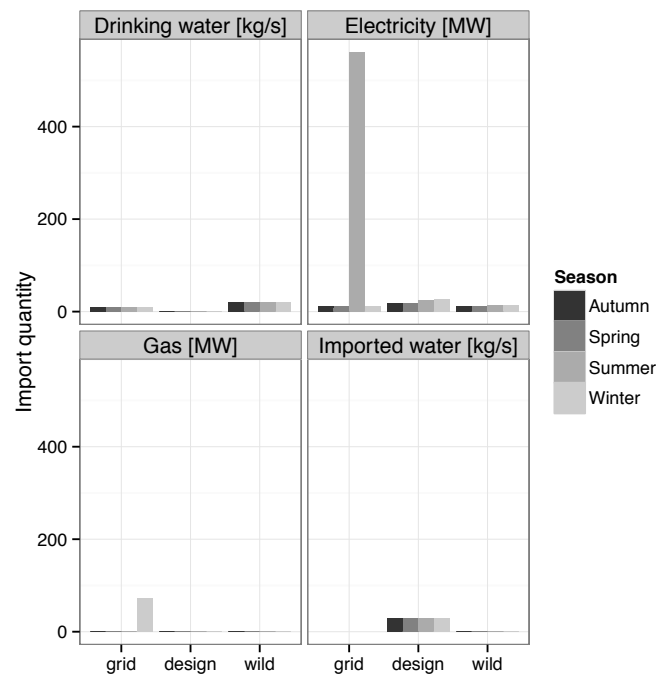


Figure 2. Annualised cost for each scenario.

11 <http://www.shangu.com>



**Figure 3. Resource imports for each scenario (by season).**

In conclusion, there is a growing awareness that the key to more efficient urban resource is a ‘system-of-systems’ approach, integrating the operation of urban resource infrastructures, that convert, transport and store energy, water, and waste. However there are currently no well-established tools for analysing such infrastructure configurations. The work presented here therefore builds on optimisation techniques that have demonstrated significant savings in the energy sector, and extends them to consider the integrated planning of multiple resource infrastructures. Accordingly the benefits of a ‘system-of-systems’ approach can be quantified according to chosen metrics, allowing stakeholders to explore a range of alternatives. More generally, PRaQ can enable us to develop a better appreciation for the key technological interventions (such as the water-source heat pump in this case study) that unlock wider resource efficiency in the urban environment.

Turning to consider the future of infrastructure, PRaQ can contribute to meeting the ‘Grand Challenge’ set out by the International Symposium for Next Generation Infrastructure<sup>12</sup>. PRaQ is a tool which moves us towards realising ‘infrastructure systems that can meet the needs of twice today’s population with half today’s resources’. Its offering is a modelling framework which considers the ‘web of interdependencies and interconnections’ between multiple types of physical infrastructure, thus adopting a ‘genuine systems perspective’ rather than ‘traditional disciplinary and sectoral’ approaches.

However, in order to be effective, this work must overcome the potentially conflicting interests of multiple decision makers. In the case study presented here, one firm manages all the resources for the urban development; but elsewhere in the world (for example, the United Kingdom) energy, water and waste infrastructures are operated by different companies, each with their own objectives. Thus, the physical ‘system-of-systems’ approach here should be incorporated into the broader economic and social ‘system-of-systems’ which dictate how infrastructure is organised. The ultimate aim being that through policy, planning, and institutional reform, we can move to a society that can fully embrace integrated resource planning, and realise the potential for mitigating against environmental problems and economic risk whilst retaining the socioeconomic benefits of urbanisation.

## ACKNOWLEDGEMENTS

The data for the model has been provided by the ShaanGu Power Co., Ltd, in collaboration with Dr Yingru Zhao of The School of Energy Research, Xiamen University. The authors would like to acknowledge Dr Nouri Samsatli for developing the original TURN model formulation and thank him for providing the GAMS code, which we modified for this study.

<sup>12</sup> <http://www.ucl.ac.uk/steapp/isngi/grandchallenge>

# Portfolio Structuring Model for Urban Infrastructure Investments

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<http://discovery.ucl.ac.uk/1469285/>

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## ABSTRACT

The objective of this work is to propose a new methodology based on the concept of portfolio structuring for urban infrastructure investment. We argue that city investments need to be treated as an integrated and interdependent entity and from this perspective, the portfolio methodology is proposed in order to assess the non-financial impacts of infrastructure projects and then combine them in a portfolio of investments from a financial perspective. The methodology is applied for a set of project under the EIB JESSICA Initiative. The methodology shows that not only is it possible to develop a practical decision support system to assist stakeholders in assessing the performance of individual urban infrastructure projects, but also how it is possible to combine projects into a portfolio. The method exceeds the simple analysis of returns of individual investment schemes and capitalizes on effective and integrated management of projects/investment. And this is the key to devising a focused response which will enable therefore cities to be globally competitive, via innovative financial and business models.

**Keywords:** City, Integrated Finance, Portfolio, Investment

## SUBHEAD REQUIRED

The present global tightening of credit has restricted local governments and private firms in their capacity to leverage debt in order to finance investments in urban development, especially when they advocate far-reaching sustainable solutions. High cost considerations and protracted delivery timetables continue to deter decision-makers and private investors from adopting innovative financing solutions as an alternative for investing in urban projects. However, we need to keep in mind that despite the bankruptcy of Detroit, city authorities continue to give the private sector *carte blanche* in some cases to invest in such piecemeal projects as, for example, multiplex cinemas, Wifi upgrades in high rise apartments and waterfront features. Nevertheless, a new urban paradigm which embeds economic, environmental and social aspects within innovative financial mechanisms is now emerging. Central to this new paradigm are creativity, knowledge and access to information as the fundamental drivers of the new urban finance.

Creativity in our context refers to the formulation of innovative financial mechanisms such as crowdsourcing, peer-to-peer lending and impact investments, to mention a few. These financial advances are particularly evident at the micro-urban level, i.e. as bottom-up manifestations where the average citizen can participate in new urban initiatives. Citizens are nowadays less passive consumers and are instead increasingly finding and building their own solutions to overcome obstacles. For instance, e-Adept is an initiative in the city of Stockholm that enables visually-impaired people to navigate the city using open data. With an investment of £500.000, the city now generates economic benefits of £20.000.000.

Urban investments should therefore be treated as an integrated and interdependent entity, and from this perspective we propose the concept of portfolio investment where, rather than piecemeal projects, cities invest in differentiated

yet integrated investments. This type of approach would constitute a viable solution for the urban investments, particular infrastructure investments.

A portfolio of diverse urban projects is not, however, a trade-off between so-called bad projects and good projects (kindergarten versus beach front hotel). A diverse portfolio allows for both risky and less risky investments, giving the private sector high financial returns while also addressing wider city/social needs. Private sector participation in urban investment is likely to increase if the portfolio offers a wide (diverse) range of urban assets in which to invest, including energy efficiency, urban development and urban regeneration. By combining different types of projects and fostering synergy between investments, a diversified portfolio with good financial returns on some projects would compensate for (cross-subsidise) the poor financial returns of other projects, which nevertheless achieve good non-financial impacts. Private sector participation, it can be argued, is likely to increase if the investment portfolio ranges across sectors and objectives to include integrated sustainable urban investments, and is also attractive to pension funds, commercial banks and regional development institutions. For instance, a cross-subsidy process between projects would allow schools to be built, importantly, without the need for grants or state aid; these investments give low financial returns but they also produce high non-financial impacts for a city.

However, the discussion above raises a critical point with regard to decision makers and how they choose to finance urban projects: programme administrators and other professionals who shape our cities are often educated and trained according to theories and experience they have derived largely through specialisation – so their problem-solving approach may in practice be carried out through a single disciplinary lens. These professionals are certainly aware of the impacts of other disciplines, and are likely to allow for such influences as they impact on, for example, funding for urban projects. Nevertheless, the tendency for decision makers to retreat into disciplinary silos and be predisposed to a specialised vantage point, although appropriate in certain contexts, is not helpful in the implementation of solutions to complex challenges posed by cities.

To make successful investment decisions it is therefore necessary to strike a balance between the interdependency between projects and the requirements for reaching an investment 'critical mass', i.e., have low investment risk and be attractive to the private sector. Given that the ultimate goal is to achieve benefits and to share risks and costs, cooperation between the public and private sector is crucial to the development of a well-designed framework for investment that will yield income for both participants: in the case of local institutions (to defray current expenditures) and for private partners (to remunerate their capital contributions).

By factoring cooperation into our definition of a portfolio approach for urban investment, as a prerequisite, we have also needed to re-envision city financial models by linking together some of the inevitable silos that arise through various urban initiatives (e.g., waste, energy, health, education, transport). Moreover, it has also been crucial to maximise the benefits of effective management of urban capital assets (e.g., human capital, natural capital and fixed capital). In order for cities to be globally competitive, investment via innovative financial and business models must be *unlocked*, and for this reason the proposed portfolio approach exceeds the simple analysis of returns of individual investment schemes, and capitalises on effective and integrated management of projects/investments in a focused response.

The development of the portfolio for urban investments intends to give stakeholders and decision makers a practical tool to structure and combine different typologies of projects. We can summarise the main reasons for implementing this approach, which are to:

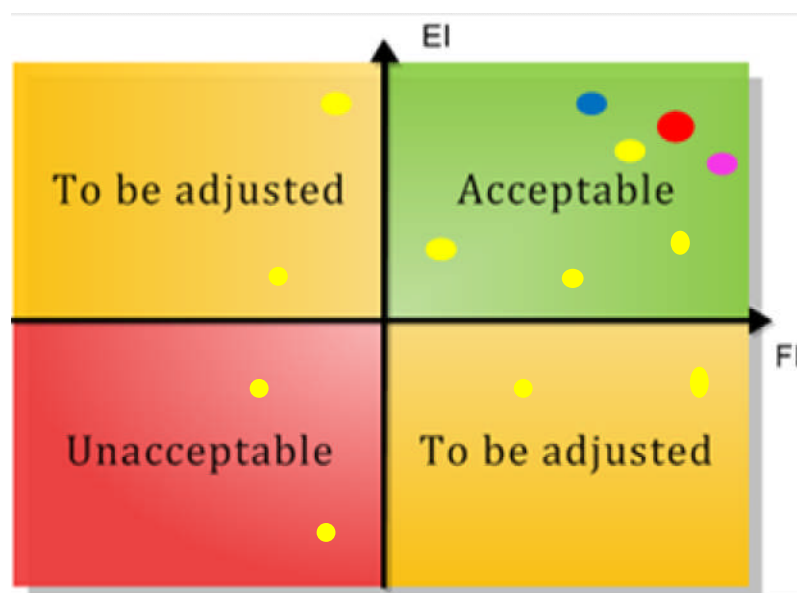
- Combine different types of projects, thereby fostering synergy between investments to obtain a diversified portfolio where the good financial returns of some projects can compensate for (cross-subsidise) the 'poor' financial returns of other projects, which nevertheless achieve good non-financial impacts (socio-economic and environmental benefits).
- Increase private sector participation by structuring a portfolio offering feasible and attractive opportunities for investment in different types of urban assets, including energy efficiency, urban development and urban regeneration.

To effectively and efficiently structure the portfolio of projects, it is necessary to account for the evaluation of risks, since a lower level of risk exposure will be an attractive feature of the portfolio, particularly for the private sector. We have observed that urban projects are often susceptible to high levels of political/government risk, particularly around land purchase, planning and building permits, which can lead to protracted delays. In the evaluation of the portfolio both political and governmental risk are directly captured.

We have mentioned the administrative and political agencies which are the overseers of projects; these agents are

fundamental to the effective implementation, successful completion and transparent monitoring and assessment of urban investments. So-called virtuous administrations may be small/middle size administrations and may not receive the largest capital share for projects, and it is noteworthy that virtuous administrations are sometimes overlooked by lending agencies and private investors who think large and thus focus mainly on the number and size of projects. Against this background, we account in the evaluation of the portfolio for good governance by assessing political and government risk in project implementation, and thus we incorporate an independent measure of the level of quality of governance in cities where projects are carried out.

The graph below depicts an example of the portfolio approach for urban investments. Non-Financial Impacts are measured on the vertical axis “EI”, and Financial Impacts are shown as “FI” on the horizontal axis. All yellow dots indicate single projects (6 in total), and the other dots (blue, red and pink) indicate various portfolio combinations of the projects (52 combined portfolios of the 6 projects).



**Figure 1: Portfolio Structuring: yellow dots are the projects; red, blue and magenta dots are the portfolios**

The portfolio that our city should select is represented by the red dot. The visualisation of projects and their portfolio combinations is an important feature of the portfolio approach. In fact, the user of the portfolio software platform can easily evaluate different portfolio options (blue, pink and red dots). For instance, the user can choose the blue or the pink portfolio in accordance with a preference for either Non-Financial or Financial impacts. If the user values financial performance above non-financial impacts then the portfolio with the highest financial impact (pink dot on the graph) will be selected. Moreover, if new projects are added to the portfolio over time, the user can verify whether or not they improve overall performance of the portfolio.

The portfolio investment approach shows that it is possible to develop a practical decision-support system to assist stakeholders in assessing the performance of individual projects, and it also demonstrates how to combine projects into an integrated portfolio approach. This type of innovative financial tool for city investments can spur further financial innovations and facilitate connections and new ownership among citizens. As has always been the case, investors (private and public) will continuously find new ways to design, interlink, make sense of, and make decisions (albeit more quickly), based on for instance, public data on consumer behaviour. We are targeting the smartness of citizens rather than installed ‘smart systems’ hovering above cities. The platform of the portfolio we propose points up cities as dynamos of diversity which are reconfigured due to the creative capacity of their citizens. As a French general was said to have responded to his head gardener when told that his plans for creating an oak forest would take hundreds of years, “Quick then, we have not a moment to lose.”



# An Agent Based Model for the Simulation of Transport Demand and Land Use

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## ABSTRACT

Agent based modelling has emerged as a promising tool to provide planners with insights on social behaviour and the interdependencies characterising urban system, particularly with respect to transport and infrastructure planning. This paper presents an agent based model for the simulation of land use and transport demand of an urban area of Sydney, Australia. Each individual in the model has a travel diary which comprises a sequence of trips the person makes in a representative day as well as trip attributes such as travel mode, trip purpose, and departure time. Individuals are associated with each other by their household relationship, which helps define the interdependencies of their travel diary and constrains their mode choice. This allows the model to not only realistically reproduce how the current population uses existing transport infrastructure but more importantly provide comprehensive insight into future transport demands. The router of the traffic micro-simulator TRANSIMS is incorporated in the model to inform the actual travel time of each trip and changes of traffic density on the road network. Simulation results show very good agreement with survey data in terms of the distribution of trips done by transport modes and by trip purposes, as well as the traffic density along the main road in the study area.

**Keywords:** Agent Based Model, TRANSIMS, Road Traffic, Transport Demand, Urban Planning

## INTRODUCTION

The ability to realistically predict the demand of transport and traffic on the road network is of critical importance to efficient urban transport and infrastructure planning. Agent based models of urban planning have been increasingly introduced over the last decades. Many agent based models for transport and urban planning can be found in the literature with different geographical scales and at various levels of complexity of agent's behaviours and autonomy. They proved that with a large real world scenario, agent based modelling, while being able to reproduce the complexity of an urban area and predict emergent behaviours in the area, has no issue with the performance<sup>1</sup>. They also show that for traffic and transport simulation purposes, agent based modelling has been considered as a reliable and well worth developing tool that planners can employ to build and evaluate alternative scenarios of an urban area.

Many models that have been reported in the literature however are unable to explicitly simulate the dynamic interactions between the population growth, the transport/traffic demands, urban mobility (i.e. residential relocation of households), and the resulting changes in how the population perceive the liveability of an urban area. The agent based model presented in this paper aims at addressing this gap in the literature. The heterogeneity of the population is represented in the model in terms of demographic characteristics, environmental perception, and decision making behaviour. Inherently, the simulated

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<sup>1</sup> Vogel, A. and Nagel, K. Multi-agent based simulation of individual traffic in Berlin. *CUPUM 2005 Conference*, <http://128.40.111.250/cupum/searchpapers/papers/paper179.pdf> (2005)

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population will evolve over time facilitating the interactions between dynamics of residential relocation of households, transportation behaviours and population growth. Thanks to this feature, the model can be used for exploring long-term (e.g. 20 year time horizon) consequences of various transport and land use planning scenarios.

Individuals are represented in this model as autonomous decision makers that make decisions that affect their environment (i.e. travel mode choice and relocation choice) as well as are required to make decisions in reaction to changes in their environment (e.g. family situation, employment). With respect to transportation, each individual has a travel diary which comprises a sequence of trips the person makes in a representative day as well as trip attributes such as travel mode, trip purpose, and departure time. Individuals in the model are associated with each other by their household relationship, which helps define the interdependencies of their travel diary and constrains their mode choice. This feature, together with the interactions between urban mobility, transportation behaviours, and population growth, allows the model to not only realistically reproduce how the current population uses existing transport infrastructure but more importantly provide comprehensive insight into its future transport demands. The router of the traffic micro-simulation package TRANSIMS is incorporated in the agent based model to inform the actual travel time of each trip (which agents use in considering new travel modes) and changes of traffic density on the road network.

Major components that constitute the agent based model in this study are (i) synthetic population, (ii) residential relocation choice, (iii) perceived liveability, (iv) travel diaries, (v) traffic micro-simulation, and (vi) transport mode choice. These components equip the model with unique features that allows it to be used as a comprehensive tool for assisting integrated travel – land use planning. These components are briefly described in Section 2 in order to provide a full picture of the model features and capabilities. The focus of this work however will be in reporting the simulation results in regards to road traffic and transport demands (Section 3). The paper closes with discussions on further developments of the model.

## MODEL COMPONENTS

This section provides an overview of the six main components that constitute the agent based model in this study<sup>2</sup>.

### Synthetic population

The purpose of the synthetic population is to create a valid computational representation of the population in the study area that matches the distribution of individuals and household as per the demographics from census data. The construction of the synthetic population involves the creation of a proto-population calibrated on socio-demographic information provided by the Australian census data (full enumeration). Different to the majority of existing algorithms for constructing a synthetic population, the algorithm used in this study uses only aggregated data of demographic distributions as inputs, i.e. no disaggregated records of individuals or households (e.g. a survey) are required<sup>3</sup>. The resulting synthetic population is made of individuals belonging to specific households and associated with each other by household relationship.

This initial population is evolved according to annual increments during the simulation period. Each individual and household is susceptible to various demographic (e.g. aging, coupling, divorcing, reproducing of individuals) and economic changes controlled by conditional probabilities. The consequent changes in the structure of households as a result of these processes are also captured. An immigrant population may be added to the existent population of the study area at the end of each simulation step.

### Residential location choice

Household relocation modelling is an integral part of both the residential and transport planning processes as household locations determine demand for community facilities and services, including transport network demands. The approach used to model residential location choice includes two distinct processes<sup>4</sup>: the decision to relocate, and the process of finding a new dwelling. A multinomial logit model was used to represent the process by which households make

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2 Berryman, M. J., Denamagage, R. W., Cao, V. & Perez, P. Modelling and data frameworks for understanding infrastructure systems through a systems-of-systems lens. *International Symposium for Next Generation Infrastructure 2013*, 1-13, University of Wollongong, Wollongong (2013).

3 Huynh, N., Namazi-Rad, M., Perez, P., Berryman, M. J., Chen, Q. & Barthelémy, J. Generating a synthetic population in support of agent-based modeling of transportation. *Sydney 20th International Congress on Modelling and Simulation*, 1357-1363, The Modelling and Simulation Society of Australia and New Zealand, Australia (2013).

4 Namazi Rad, M., Shukla, N., Munoz Aneiros, A., Mokhtarian Dehkordi, P. & Ma, J. A probabilistic predictive model for residual mobility in Australia. *International Symposium for Next Generation Infrastructure 2013*, 1-6, University of Wollongong, Wollongong (2013).

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decision to relocate. The attributes of this model are change in household income, change of household configuration (e.g. having a newborn, divorced couples, newly wed couples), and the tenure of the household. The HILDA data was used to regress the coefficients associated to each of these attributes needed in the binomial logit model.

Once a household is selected for relocation, the second decision determines where the household will relocate and whether they will be renting or buying a dwelling in the target location, if a suitable dwelling is found. This process of finding a new dwelling is modelled as a constraint satisfaction process, whereby each household will attempt to find a suitable dwelling based on three factors, affordability, availability, and satisfaction.

### **Perceived liveability**

A significant departure of the current model to other existing approaches is the assumption that residential location choice is based not only on availability and affordability principles but also on the perception that individuals have of the quality of their living environment. The perceived liveability component uses a semi-empirical model to estimate individual levels of attraction to and satisfaction with specific locations<sup>5, 6</sup>. The semi-empirical model is a statistical weighted linear model calibrated on a computer assisted telephone interviewing survey data collected in the study area.

### **Travel diaries**

Each individual in the synthetic population is assigned with a travel diary which comprises a sequence of trips the person makes in a representative day as well as trip attributes such as travel mode, trip purpose, departure time, origin and destination. Because these details of travel behaviours of the population are not completely available in any single source of data (for confidentiality reasons), the process of assigning travel diaries to individuals comprises two steps. The first step assigns a trip sequence each individual makes in a representative day using the Household Travel Survey data. Details of each trip in this trip sequence include trip purpose, travel mode, and departure time. The second step assigns locations to the origin and destination of each trip in the trip sequence.

Due to changes in the synthetic household attributes (e.g. household type, number of children under 15, etc) as the population evolves, travel diaries may need to be reassigned in subsequent simulation steps to these households in the model.

### **Traffic micro simulation**

TRANSIMS was chosen as the traffic micro-simulator as, in its current iteration, it is a clean, efficient, C++-based platform that supports an individual level of modelling.

Normally one would use a process analogous to simulated annealing to arrive at the solution; running the router to establish initial routes, then finding when vehicles jam, and either redirecting them off the street temporarily into a park (if the numbers are sufficiently low) or by then re-routing them using the router and then running the simulation until numbers jammed are sufficiently low. Given the typical travel volumes (around 100,000 commuters), and our desire to simulate a 20-year period, we are forced to run only one typical weekday and weekend in simulation per year, and run only one iteration of the router. We have compared this with test runs of multiple iterations of router and the core micro-simulator of vehicle movements, and found that travel times are within 5%; this we consider sufficient for our purposes.

### **Transport mode choice**

The purpose of the travel mode choice algorithm was to accurately describe the decision-making processes of individuals travelling on the transport network in the study area, thus enabling the prediction of the choice of travel modes of individuals. Travel modes considered in this study are car driver, car passenger, public transport, taxi, bicycle, walk, and other.

A multinomial logit (MNL) model was developed for this purpose. At the heart of the MNL formulation is a linear part-worth utility function that calculates the utility of each alternative travel mode choice. Independent variables for this function include the difference of fixed cost and difference of variable cost of the selected travel mode with the cheapest mode. The variable cost is dependent on the estimated travel time, which is the output of the traffic micro-

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5 Namazi Rad, M., Perez, P., Berryman, M. & Lamy, F. An experimental determination of perceived liveability in Sydney. ACSPRI Conferences, RC33 Eighth International Conference on Social Science Methodology, 1-13, ACSPRI, Australia: (2012).

6 Namazi Rad, M., Lamy, F., Perez, P. & Berryman, M. A heuristic analytical technique for location-based liveability measurement. The Fifth Annual ASEARC Research Conference: Looking to the future, 35-38, University of Wollongong, Wollongong (2012).

simulation. Another independent variable is the individual's income, acting as a proxy for the individual's perception of value of time. MNL regression was used on the HTS data to estimate the utility coefficients.

### **Simulation results with regards to transport demands and road traffic**

The agent based model described in Section 2 is applied to simulate the dynamic interactions between population growth, urban relocation choice and transport demands for Randwick — Green Square, a metropolitan area in south east of Sydney, Australia. This area has a population of approximately 110000 individuals in around 52000 households that live in private dwellings.

The simulation period is from 2006 to 2011. The initial synthetic population is constructed using the 2006 census data that is available from the Australian Bureau of Statistics. This initial synthetic population was validated that it matches the demographics of the real population at both individual level and household level, and thus is a realistic computational representation of the real population in the area<sup>3</sup>. It was also shown that the synthetic population in year 2011 (i.e. after 5 simulation years) matches the demographics of the population in the study area as described in the 2011 census data. This affirmed that the algorithm to evolve the population while simulating the evolution at individual level can capture the dynamics of household structures in the population.

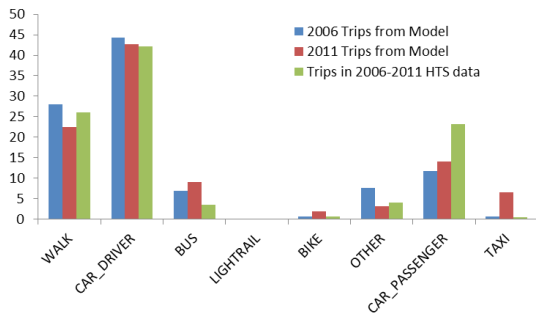
Figures 1 and 2 respectively show the percentage of trips by each mode and each purpose with respect to the total number of trips made by the whole population for year 2006 (initial year) and simulation year 2011. Figure 3 compares the percentage of individuals in the synthetic population against that in the HTS data by the number of trips made daily. The distributions in these graphs are in very good agreement with the HTS data for the whole Sydney Greater Metropolitan Area.

Trip counts by purposes over 24 hours of a representative day in year 2011 are shown in Figure 4. It can be observed that the model can realistically reproduce the patterns of travel demand of the population in the study area as well as the change of these patterns as the population evolves.

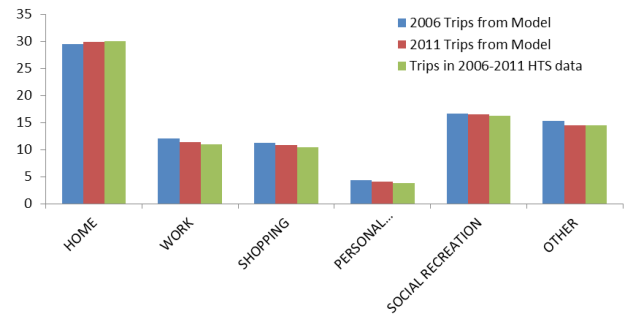
Traffic density (that was outputted from TRANSIMS) at one major intersection along Anzac Parade, the main road in the study area, in the morning peak hour (8.00am to 9.00am) compared against its congestion profile from Google Maps<sup>7</sup> is shown in Figure 5. The model is able to reproduce the relatively higher northbound traffic density. These results are in agreement with observations of traffic profiles from Google Maps. Qualitative trends of traffic counts at major cross sections from simulation results were also analysed and in good agreement with survey data in the study area.

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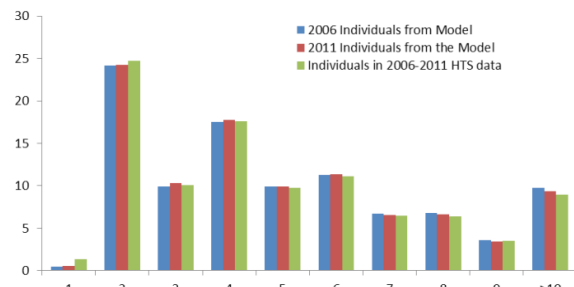
<sup>7</sup> Google Maps, <https://maps.google.com/> (accessed on 31/01/2014)



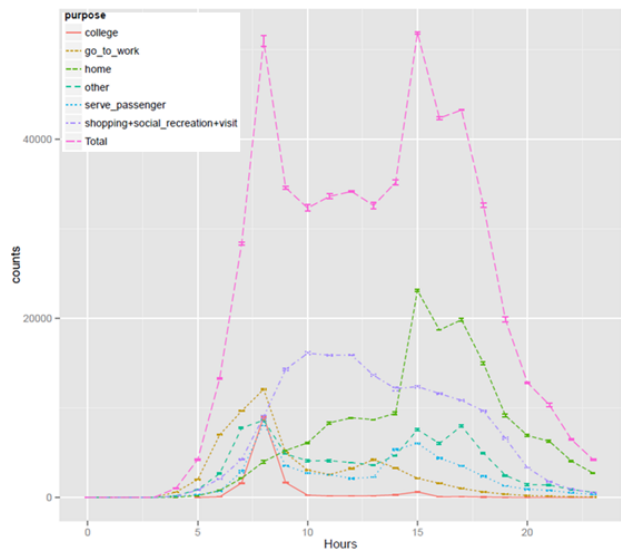
**Figure 1: Percentage of trips by modes from simulation years 2006 and 2011 vs 2006-2011 HTS data.**



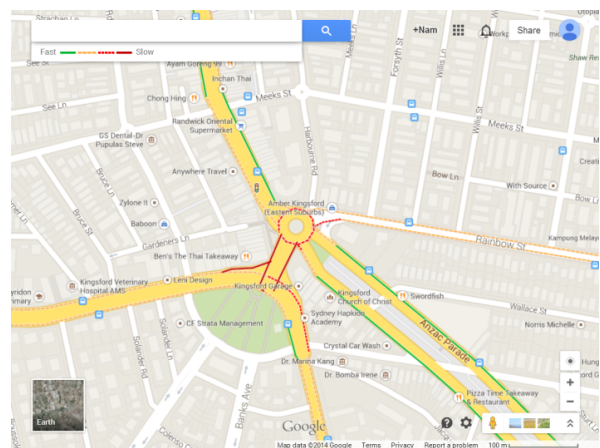
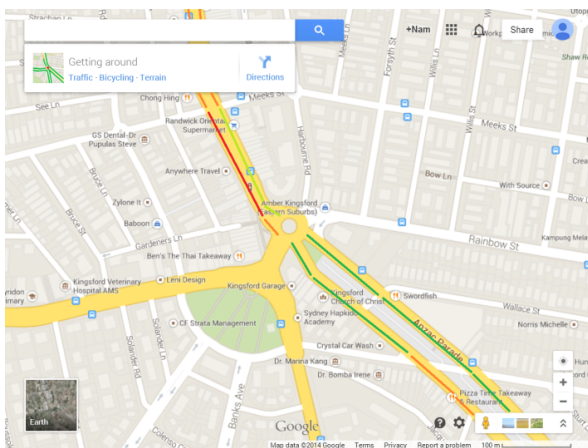
**Figure 2: Percentage of trips by purposes from simulation years 2006 and 2011 vs 2006-2011 HTS data.**



**Figure 3: Percentage of population by number of daily trips for simulation years 2006 and 2011 vs 2006-2011 HTS data.**



**Figure 4: Trip counts by purposes over 24 hours of a representative day in year 2011.**



**Figure 5: Traffic density on Anzac Parade near the intersection with Rainbow street in the morning peak hour. Left panel: traffic density from simulation results. Right panel: congestion profile from Google Maps**

Such agreement however does not occur on all parts of the road network. This could be attributed to the randomness in the assignment of activity locations to origin and destination of trips in the travel diaries of the population. While the assignment of destination locations of trips related to work is constrained by the Journey To Work data, the randomness in assigning destination locations to trips of other purposes does not guarantee a realistic representation of traffic profiles in the model.

## CONCLUSIONS

This paper has presented an agent based model for the simulation of transport demands and land use for an urban area in south east Sydney, Australia. Being comprised of six major components the model is able to capture the decision making of the population with respect to relocation and transport, and thus is able to explicitly simulate the dynamic interactions between population growth, transport demands, and urban land use. This is a unique feature that has not been found in many other agent based models for urban transport and urban planning. Thanks to this feature, the model can be used for exploring long-term consequences of various transport and land use planning scenarios.

Various aspects of the simulation results on transport demands of the study area were presented. Being in good agreement with the corresponding survey data, these results affirm that the model's capability to realistically reproduce travel demand of an urban area and any changes to this travel demand as the population evolves. This is because individuals in the model are associated with each other by their household relationship, which helps define the interdependencies of their travel diary and constrains their mode choice.

Traffic density at various locations along the main road in the study area also matches with the observations of traffic congestion on the same road from Google Maps. Mismatches however occur on other (smaller) roads in the study area. This could be attributed to two factors. The first is the lack of a survey data on the origin and destination of non-work trips. The randomness in assigning a location to the destinations of these trips obviously cannot guarantee a realistic representation of traffic demands in the simulation model. The second factor is the limited ability of the TRANSIMS router to realistically reproduce the reasoning of a person in choosing a possible route for the trips the person makes, including dynamic routing to avoid heavy traffic in real time.

# **Infrastructure Financing and Economics**



# Municipal Energy Companies in the UK: Motivations and Barriers

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## ABSTRACT

Municipal energy companies have the potential to contribute to low-carbon transition in the UK but could also deliver a wider range of benefits, such as fuel poverty reduction and economic growth. There are myriad ways that municipalities could engage in energy provision; however, local authorities face challenges related to matching their motivations to appropriate business models which are exacerbated by unsupportive policy and regulation. More effective decision support tools are required, in addition to changes in policy and regulation, to exploit the potential social and environmental benefits offered by municipal energy companies. An interdisciplinary approach is needed to take this initial work forward to explore business models that match actor motivations and a more complex definition of value.

**Keywords:** Municipal Energy Companies, Social Value, Business Models, Decision Support

## INTRODUCTION

In order to provide secure and affordable energy services and avoid dangerous climate change, the UK needs rapid, systemic transformation of its energy systems to decarbonise generation and reduce demand<sup>1</sup>. The prevalent mode of energy-system operation in the UK is based on large utility companies selling units of energy to customers. Profits are increased by selling more units and by making marginal efficiency savings. This disincentivises both the adoption of low carbon technologies and the necessary scale of demand reduction<sup>2</sup>.

Alternative modes of operation are emerging where infrastructure services are supplied by unconventional providers, motivated by goals other than profit. In this paper we focus in particular on the potential for municipalities to locally manage one part (or more) of the energy system. These 'municipal energy companies' could deliver a wider range of benefits, such as fuel poverty reduction and economic growth, as well as contributing to a low-carbon transition through acceleration of low-carbon technology roll-out and demand management. Despite their potential contribution to energy system transition, municipal energy companies face many constraints. These limit their growth in number and scale. Some of the most severe constraints originate from the economic regulatory system, which controls the UK's privatised energy system.

This paper investigates the motivations that municipalities have, and the barriers they face, in setting up municipal energy companies. We start by examining the characteristics of the current energy system in section 2 then describe

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1 J. W. Hall, J. J. Henriques and R. J. Nicholls (eds), *A Fast Track Analysis of strategies for infrastructure provision in Great Britain: Technical report*. Oxford 2012.

2 K. Roelich et al., "Towards resource-efficient and service-oriented integrated infrastructure operation," *Technological Forecasting and Social Change* (submitted) 2014.

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how municipalities might engage in this system in section 4. We discuss some of the barriers which municipalities face in section 5 and present recommendations to overcome these barriers in section 6.

## ENERGY INFRASTRUCTURE IN THE UK

In the early 20<sup>th</sup> century, energy was provided in the UK at a municipal level by a range of public and private actors, including municipalities<sup>3</sup>. Energy systems were small and localised, and evolved to serve specific users and locations<sup>4</sup>. The 1920s saw the start of a phase of standardisation and centralisation to improve economies of scale, including development of the national grid, and the UK energy system was nationalised in the late 1940s<sup>5</sup>. Energy remained within state hands until the late 1980s when the government of the time started a process of privatisation, motivated by the belief that state operation of infrastructure was inefficient. During the 1990s, generation and supply were separated and the retail markets were liberalised to enable competition for both electricity and gas. Despite this, both generation and supply are dominated by large international energy companies, who supply over 98% of electricity in the UK<sup>6</sup>. The transmission network, which transports power from generation to sub-stations, was also privatised but is operated as a regulated monopoly by National Grid. Generators pay a charge to use the transmission network. Electricity is transported from substations through regional distribution network to end-users by distribution network operators (DNOs). Suppliers pay a charge to DNOs for the use of the distribution system.

This model has served the UK well by delivering operational efficiency, but has limited potential to address climate change and affordability<sup>1</sup>. There is increasing evidence that a move towards decentralisation of the energy system, (both in terms of technology and governance) could result in National Infrastructure performance increases<sup>1</sup>. This opens the way for municipal engagement in the energy system. This has the potential to deliver benefits not only in sustainability and affordability but also to contribute to local economic growth and self-sufficiency.

The scope of potential local authority engagement is broad; and could include generating, distributing and/or supplying energy. The benefits derived from engaging in these different aspects of the system vary, as do the capabilities and motivations of local authorities. It can be difficult to determine how local authorities might engage, and with which part of the system to achieve their motivations, which can be a significant deterrent to participation. Furthermore, the physical and institutional structures that mediate the energy system have evolved to favour incumbent operators and present significant barriers to entry by municipalities. These barriers are discussed in section 5 but first we discuss how and why municipalities might engage in the energy system.

## METHODS

We draw on research conducted under several research projects<sup>7</sup> over the period from 2010 until present. In these projects over 30 interviews were conducted with stakeholders in a variety of roles across the energy systems in the UK, including local authorities, energy companies, central government and other public and private sector partners. Additional details of the methods and analysis conducted on this work can be found in associated publications<sup>8,9,10</sup>. In addition, the authors have participated in informal meetings with municipal stakeholders, providing an insight into

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3 R. Fouquet and P. J. G. Pearson, "A thousand years of energy use in the United Kingdom," *Energy Journal*, vol. 19, no. 4, pp. 1-41, 1999.

4 Hughes, *Networks of power: electrification in Western society, 1880-1930*. Baltimore: Johns Hopkins University Press, 1983.

5 Grid, "The National Gas Archives - Nationalisation," 2005. [Online]. Available: <http://www.gasarchive.org/Nationalisation.htm>. [Accessed: 08-Mar-2014].

6 Office of Fair Trading, *Infrastructure Ownership and Control Stock-take*. 2010.

7 See acknowledgements for details

8 C. S. E. Bale, T. J. Foxon, M. J. Hannon, and W. F. Gale, "Strategic energy planning within local authorities in the UK: A study of the city of Leeds," *Energy Policy*, vol. 48, pp. 242-251, 2012

9 R. Bush, C. S. E. Bale, and P. Taylor, *Spatial mapping tools for district heating (DH): helping local authorities tackle fuel poverty. Leeds: Report for Chesshire Lehamnn Fund*. 2014.

10 K. Roelich, "Physical and institutional challenges of infrastructure transitions: constraints and potential solutions," Phd Thesis. University of Leeds, 2014.



the decision-making process within local authorities by using the method of overt participant observation<sup>11</sup>. This method allowed for detailed information about practices within the local authority to be drawn out and has allowed the authors to gain insight into the practical challenges of delivering municipal energy.

## MUNICIPAL ENERGY COMPANIES

There are myriad ways that municipalities could engage in energy provision, depending on the scope of their engagement and on their motivations for engagement. These dimensions of engagement are discussed in this section, with examples.

## SCOPE OF MUNICIPAL ENERGY COMPANIES

There is potential for municipalities to engage with each or many parts of the energy system, including generation, distribution and supply and a real appetite to take more control of local energy provision<sup>12</sup>.

## GENERATION

There is a nascent movement of local authority-led energy generation projects which tend to generate energy to supply local authority properties<sup>13,14</sup>. Although many local authorities have set up an Energy Services Company for the purpose of operating generation equipment, self-supply excludes the need for a separate 'supplier' and reduces governance complexity. Many of these projects use combined heat and power, which has significant potential to reduce local authority energy bills and contribute to carbon emissions reductions targets<sup>15</sup>.

## DISTRIBUTION

There are few current examples where local authorities have developed network infrastructure or set up independent distribution operators. One of the exceptions is the Thamesway project initiated by Woking Borough Council, that developed a private-wire network between electricity generation and end-users as well as the examples of district heat networks in the UK<sup>15</sup>. However, there is a great deal more potential for local authorities to engage in distribution, in particular the implementation of smart grids to better balance supply and demand. This not only contributes to emissions reductions but could also offer significant benefits with regard to economic development<sup>16</sup>.

## SUPPLY

Many local authorities have made initial ventures into supply by engaging with the Big Switch campaign<sup>17</sup>, teaming up with Which? magazine to negotiate bulk discount for a group of customers willing to switch suppliers<sup>18</sup>. It is possible that local authorities could buy energy in bulk from the wholesale market and sell energy directly to customers in their

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11 D. L. Jorgensen, *Participant Observation: A Methodology for Human Studies*. London: Sage Publications, 1989.

12 Core Cities, *Core Cities Growth Prospectus Policies Step 6 : Power Up the Cities*. 2013.

13 J. P. Thorp, "Woking: Driving Sustainable Innovation," in *Sustainable Innovation: Building & Construction Technologies*, 2007

14 D. Hawkey, "District heating in the UK: A Technological Innovation Systems analysis," *Environmental Innovation and Societal Transitions*, vol. 5, pp. 19-32, 2012

15 J. P. Thorp, "Delivering affordable and sustainable energy: the results of innovative approaches by Woking Borough Council, UK," in *System Innovation for Sustainability 4: Case studies in sustainable consumption and production - Energy use and the built environment*, vol. 44, S. Lahlou, Ed. Greenleaf Publishing Limited, 2011.

16 S. Hall and T. J. Foxon, "Values in the Smart Grid: the co-evolving political economy of smart distribution.," in *ESEIA-IGS Conference: Smart and Green Transitions in Cities / Regions: 24-25 April 2014*, 2014

17 Which? "More than 36,000 people make The Big Switch," 2013. [Online]. Available: <http://www.which.co.uk/news/2012/06/more-than-36000-people-make-the-big-switch-287912/>.

18 Leeds City Council, "Leeds residents to use people power for cheaper energy," 2013. [Online]. Available: <http://www.leeds.gov.uk/news/pages/Leeds-residents-to-use-people-power-for-cheaper-energy-.aspx>.

locality and beyond, which would require them to comply with supply codes, and to apply for, and hold a supplier licence. The Greater London Authority is the first municipality in the UK to hold a licence to supply. It will initially buy surplus electricity produced by London's boroughs and public bodies before selling it on, at cost price to other public sector bodies. If successful the scheme may extend to include private sector energy producers in London. It is hoped that bulk buying in this way could reduce prices for residents and improve the viability of local energy projects<sup>19</sup>.

## MOTIVATIONS AND BENEFITS OF MUNICIPAL ENERGY COMPANIES

The motivations of municipalities seeking to enter the energy market are diverse; table 1 presents a selection of motivations for engagement in municipal energy companies reported by local authorities<sup>9,12</sup>. The motivations can be delivered by engagement with different parts of the system, as described in the examples given in the previous sections. For example, fuel poverty could be addressed by engagement in supply and controlling unit charges, reducing costs to customers. Conversely; emissions reductions motivations might be best achieved through engagement with low-carbon supply. Local authorities often report multiple motivations which can make it difficult to identify the most appropriate scope of engagement. Furthermore, motivations vary significantly between different authorities, which means that there is little standardisation and little opportunity to learn from predecessors.

**Table 1: Motivations for engagement in municipal energy companies<sup>9,12</sup>**

Area	Motivation
Economic	Competitiveness
	Job creation
	Economic growth
Social	Fuel poverty
	Regeneration
	Fairness e.g. tariff discrepancy
Environmental	Carbon emissions reduction
	Air quality
Other	Local accountability & control

## BARRIERS FACED IN SETTING UP MUNICIPAL ENERGY COMPANIES

In addition to challenges relating to marrying scope and motivations, municipal energy companies face a series of barriers during set-up and operation.

### INTERNAL BARRIERS

Local authorities have not had a role in energy governance, beyond spatial planning, since the energy system was merged and nationalised in the 1940s. Furthermore, a cultural ethos of aversion to risk and revenue generation limits the willingness of local authorities to engage in infrastructure operation<sup>20</sup>. The institutional lock-in created by historic constraints on the role of local authorities limits many to traditional ways of operating and a risk-averse ethos persists<sup>20</sup>. Changes in financing and accounting practices could be slow in the face of this lock-in, limiting the number of local authorities willing to get involved<sup>8</sup>.

The development stages of projects take a great deal of resources, and in the face of reducing budgets for core activities, it is often difficult to find or justify this resource. It's not just the quantity of the resource but a lack of internal

19 Greater London Authority, "Licence Lite," *london.gov.uk*, 2013. [Online]. Available: <http://www.london.gov.uk/priorities/environment/tackling-climate-change/energy-supply/licence-lite>. [Accessed: 31-Dec-2013].

20 D. Hawkey, J. Webb, and M. Winskel, "Organisation and governance of urban energy systems: district heating and cooling in the UK," *Journal of Cleaner Production*, vol. 50, pp. 22-31, 2013

technical knowledge, which leads to a lack of confidence in decision making processes<sup>8</sup>. This is particularly important when identifying the scope of engagement most likely to deliver outcomes of importance to a particular local authority, which as discussed in section 3.2, can vary significantly.

## EXTERNAL BARRIERS

The post-privatisation policy and regulatory system has evolved around, and favours, the mainstream mode of operation, which is profit-oriented, throughput-based and large-scale<sup>21</sup>. The scale and motivations of municipalities differ greatly from the mainstream, which means they face a series of constraints that limit their potential to contribute to energy service delivery. Our analysis has identified a series of crucial constraints to current activities and future developments.

The pro-market focus of regulation views markets and competition as the most effective way of meeting society's choices and considers that policy should foster markets as far as possible. However, this reinforces the narrow definition of value in purely economic terms, which overlooks the non-monetary benefits that end-users receive from more efficient and inclusive infrastructure operation, such as reduction in fuel poverty (which is barely affected by price control) and local employment.

Specific regulator instruments, such as Supplier Licencing constrain small providers. Although the motivation for licencing is justifiable, the licence terms are extremely onerous for small suppliers and act as a severe deterrent constraining the size of individual operations.

## POTENTIAL RESPONSES TO BARRIERS

More appropriate support is needed to help local authorities identify how to match the scope of their engagement with their motivations. This might require decision support tools that enable local authorities to integrate social and environmental value into decision making processes as well as economic value.

A more integrated approach to policy is necessary, which respects the range of values and priorities of local authorities. This includes adapting funding and incentive criteria to encourage wider benefits, such as fuel poverty reduction. Social benefit generated by more local schemes must be captured and assessed on a more equal footing with financial benefit. A new approach to accounting and valuation is required which takes into account these non-monetary benefits as well as the benefits derived by future users, for example, by avoiding dangerous climate change.

Targeted support for municipal energy companies is necessary to reduce risk and uncertainty and drive innovation. Targeted support offers advantages over market mechanisms, particularly for initiatives at an early stage of development<sup>22</sup>. Support is particularly important during crucial stages of scaling up from a small experiment to a fully commercial business.

New approaches to regulation are required that realign the goals of economic regulators with wider goals of transitioning to a low-carbon energy system. Sustainability goals need to be equal to, or take precedence over, economic goals. This should be accompanied by simplification of supply licencing arrangements, including removal of the need for smaller operators to enter into agreement with large, incumbent operators.

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21 C. Mitchell, *The political economy of sustainable energy*. Palgrave Macmillan, 2010.

22 Gross et al., "On picking winners: The need for targeted support for renewable energy." 2012

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## CONCLUSIONS

It is clear that there are a number of diverse motivations for municipal actors in delivering energy and this diversity in motivations has the potential to deliver a wider range of benefits than the incumbent energy providers. However, these motivations need to be matched to appropriate scope of engagement in energy provision. The capabilities of local authority actors and current energy policy and regulation can present significant barriers to identifying and implementing appropriate business models for municipal energy companies. More effective decision support tools are required, in addition to changes in policy and regulation, to exploit the potential social and environmental benefits offered by municipal energy companies, which are not currently captured with standard economic models.

An interdisciplinary approach is needed to take this initial work forward to explore business models that match actor motivations and a more complex definition of value.

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# Portfolio Infrastructure Investments: an Analysis of the European and UK Cases

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## ABSTRACT

Infrastructure has been receiving much attention in recent years. Investment banks and fund managers are increasingly promoting the investment characteristics of infrastructure assets and they argue that investing in infrastructure should be ideal for institutional investors such as pension funds. However, the claim lacks empirical support. We suggest that the limited research on infrastructure is mainly due to scant empirical data. The objectives of this paper are to examine the significance of economic infrastructure as an asset class by assessing the investment characteristics and performance of infrastructure indexes in Europe and UK from 2000-2014, to analyse how an infrastructure portfolio should be constructed and to determine whether the private sector should invest in an infrastructure portfolio containing a variety of infrastructure sectors or if the private sector should invest in one specific sector only.

**Keywords:** Portfolio optimisation, infrastructure indices, diversification benefit, infrastructure sub-sectors, and mean-variance analysis.

Infrastructure has been receiving deserved attention in recent years. Investment banks and fund managers are increasingly promoting the investment characteristics of infrastructure assets and they argue that investing in infrastructure should be ideal for institutional investors such as pension funds. One key characteristic of infrastructure assets that distinguishes them from all other traditional assets, is that they usually operate as natural monopoly. Thus, infrastructure assets usually have one or more of the following characteristics: high barriers to entry, economies of scale, inelastic demand, and long duration. These characteristics convey many attractive investment features to the infrastructure assets such as: secure stable cash flows, low correlation to other assets, insensitivity to macroeconomic conditions, relatively low default rates and inflation hedging properties<sup>1</sup>. However, all these claims have insufficient empirical support.

Nevertheless, the outlook for infrastructure deal flow in 2014 is particularly positive, with 71% of managers surveyed agreeing to deploy more capital than in 2013<sup>2</sup>. European infrastructure assets have historically accounted for a higher proportion of deals per year than assets in any other region. Of the more than 3,700 infrastructure deals finalised since 2008, European assets have accounted for 47% of total deals on average per year<sup>3</sup>. Despite increasing demand for infrastructure, and particularly European infrastructure, research in this area is still limited. We suggest that the limited research on infrastructure finance is due mainly to scant empirical data. Existing research

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1 Helm, D and Tindall, T. (2009), 'The Evolution of infrastructure and Utility Ownership and its Implications'. *Oxford Review of Economic Policy*, 25(3), pp. 411-434; Newell, G., Peng, H., and De Francesco, A. (2011), The performance of unlisted infrastructure in investment portfolios. *Journal of Property Research*, Special Issue: Infrastructure and Regeneration 28,1, pp. 59-74.

2 Preqin (2014) Preqin Special Report: Infrastructure Transaction Activity, London.

3 Preqin (2014) Preqin Special Report: Infrastructure Transaction Activity, London.

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examines the performance of listed infrastructure characteristics, but usually without distinguishing between different infrastructure sectors<sup>4</sup>. The present paper is developed as a study of two main objectives. The first objective is to verify if the investment characteristics of infrastructure are shared by all infrastructure sub-sectors i.e. ports, airports, electricity etc. The second objective is to determine whether by investing only in one infrastructure sector only, a private investor will still be able to enjoy diversification benefits.

In the first part of the work, we take as our point of departure the argument that infrastructure should be treated by investors as a separate asset class. The objectives of the paper are twofold. The first aim is to verify if the investment characteristics of infrastructure are shared by all infrastructure sub-sectors. Specifically, the paper examines the significance of European Energy and Transportation sub-sectors (e.g. ports, airports, electricity, natural gas etc.) by assessing the investment characteristics and performance of listed infrastructure indexes in Europe from 2004-2014. The investment characteristics of infrastructure sub-sectors are then compared with traditional assets such as (e.g. government bonds, real estate and stocks). The second objective is to confirm the best approach to construct a European infrastructure portfolio and determine whether the private sector will enjoy diversification benefits by investing in only one specific sector.

Data for this research is collected from the Reuters Thomson Database. We collect weekly prices of European sub-sector listed infrastructure indices for the following listed assets: Ports, Airports, Toll Roads, Natural Gas, Electricity, Fossil Fuels, Renewable Energy, Bonds (Government bonds), Real Estate and Stocks, for over a timespan of 10 years, from 2004-2014. In this way we are also able to capture and analyse the financial crisis and therefore test the robustness of infrastructure compared to other assets when macroeconomic conditions are very low. Risk free returns for the same period are collected from the Kenneth R. French - Data Library in order to calculate the Sharp Index of each asset.

In relation to the first objective, European performance analysis among assets is evaluated on three aspects. First of all, this research compares the performance of all the assets for the period 2004-2014 by calculating the annual return, average volatility and Sharp Index of each asset. Secondly, we examine the diversification benefits among listed infrastructure sub-sectors by calculating the inter-correlation among the sectors as well as with other traditional assets. Lastly, we evaluate the robustness of the infrastructure sub-sector during the crisis by calculating the annual average return, average volatility and Sharp Index of each asset during the period of the recent financial crisis Q4.2007 to Q2.2009.

In the second objective we use the GAMS modelling tool to examine how is best beneficial to construct a portfolio with infrastructure investment and evaluate the significance of including one specific infrastructure sector in traditional portfolios. We use the traditional Markowitz's mean-variance analysis in the following two portfolio scenarios:

Portfolio 1 specialises only on Energy sub-sector assets within a traditional portfolio. The assets included are European government bonds, real estate, stocks, natural gas, electricity, fossil fuels and renewable energy.

Portfolio 2 specialises only on Transport sub-sector assets within a traditional portfolio. The assets included are European government bonds, real estate, stocks, ports, airports and toll roads.

The results of the objective 1 show that Listed infrastructure sub- sectors vary widely in terms of performance. Ports and Electricity indices demonstrates the most superior performance among economic listed infrastructure sub-sectors while; Fossil Fuels and Renewable Energy demonstrates the worst performance of all the sectors. When compared with more traditional assets all listed infrastructure sub- sectors except Fossil Fuels and Renewable Energy outperform Stocks and Real Estate as indicated through a higher Sharp ratio. There are some infrastructure sub-sectors that outperform Government Bonds however; this is due to higher returns. Government bonds are less volatile than all other assets.

The claim that infrastructure has low correlation with traditional assets is confirmed partially. All infrastructure sub-sectors show diversification benefits with Government bonds. However, all infrastructure sectors have significant correlation with Stocks and Real Estate. Additionally, our inter-correlation matrix shows that there are portfolio diversification

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4 Oyedele, (2013). Performance and Significance of UK listed infrastructure in a Mixed Asset Portfolio [pdf] See: [http://eres.architexturez.net/system/files/pdf/eres2013\\_14.content.pdf](http://eres.architexturez.net/system/files/pdf/eres2013_14.content.pdf)

;Peng, H., and Newell, G. (2007), The Significance of Infrastructure in Investment Portfolios. Pacific Rim Real Estate Society Conference; RREEF (2007a). "Performance Characteristics of Infrastructure Investments". RREEF Research.

benefits even within one specific sector. However, our results indicate that in the Transportation sector there are greater diversification benefits than in the Energy sector. The results showed that there are low correlations between ports, airports and toll roads, indicating the presence of diversification benefits, even if specialising in a single sector, i.e., Transport.

Last but not least, when the data is contracted to the period of the financial crisis, in order to examine the robustness of infrastructure sub- sectors, it's observed that even though all assets are negatively affected by the recession; all of the infrastructure sectors were less negatively impacted than Stocks and Real Estate during the crisis.

In the second objective the results of both the European Energy and Transport sub-sector analysis indicate that specialising in one infrastructure sector within a traditional portfolio can still offer diversification benefits. In both cases constructing a portfolio of merely government bonds, stocks and real estate offered only modest diversification benefits. However, when infrastructure sub-sectors was added in the portfolio you could achieve a higher return for the same level of risk. In both the Energy and Transportation case, adding infrastructure into the portfolio boosts returns rather than lowers risk. Furthermore, the results showed that in both the Energy and Transportation sub-sector portfolios, one could still enjoy diversification benefits. In portfolio 1, the portfolio invests in the Energy sector within a traditional portfolio. The portfolio that maximises the Sharp Index invests in Government Bonds, Natural Gas and Electricity offering a modest diversification benefit of 3.5%. On the other hand, greater diversification benefits are observed in our Portfolio 2 scenario where the private investor invests only in Transportation within a traditional portfolio. The portfolio that maximises the Sharp ratio shows a diversification benefit of 15.6% and invests in Ports, Airports and Government Bonds.

The results of the performance analysis showed that each listed infrastructure sub- sector has its own historical performance. This is important since if performance of listed infrastructure sub-sectors varies significantly, this implies that good knowledge of the specific sector is required. The results of the minimum-variance portfolio analysis indicate that when the infrastructure sector is combined with other traditional assets, the portfolio often yields a Sharp ratio higher than any single asset. Nonetheless, infrastructure should not be considered as an asset on its own, but rather it is only beneficial when infrastructure assets are included as a subset of a traditional portfolio. This highlights the role of government as catalyst for resources, in particular government's vital role in attracting the private sector to invest in infrastructure. Governments need to be more active and introduce more policies to attract private sector participation if they want to observe any increases in the investments of institutional investors. Last but not least, this research showed that by specialising in one infrastructure sector only, it is still possible to obtain many diversification benefits. Thus, fund managers can specialise on an infrastructure sector and not only they will gain diversification benefits but they will be able to create deep understanding of that sector's performance and idiosyncratic risks.





# Financial Transmission Rights (FTR) as a Congestion Management Scheme in Electricity Transmission: Strategic Behavior in a Coupled FTR — Electricity Market Model

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## ABSTRACT

With the emergence of liberalized markets, transmission line congestion has been a prominent technical constraint that has to be accounted for in designing the new markets. Transmission line congestion is a phenomenon in electricity markets that emerges more severely in time with ever increasing demand in electricity and resultant excessive loading of transmission lines. Various congestion management techniques such as market splitting, market coupling etc. are utilized currently in energy markets. However on the long run financial transmission rights (FTR), which is readily used by some US electricity market operators such as PJM, New York and New England operators, has potential to dominate other markets too. Modelling financial transmission rights to test some strategic hypotheses is imperative to be able to introduce suitable policies and regulations. In this paper we present a modelling approach for financial transmission rights and examine strategic use of hidden knowledge in a hypothetical electricity — FTR market.

**Keywords:** Finance, Institutions, Transmission Rights

## SUBHEAD REQUIRED

Electric industry has been going through fundamental institutional changes by constantly moving away from an integrated centralized regulated system towards a market based decentralized self-organizing industry. There remains various mechanism design questions that would ideally guide the system towards a state where certain technical and socio-economic constraints are not breached.

With the emergence of liberalized markets, transmission line congestion has been a prominent technical constraint that has to be accounted for in designing the new markets. Transmission line congestion is a phenomenon in electricity markets that emerges more severely in time with ever increasing demand in electricity and resultant excessive loading of transmission lines. Various congestion management techniques such as market splitting, market coupling etc. are utilized currently in energy markets. However on the long run financial transmission rights (FTR), which is readily used by some US electricity market operators such as PJM, New York and New England operators, is expected to dominate. Additionally with the emergence of a need for a pan-European grid, FTR is being increasingly considered as a Europe wise mechanism to tackle congestion management problem. Modeling financial transmission rights to test some strategic hypotheses regarding this emerging market in Europe is crucial to be able to introduce suitable policies and regulation rule. Hence in this working paper we present a modeling approach for financial transmission rights markets for testing strategic hypotheses. A research agenda, which utilizes the mentioned approach, is set.

Every networked infrastructure needs to be treated in light of their particular technical functionalities as well as

associated social and political acceptances. The electricity system is not different in this regard, given its broad application field that affect three quarters of people on earth <sup>11</sup> and its very complex technical specifications. These specifications include but are not limited to storage problems, requirement of market clearance and loop flows. Safeguarding these critical technical specifications, which emerge from the very nature of these industries, is an obligation. In some situations strategic behavior exercised by the competitive companies of the deregulated markets may hinder the delivery of the critical service <sup>2</sup>.

Congestion in transmission lines is a particular phenomenon to be considered in this regard <sup>3</sup>. Thermal limits, voltage stability and voltage drop regulations impose transmission capacity limitations on transmission lines. Thus distribution of electricity flows among the transmission lines should be regulated in order not to exceed these transmission capacity limits. Owing to this fact, many congestion management methods have been devised in the literature <sup>4</sup> and many of them are actually utilized in various electricity markets <sup>5</sup>

Electric power transmission systems are utilized to transfer bulk electricity from generators to loads. The transmission occurs on the transmission networks or power grids, which is comprised of high voltage transmission lines. These transmission lines cannot carry beyond a certain limit depending on the heat related properties of the cable. Electricity transmission congestion refers to the situation when this limit is reached and no marginal megawatts can be pushed into the transmission network. The effects of congestion over a line can jeopardize the security of the entire system. A higher quantity of permitted flow through the line might overheat it, causing the elongation of the material which in some cases can be permanent. This situation enhances the probability of failure or even blackout with severe social and economic consequences <sup>6</sup>.

According to general equilibrium theory, a market is called perfect if information is transparent, no barriers of entry or exit exist, no participant abuses market power to set prices and equal access to production technology is provided <sup>7</sup>. Projection of this view of perfect market would mean that an ideal market for electricity must provide a platform that is spatially homogeneous in terms of pricing, in order to allow for entrance and exit of traded power with the same price. However since electricity flows according to Kirchhoff's laws, and the flow can be constrained by cable flow capacities, the free flow of traded power may be hindered. This is usually overlooked by the scholars who employ a purely economic perspective. Instead of utilizing the cheapest power, more expensive power has to be utilized in order to satisfy the demand due to transmission capacity constraints. As a result some price differences between the nodes occur. This is frequently referred to as congestion cost. The different prices, caused by spatial heterogeneity, are called locational marginal prices (LMP) or nodal prices in the literature.

The management of congestion implies different results for the efficiency of the generation market. Hence different mechanisms for congestion management have been suggested to allocate scarce transmission and to maintain a competitive market. Some methods are more focused on preventive measures, since they try to avoid the congestion beforehand, while others attempt to solve the congestion in real time. The methods used are dependent on the evolution of the institutional setting within the respective region because of different pace of development in different parts of Europe. Some points must be taken into account while considering market mechanisms for congestion management. First of all, it should be noted that the transmission operator is a natural monopoly and it always has a pivotal position. The network operator cannot be relied upon without regulation to secure the public interest. The regulation applied to TSO is crucial with respect to market power concerns. Secondly it should be realized that the supply and demand varies instantaneously while the market clearance must occur at all times. This may result in volatility since the demand as well as the supply might be volatile due to many factors. Thirdly it is important to note that the configuration of the physical network causes network externalities called loop flows. Transportation of electricity does not occur as in the case of a transportation of a physical good in a classical market. Electricity flows through the least

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1 Gronewold, N. One-quarter of world's population lacks electricity. *Scientific American* (2009).

2 Borenstein, S., Bushnell, J. & Knittel, C. Market power in electricity markets: Beyond concentration measures. *Energy Journal* **20**, 65-88 (1999).

3 Knops, A. & Vries, D. Congestion management in the European electricity system: an evaluation of the alternatives. *Competition and Regulation in Network Industries* **2**, 311-352 (2011).

4 Kumar, A., Srivastava, S. & Singh, S. Congestion management in competitive power market: A bibliographical survey. *Electric Power Systems Research* **76**, 153-164 (2005).

5 De Vries, L. & Hakvoort, R. The question of generation adequacy in liberalised electricity markets. *Delft University of Technology* (2004).

6 Fang, R. S. & David, A. K. Transmission congestion management in an electricity market. *IEEE Transactions on Power Systems* **14**, 877-883 (1999).

7 Debreu, G. *Theory of value: An axiomatic analysis of economic equilibrium*. (Yale Univ Pr, 1959).

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resistant cables from high voltage to low voltage level. So, in a hypothetical three node network, sending power from node A to node B is always affected by the resistance of the lines including those involving node C.

## LOCATIONAL MARGINAL PRICING (LMP) AND FINANCIAL TRANSMISSION RIGHTS (FTR)

LMP is spatial pricing of electricity in which different price zones are formed based on occurrences of transmission congestion on the electricity transmission lines. The electricity prices resulting at each node are called locational marginal prices. In a fully connected network, LMPs on different nodes may end up with different values even if only one transmission line is congested throughout the network. Due to Kirchoff laws, injection and withdrawal of electricity on any node possibly affects the electricity load on any transmission line <sup>8-11</sup>.

FTR is a hedging tool against congestion charges for markets that are based on locational marginal pricing (LMP). Thus LMP or nodal pricing is the prime mechanism on which FTR is built on and has been applied in the electricity networks of New York, PJM and New England regions in the US <sup>9</sup>. Since LMP is the underlying mechanism that brings about the need for FTRs, in this sections we further elaborate on LMP together with FTR. Then we will explain the functionality of FTRs and finally test the strategy-proneness of FTRs in a game theoretical model.

With FTR model, the TSO computes the LMP for each congestion-prone node, which carries the associated congestion costs. This would result in volatile prices in electricity as the congested lines fragment the markets spatially into minor regions. To hedge these volatilities the generation companies can buy FTRs offered by the TSO's. The FTRs entitle the holder to receive the price difference between two stated nodes on the FTR. FTRs are funded by the congestion rent collected by the TSO.

FTRs are utilized as a hedge against the congestion costs due to different LMPs on the generation and consumption nodes. The price differences across the nodes may result in unexpected costs due to the foreseen or unforeseen congestion occurrences.

## A GAME THEORETICAL MODEL OF COUPLED FTR-ELECTRICITY MARKET

The model proposed in this research is a coupled electricity and FTR market model. It features both FTR market and the electricity market which are coupled by the decisions of the electricity firms and the price signals that affect each market recursively. Most of the models readily available in the literature are based on assumed LMPs, thus ignore electricity market part of the mechanism or based on stochastic FTR values in conjunction with the electricity equilibrium models. However two distinct market structures, the signals of which affect each other is a more accurate view of the total system. This is the perspective that we employ in this research.

One specific strategic hypothesis that we test in this analysis can be formulated as follows: "Can firms exercise market power in electricity market by keeping their generation information private?" This question requires us to consider market power of the firms in the electricity market and amount of FTRs it can acquire. Moreover two markets are interrelated as the evaluation of FTRs depend on the results of electricity market. To test strategic hypotheses such as the one stated here, one needs to model electricity market as well as the FTR market.

In order to assess the strategy-proneness of FTR method, we use our coupled FTR — electricity market model that is briefly described above. The model simulates a scenario of strategic behavior based on hidden information. The scenario clearly shows that hiding private information, which is about a generation technology upgrade in this case, can give a generation company or any other market participant tremendous market edge, making FTR markets quite information sensitive. The information sensitiveness clearly serve to the incumbent firms, which has larger presence in the generation market and hence more opportunity to hoard information. As a result introducing FTRs without a mechanism to protect small players from information hoarding would contradict with the goal of creating a perfect market with low barrier of entry and high number of players.

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8 Green, R. J. & Newbery, D. M. Competition in the British electricity spot market. *Journal of political economy*, 929-953 (1992).

10 Oruç, S. & Cunningham, S. W. 1-6 (IEEE).

11 Oruç, S. & Cunningham, S. W. Transmission Rights to the Electrical Transmission Grid in the Post Liberalization Era. *Journal of the Knowledge Economy*, 1-20, doi:10.1007/s13132-012-0130-7 (2012)

9 Hogan, W. W. Contract networks for electric power transmission. *Journal of Regulatory Economics* **4**, 211-242 (1992).

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As far as the policymaking is concerned, the main takeaway from this study is that FTR markets can give further opportunity for the market participants in the electricity financial transmission rights market. FTR could be an appropriate mechanism for the generators to hedge their congestion risk. However the increasing complexity of the total electricity system would render the system more prone to strategic behavior. In addition to the strategic behavior by creating congestion that is discussed in the literature, we discussed another strategic behavior by hidden knowledge in this study. On the other hand the other congestion management methods have their respective disadvantages as well as advantages with respect to the FTR scheme that we analyzed in this study. A comparison of different schemes falls out of the scope of this study and can be treated as a future extension.

As for possible remedies against strategic behavior based on hidden knowledge, policy makers might consider looking at the rules and regulations of the stock markets as some analogy between the stock markets and FTR markets can be drawn as long as the hidden knowledge is concerned. To our knowledge, insider trading is forbidden in stock exchanges and the stock mobility of the executives of the companies are heavily regulated. Some similar regulations regarding the FTR movements of the generation companies can also be implemented in FTR markets.

# Real Options Theory and EU Member States Energy Investment Strategies

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## ABSTRACT

According to the European Commission's latest energy and climate proposals ("Europe 2030"), Member States will be obliged to draft National Action Plans for competitive, secure and sustainable energy. In particular, these plans need to simultaneously address issues of achieving domestic objectives regarding renewable energy, energy savings, energy security, research and innovation, greenhouse gas emissions, nuclear energy, shale gas, carbon capture and storage, European Union level climate and energy objectives etc. Furthermore, coordination with neighboring Member States as well as regional effects will also have to be taken into consideration.

Drafting these medium and long-term plans may be a challenging task for the Member States, especially given the uncertainties that the energy sector faces. In this paper, we examine how real options theory can be utilized to formulate these national plans, especially the underlying Member State energy investment strategies, through illustrative examples.

**Keywords:** Infrastructure, Investments, Energy, Finance, Real Options

## INTRODUCTION

Energy is at the core of economic and social activity in industrialized countries. The future of the energy sector in Europe has been receiving increased attention. In particular, the International Energy Agency is anticipating an increasing EU reliance on imported oil from around 80% today to more than 90% by 2035, while gas import dependency is expected to rise from 60% to more than 80%. In 2012, Europe's oil and gas import bill amounted to more than 400 billion representing some 3.1 % of EU GDP.<sup>1</sup> Simultaneously, policies aimed at reducing and mitigating climate change also receive much attention, at least within the confines of the European Union.

On January 22, 2014 the European Commission proposed energy and climate objectives, to be met by 2030.<sup>1</sup> According to the relevant Communication by DG ENER, "*The objectives send a strong signal to the market, encouraging private investment in new pipelines and electricity networks or low-carbon technologies.*" One of the innovations of these proposals is the New Governance System, according to which, Member States will be obliged to draft and submit National Action Plans (hereafter "national plans") for competitive, secure and sustainable energy.

In particular, these plans will have to simultaneously address issues of achieving domestic objectives regarding

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<sup>1</sup> Communication from the Commission to the European Parliament, The Council, The European Economic and Social Committee and the Committee of the Regions: A policy framework for climate and energy in the period from 2020 to 2030. COM(2014) 15 final. URL: <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2014:0015:FIN:EN:PDF>

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greenhouse gas emissions, renewable energy, energy savings, energy security, research and innovation, nuclear energy, shale gas, carbon capture and storage, achieving European Union level climate and energy objectives etc. Furthermore, coordination with neighboring Member States, as well as regional effects, must also be taken into consideration.

In this context, Member States face increased challenges in designing strategies that are subject to unforeseen contingencies, especially as there is an explicit requirement by the European Commission for formulating long-term and overall investment strategies for energy.

In this paper, we identify the challenges and in particular the tradeoffs that Member States will face in drafting their national plans. Furthermore, this paper examines the possibility of using real option theory methodologies for drafting these national plans. We focus on two sets of issues that the proposed methodological framework fruitfully addresses. First, we present and categorize uncertainties to which national plans are subject to, with illustrations of typical cases. Secondly, we illustrate the ability of the Real Options framework in addressing strategic questions across Member States, as well as within a certain Member States energy industry.

## WHAT IS REQUESTED FROM THE MEMBER STATES

Three key elements are identified from the European Commission's relevant press release on the "2030 climate and energy goals for a competitive, secure and low-carbon EU economy":<sup>2</sup>

- New targets: For example, there is a requirement of reducing greenhouse gas emissions by 40% below the 1990 level, an EU-wide binding target for renewable energy of at least 27% and renewed ambitions for energy efficiency policies.
- A new governance system: "The 2030 framework proposes a new governance framework based on national plans for competitive, secure and sustainable energy. Based on upcoming guidance by the Commission, these plans will be prepared by the Member States under a common approach, which will ensure stronger investor certainty and greater transparency, and will enhance coherence, EU coordination and surveillance. An iterative process between the Commission and Member States will ensure the plans are sufficiently ambitious, as well as their consistency and compliance over time." (emphasis in original)
- A set of new indicators: "to ensure a competitive and secure energy system."

In particular, regarding the New Governance System, the European Commission's communication<sup>1</sup> states that: *"Meeting the relevant targets would be met by a mix of Union measures and national measures described in Member States' national plans for competitive, secure and sustainable energy which would: ensure that EU policy objectives for climate and energy are delivered, provide greater coherence of Member States' approach, promote further market integration and competition and provide certainty to investors for the period after 2020."*

Furthermore, it is stated that: *"The explicit aim should be to create more investor certainty and greater transparency; to enhance coherence, EU coordination and surveillance, including assessment of such plans against Union level climate and energy objectives, and progress towards the objectives of the internal energy market and state aid guidelines."*

The evolution of the energy sector in Member States will be monitored by a set of new and informative energy indicators that will examine energy price differentials, diversification of energy imports, deployment of smart grids and interconnections, intra-EU coupling of energy markets, competition and market concentration (national and regional scale) and technological innovation. Therefore, these indicators, their dynamic and evolution, will indirectly identify the effects the implementation of the national plans.

The compilation of national plans should be a challenging task for many of the Member States. Compiling complete, proper and realistic national plans are of particular interest for the Member States, especially as these will potentially be a prerequisite for obtaining funding from cohesion/structural programs.

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<sup>2</sup> European Commission (2014), *Press release: 2030 climate and energy goals for a competitive, secure and low-carbon EU economy*, IP/14/54 22/01/2014. URL: [http://europa.eu/rapid/press-release\\_IP-14-54\\_en.htm](http://europa.eu/rapid/press-release_IP-14-54_en.htm)

## METHODOLOGICAL APPROACH FOR MEDIUM AND LONG-TERM ENERGY INVESTMENT STRATEGIES

This section focuses on the national plans' energy sector investment projects.

Project investment decisions are usually based on the Discounted Cash Flow (DCF) methods, in particular in the Net Present Value traditional capital budgeting framework. However, in the case of medium and long term energy investments strategies, there are two key components which render these methods inappropriate:

1. *Dealing with uncertainties.* DCF considers immediate, irreversible investments. In other words, it is assumed that an investment is immediately implemented and committed to sturdily, and thus, it cannot be undone and have the expenditures recovered. Alternatively, it presupposes that if a project is not undertaken at a certain time then it will not be able to be undertaken in the future.<sup>3</sup> Thus, the traditional framework is unable to embody the possibility of *discretionary actions* at a future date that will capitalize on unexpected opportunities arising in the course of the project, as well as mitigate the losses of an unforeseen challenge.
2. *Internalizing externalities.* When taking investment decisions private companies usually do not take into account the positive and negative externalities that are produced as a result of an individual actor's activity. However, it is desirable that Member States compile their national plans while simultaneously viewing the whole system and the interactions between investments and other stakeholders. Hence, the traditional capital budgeting framework abstracts from strategic considerations.

Due to the above mentioned shortcomings of the traditional capital budgeting framework and the fact that they are designed more for individual projects rather than for an overall policy strategy, an alternative methodology must be adopted. One such alternative is the real options methodology which provides the decision maker with flexibility for evaluating different scenarios with high levels of uncertainty. In particular, "*real options provide the owner with the right, but not an obligation, to take action*".<sup>4</sup> Thus, an "option" may refer to the right of a project initiator to defer the investment decisions, to abandon a project at a later stage, to change the operating scale, to switch inputs and outputs, to expand or contract etc.<sup>5</sup>

In other words, as there is uncertainty as to when, and how, environmental or other conditions will eventuate, the real options methodology provides increased flexibility, e.g. as to the timing of the relevant project(s) and constitutes optionality.

With real options theory, the assumption is that projects should not only be evaluated based on their current state, but all their future opportunities should be evaluated as well.<sup>6</sup>

In the context of this paper, important components of real options theory are the so-called *sequencing options*. In particular, these options provide flexibility as to the timing of more than one inter-related projects, that is, whether it is advantageous to implement these sequentially or in parallel. A firm or a government may prefer to defer the continuants of an investment so as to first evaluate the outcomes of a first project. In this manner, the policy maker can address, or even resolve, some of the uncertainty relating to the overall venture, before deciding whether to proceed or not with the development of the other projects. For example, the "option to expand" in the case of energy production from renewable sources subsidies, would allow to select between a number of different competing projects on the basis of the future growth potential and initial investment at an early (test) stage. Given that the concept is working, additional investment can be allocated.<sup>6</sup>

Another key component of the real options methodology is that it is scalable and thus can be introduced for a single power generator and also for a whole energy system. Examples for the latter for renewables are provided for Turkey,<sup>7</sup> Taiwan<sup>8</sup> and for the USA.<sup>9</sup>

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3 Fernandes, B., Cunha, J., & Ferreira, P. (2011) The use of real options approach in energy sector investments. *Renewable and Sustainable Energy Reviews* **15**(9), 4491-4497.

4 Frayer, J., & Uludere, N. Z. (2001). What is it worth? Application of real options theory to the valuation of generation assets. *The Electricity Journal*, **14**(8), 40-51.

5 Trigeorgis L. (2000) Real options: a primer. In Alleman, J. and E. Noam (eds) *The new investment theory of real options and its implication for telecommunications economics*, Springer, 3-33.

6 Sadowski, B. (2007), *New Perspectives of Real Options Theory for Policy Analysis*, Working Paper, University of Technology Eindhoven.

7 Kumbaro lu, G., Madlener, R., & Demirel, M. (2008). A real options evaluation model for the diffusion prospects of new renewable power generation technologies. *Energy Economics*, **30**(4), 1882-1908.

8 Lee, S. C., & Shih, L. H. (2010). Renewable energy policy evaluation using real option model—The case of Taiwan. *Energy Economics*, **32**, S67-S78.

9 Davis, G. A., & Owens, B. (2003). Optimizing the level of renewable electric R&D expenditures using real options analysis. *Energy Policy*, **31**(15), 1589-1608.

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Furthermore, through real options methodology one can consider valuation framework as a multi-dimensional real options problem involving path-dependent (dis-) investment decisions (e.g. multiple options on multiple underlying assets, investment synergies, learning effects, a dynamic budget). An interesting point is that an increase of the volatility of an underlying asset could increase the value of a portfolio of real options related to this asset, but it could also reduce the value of a portfolio of real options.

A key component of formulating these plans regards the uncertainties that accompany all medium and long-term energy strategies. In particular, there are many sources of uncertainties which directly affect investment decisions such as: evolution of energy costs and prices (e.g. extreme fluctuations of oil prices), shifts in geopolitics (e.g. the Ukrainian situation), development of new technologies (e.g. fusion reactors) and energy sources (e.g. unconventional hydrocarbons), social acceptance for new investments (e.g. transmission lines, wind turbines), available funding (e.g. economic crises) etc. Thus, it is necessary to follow an integrated approach for formulating the necessary energy investment strategies. This approach must be able to take into consideration the above uncertainties, as well as the fact that the policies should be flexible to adapt to new situations and also take into account that there will be a discrepancy between those who formulate the plans and those who will need to implement them (i.e. governments have a shorter lifespan than the medium-term plans that they formulate).

## SUMMARY

European Union Member States will be obliged to formulate single energy and climate national plans for competitive, secure and sustainable energy. In these plans, they will have to simultaneously address issues of achieving domestic objectives regarding greenhouse gas emissions, renewable energy, energy savings, energy security, research and innovation, achieving European Union level climate and energy objectives etc. Furthermore, coordination with neighboring Member States as well as regional effects must be taken into consideration. Therefore, the Member States will have to formulate medium and long-term energy investment strategies. However, there are currently no available analytical tools for this challenging task.

In this paper, we explore the uncertainties that Member States have to address while formulating these national plans. Furthermore, we examine how real options theory can be utilized to formulate these national plans, especially explicit energy investment strategies, through illustrative examples.



# Transmission Capacity as a Common-Pool Resource: The Case of Gas Interconnector Capacity

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## ABSTRACT

We investigated the very real problem of congestion at gas interconnectors. Instead of suggesting further incremental change to the European regulation in force to remedy congestion problems, we took a step back and consider gas interconnectors as a Common-Pool Resource (CPR). We suggest to wait and see what institutions the shippers let emerge to govern and manage interconnector capacity.

To explore this idea, we developed a model to simulate the possible emergence of institutions that would coordinate the shippers and help overcome congestion. We simulate 40 shippers at the Dutch and Belgian interconnectors and allow them to autonomously book capacity. Agents can learn over time to improve their behaviour and coordinate with each other to collectively define a new institution in the system. The main simulator indicators are the observed booking behaviour, agent profits and emerging institutions. We present and discuss preliminary results from a set of simulation runs.

**Keywords:** Agent-Based Modelling, Common-Pool Resources, Congestion Management, Emerging Institutions, Gas Interconnectors

## INTRODUCTION

Liberalization of the European gas sector has caused an increase in the number of active market parties, which increases the complexity of delivering ancillary services, such as managing the grid pressure (balance). Increasingly, control is becoming distributed amongst market players, which results in a situation where no single player alone is delivering the balancing service. Ultimately, the TSO is responsible for the system balance, but we see a shift to decentralized market-based balancing.

A condition for decentralized market-based balancing is a high traded-volume (liquidity) on gas hubs such as the Dutch Title Transfer Facility (TTF) which introduced a within-day market in June 2014<sup>1</sup>

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1 GTS. Within Day Balancing Action (WDBA) as of 3 June 2014. (2014). at <<http://www.gasunie transportservices.nl/en/transportinformation/about-balancing/within-day-balancing-action-wdba-vanaf-3-juni-2014>>

2 GTS. Dataport. at <<http://www.gasunie transportservices.nl/en/transportinformation/dataport>>

3 GTS. *Transport insights 2012*. (2013). at <<http://www.gasunie transportservices.nl/uploads/download/cd8f8651-efc6-424a-b564-ab3f89ac0884>>

4 Harris, D. & Lapuerta, C. *Gas market integration via implicit allocation: Feasibility from the North-West European gas market perspective*. (2012). at <[http://www.acer.europa.eu/Gas/Regional\\_Initiatives/North\\_West\\_GRI/Documents/The Brattle Group gas implicit allocation report.pdf](http://www.acer.europa.eu/Gas/Regional_Initiatives/North_West_GRI/Documents/The%20Brattle%20Group%20gas%20implicit%20allocation%20report.pdf)>

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. Cross border gas-trading increases the liquidity of gas hubs and can lower the costs of balancing if there is a price difference between hubs, and if there is transmission capacity available. However, interconnectors between the Netherlands and Belgium can be congested, meaning that there is no capacity available to accommodate cross-border gas flows<sup>2</sup>.

The congestion may be caused by shippers who book more capacity than that they use in practice. They do this because gas demand depends heavily on ambient temperature, which is unpredictable, and because they must respect safety margins. Furthermore, booked capacity has a value, because it gives shippers the option to freely trade on various connected hubs and leverage price differences<sup>3</sup>. When the booked capacity increases, so do revenues for the transmission system operator (TSO). The ensuing congestion, however, requires capacity expansion or other congestion management measures. Improving the coordination between capacity booking and gas allocation will result in better interconnector investment signals<sup>4</sup>. The latest Network Code, Regulation (EU) No 984/2013, focusses on reducing interconnector congestion through congestion management measures.

An overview of congestion management measures is given in the study done by The Brattle Group<sup>4</sup>. A qualitative description of likely effects is available for the congestion management measures, but a quantitative assessment of a practical case is currently missing. Furthermore, it is unclear how these measures will perform on the borders between Member States where they are subject to different conditions, institutions and network characteristics. The question then is 'to what extent shipper behaviour can be influenced to reduce congestion at border points'.

Institutions are a means to govern behaviour. Since interconnector capacity can be considered a shared resource that maybe overused, which leads to congestion problems, one possibility to define effective institutions is to apply solutions provided for the management of Common-Pool Resource (CPR) systems. Therefore, in this paper, we explore the applicability of CPR problems as an alternative to top-down coordination of gas interconnectors. The emergence of endogenous institutions has proven<sup>5-7</sup> to be successful at avoiding Hardin's Tragedy of the Commons<sup>8</sup>. Using agent-based modelling (ABM), it is possible to replicate emerging institutions in CPR systems, which are commonly observed in the field<sup>9</sup>. ABM is well suited to study the coordination between agents in CPR systems by means of virtual experiments<sup>10,11</sup>.

The paper is structured as follows. Section 2 gives a definition of CPR and argues the applicability to interconnector capacity. Section 3 presents our modelling and simulation approach. The simulation results are presented in section 4. The paper is concluded in section 5.

## INTERCONNECTOR CAPACITY AS A COMMON-POOL RESOURCE

CPR are characterized by finite quantities, non-exclusiveness and rivalry amongst their users. Since it is difficult or costly to exclude users from consuming the resource<sup>12</sup> it is likely that valuable resources are overexploited, or even destroyed in the process. Consumption by one user lowers the availability of the resource for other users. High value CPR are attractive targets of consumption, and consumption by one user is likely to cause negative externalities for other users<sup>13</sup>.

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5 Anderies, J.M. & Janssen, M. A. *Sustaining the commons*. Tempe (Center for the Study of Institutional Diversity, 2013).

6 Ostrom, E. *Governing the commons: The evolution of institutions for collective action*. (Cambridge university press, 1990).

7 Ostrom, E. *Understanding institutional diversity*. (Princeton University Press, 2009).

8 Hardin, G. The tragedy of the commons. *Science* (80-. ). 162, 1243–1248 (1968).

9 Ghorbani, A. & Bravo, G. The Emergence of Institutions for the Management of the Commons. in *Soc. Simul. Conf. (SSC14), Barcelona, 1-5th Sept. 2014* (2014).

10 Bravo, G., Squazzoni, F. & Boero, R. Trust and partner selection in social networks: An experimentally grounded model. *Soc. Networks* 34, 481–492 (2012).

11 Poteete, A. R., Janssen, M. A. & Ostrom, E. *Working together: collective action, the commons, and multiple methods in practice*. (Princeton University Press, 2010).

12 Ostrom, E., Gardner, R. & Walker, J. *Rules, games, and common-pool resources*. (University of Michigan Press, 1994).

13 Ostrom, E. Reformulating the commons. *Swiss Polit. Sci. Rev.* 6, 29–52 (2000).

14 Finger, M.P., Groenewegen, J. P. M. & Künneke, R. W. The Quest for Coherence Between Technology and Institutions in Infrastructures. *J. Netw. Ind.* 6, 227–259 (2005).

15 Feeny, D., Hanna, S., Mcevoy, A. F. & Mcevoy, F. Questioning the assumptions of the "Tragedy of the Commons" Model of Fisheries. *Land Econ.* 187–205 (1996).

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Apart from classical examples like forests, fisheries and water basins, CPR also include man-made systems such as mainframe computers and the Internet<sup>13</sup>. We argue that transmission capacity at gas interconnectors can be seen as an example of CPR. Firstly, the resource is finite and is determined by the physical capacity of the interconnector pipelines. Secondly, the booking of capacity by one shipper lowers the capacity available for other shippers. Thirdly, over-booking causes negative externalities as the interconnector can become congested. Fourthly, it is not allowed for TSOs to restrict access to the resource due to the third party access-requirements in Europe; thus licensed shippers are free to procure the capacity they deem necessary. Finally, while there are costs associated with the booking of capacity, these costs are too low to deter shippers from overbooking. These characteristics lead to problems with two essential infrastructure properties: capacity management and interconnection<sup>14</sup>.

Like most studied CPR systems<sup>15</sup>, gas interconnectors can be considered a relatively simple physical system. However, interconnectors are complex socio-technical systems that comprise many stakeholders, institutions and technical artefacts. Furthermore, interconnectors are the link between two, often very different, national gas systems. In order to study the overuse of interconnectors as a CPR problem we have made a number of assumptions that are common for CPR studies:

1. Interconnector capacity, expressed in kWh, is a finite resource that can only be increased by physical expansion of the interconnector pipelines.
2. Shippers are homogeneous in their demand, capability to procure capacity, and discount rates.
3. Shippers focus on maximizing their short-term profits.
4. Shippers have complete (public) information about the availability of interconnector capacity<sup>2</sup>.
5. All shippers have open access to book interconnector capacity.<sup>3</sup>

Such a simplification would likely lead to a system representation able to reproduce the observed overuse of transmission capacity. Due to the self-interest of shippers we would observe a tragedy of the commons<sup>8</sup>. In line with this observation we see that policy makers are imposing institutions, such as congestion management measures, to change the behaviour of the shippers.

However, other complex CPR systems have demonstrated the ability to achieve better social behaviour through coordination between users<sup>16–19</sup>. It is not unlikely that coordination between shippers can lead to reduced congestion at interconnectors. In fact, interconnectors have favourable attributes that stimulate self-governance<sup>20</sup>:

6. Interconnector capacity cannot deteriorate because of overuse, meaning that there is no point beyond which self-governance is senseless.
7. Interconnector capacity is monitored and made available to shippers in near-real time<sup>21</sup>.
8. Available interconnector capacity is relatively predictable due to long-term capacity contracts<sup>3</sup>.
9. Interconnectors are part of larger natural gas systems, and can be seen as one of the many entry- or exit-points with active shippers. As a result, the spatial extent of interconnectors is limited.

Shippers with cross-border gas flows are dependent on the interconnector capacity. Thus, there is an incentive to coordinate between shippers. However, overbooking is currently a cheap risk-mitigating strategy against penalties that might hamper coordination.

There is much research on endogenous CPR institutions that emerge with time, for example, in the case of small- to medium-sized irrigation systems<sup>13</sup>. As gas interconnectors can be seen as CPR, new institutions around them may emerge, too. This is the more interesting, as the current gas connector system has only been opened up to competing shippers between 2000 and 2005 as a result of the liberalization. Since then the system has seen many

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16 Cordell, J. *A Sea of Small Boats*. (Cultural Survival, 1989).

17 Wade, R. *Village Republics: Economic Conditions for Collective Action in South India*. (ICS Press, 1994).

18 Ruddle, K. & Johannes, R. *The Traditional Knowledge and Management of Coastal Systems in Asia and the Pacific*. (UNESCO, 1985).

19 Sengupta, N. *Managing Common Property: Irrigation in India and the Philippines*. (Sage, 1991).

20 Ostrom, E., Burger, J., Field, C. B., Norgaard, R. B. & Policansky, D. Revisiting the commons: local lessons, global challenges. *Science* (80-. ). 284, 278–282 (1999).

21 GTS. Entry-/Exitcapacity. at <<http://www.gasunie.nl/en/products-services/entry-exitcapacity>>

institutional changes, with the latest changes in 2014 when capacity auctions replaced the first-come-first-served system. However, the emergence of institutions may require a period spanning years or decades.

To learn about emerging institutions, we are not forced to wait. We can build models to play out and simulate multiple futures, and study by what patterns institutions would emerge under what conditions. We formulate the following additional assumptions to extend the classical study of CPR:

10. Shippers can make an effort to change their behaviour and prevent the over-booking of interconnector capacity to reduce the external effects of congestion.
11. Shippers can communicate and coordinate, allowing for the selection (emergence) of institutions within the system to which the shippers will comply.

## MODELLING EMERGING INSTITUTIONS AT GAS INTERCONNECTORS

When studying the coordination between shippers at interconnectors there are two issues that have to be overcome. Firstly, preliminary data analysis of open interconnector data does not seem to indicate coordination between shippers and it is not known when such coordination can be expected to occur. Secondly, observations can take a long time to complete, which is time consuming and also makes it difficult to control the external variables of the experiment. ABM is suitable to simulate coordination at interconnectors, because agents have the following attributes<sup>22</sup>:

- Autonomy; agents operate individually and act in their self-interest. Shippers have shown to overuse interconnector capacity when they act autonomously.
- Co-operation; agents can interact with one another. By sharing a common interface the agents can exchange information about their actions and norms for example.
- Learning; agents can learn from their actions, and those of other agents, to improve their future performance. Learning is important for the emergence of new institutions.

An existing model for simulating emergence of institutions for CPR problems is used<sup>9</sup>. This evolutionary model has already shown that emerging institutions through collective intelligence of agents can help in managing CPRs. The model is implemented using NetLogo 5.0.3<sup>23</sup>.

### Model description

The model primarily focusses on the booking behaviour of shippers on the interconnectors from the Netherlands to Belgium. In total there is an estimated physical interconnector capacity of 110 million kWh, based on 2011 open capacity data<sup>2</sup>. The capacity is assumed to be fixed during the simulation and is reset every day (model tick), because the physical capacity does not deteriorate when used.

We simulate 40 heterogeneous shippers (agents) that represent the active shippers. Each day the shipper is assigned a random gas demand, based on the aggregated gas demand per day in 2011<sup>2</sup>. Every day the shippers book new capacity, which is a simplification of the real-world situation in which there are yearly, quarterly, monthly and daily capacity auctions. This allows us to simulate shipper learning and emerging institutions more rapidly, but can overestimate effects on booking behaviour.

The goal of the shippers is to autonomously book interconnector capacity and to maximize their short-term profits. Profits are maximized by acquiring capacity, because it avoids penalties for being out of balance and the value of capacity can be higher than its market price. Initially the shippers choose a random strategy, but over time they can change their booking behaviour as follows:

- Selection; shippers learn from their own strategies and select new strategies that give a higher payoff. Shippers can also copy the behaviour of others who are using better strategies. Selection is expected to result in shippers avoiding penalties and acquiring as much capacity as possible.

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22 22 Nwana, H. S. Software agents: an overview. *Knowl. Eng. Rev.* 11, 205–244 (1996).

23 Wilensky, U. NetLogo. (1999). at <<http://ccl.northwestern.edu/netlogo>>

- Coordination; agents can coordinate by establishing a new capacity booking institution if the emergence of institutions is enabled. An institution will emerge after a certain period of time if a threshold of shippers is reached that use the same strategy. If such an institution has emerged the shippers have to comply, as we have not included non-compliance in the current model.

### Experimental setup

Due to the recent introduction of capacity auctions it is unclear how these auctions will perform and what their impact on the booking behaviour of shippers will be. Well performing auctions are expected to result in capacity prices that are closer to the value that shippers assign to capacity, which is expected to reduce over-booking. On the other hand, if the auctions do not perform well it is expected that prices will not increase enough. It should be noted that we do not simulate the auctioning processes, but rather assume that shippers assign a higher value to capacity when bidding.

Furthermore, we are interested in exploring the impact of coordination on the booking behaviour of shippers. A new institution is observed when both the time threshold (50 ticks) and shared shipper strategy threshold (50%) are satisfied. This results in four virtual experiments, summarized in table 1.

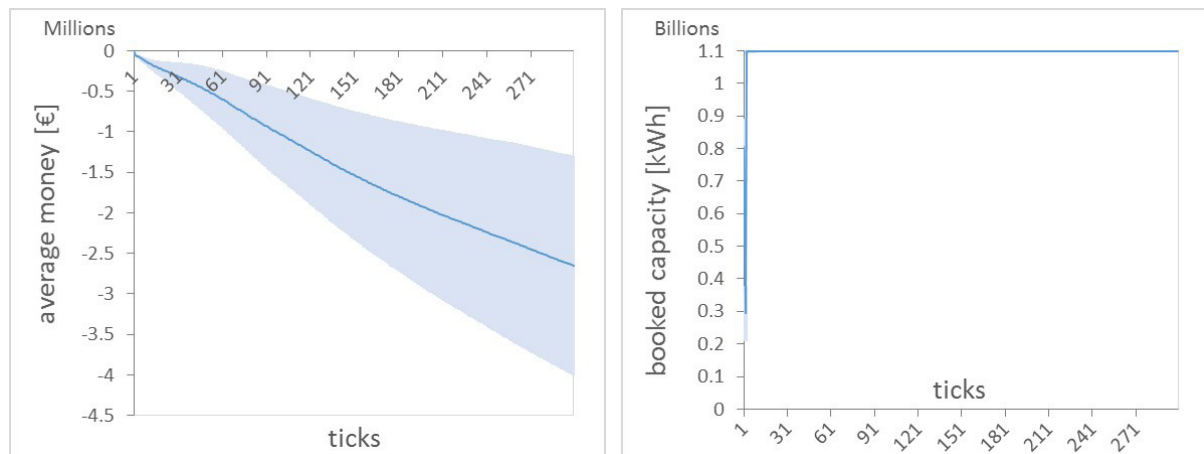
**Table 1 – Summary of scenarios**

#	Auction	Coordination	Objective	Expected outcome
1	No	No	Replicate 2011 observations	Over-booking, but capacity is re-allocated through learning
2	Yes	No	Evaluate the effect of the new auctions introduced in 2014	Reduced over-booking, as there is little additional value in acquiring capacity
3	No	Yes	Observe emerging institutions compared to the 2011 situation	Emergence of an institution to over-book, as this is the status quo
4	Yes	Yes	Observe emerging institutions compared to the 2014 situation	Emergence of an institution to book what is necessary to avoid penalties

### RESULTS AND INSIGHTS

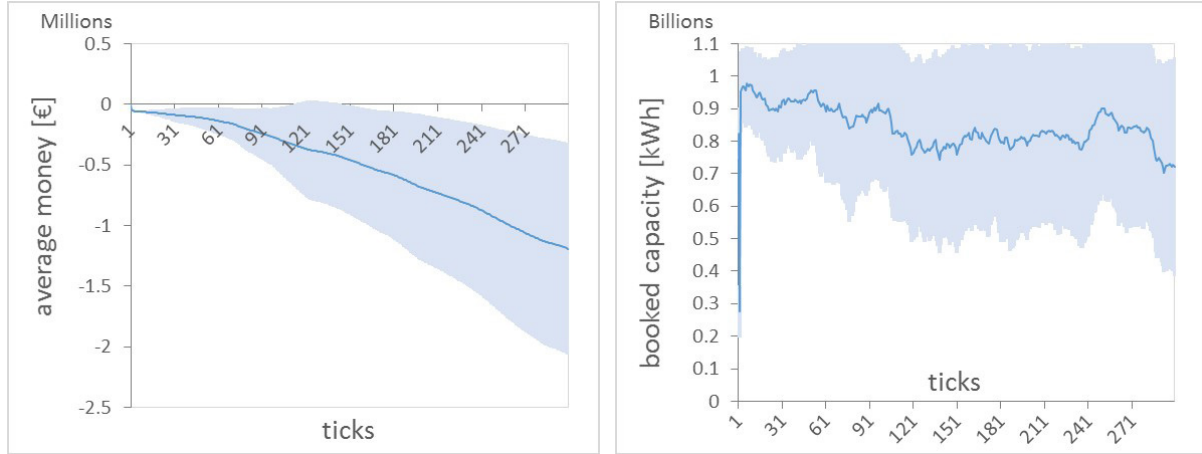
In this section we present the preliminary results, from the first version of our gas interconnector model. Please note that these are initial results, which are based on a limited set of runs. Here we present the aggregated results of 200 model runs, to get a first idea of likely behaviour under different scenarios and to observe the collective behaviour of shippers.

**Experiment 1.** As expected, we observe that the shippers are over-booking the interconnector capacity. What we observe here could be labelled an institution, since most shippers are behaving in the same way. Even though we can observe attempts by shippers to redistribute the capacity amongst each other to avoid penalties we see that this is futile in the long run. Capacity is simply too valuable for agents to not acquire. As a result of the over-booking, there are shippers who receive large penalties, which is reflected in the decreasing average money of the shippers.



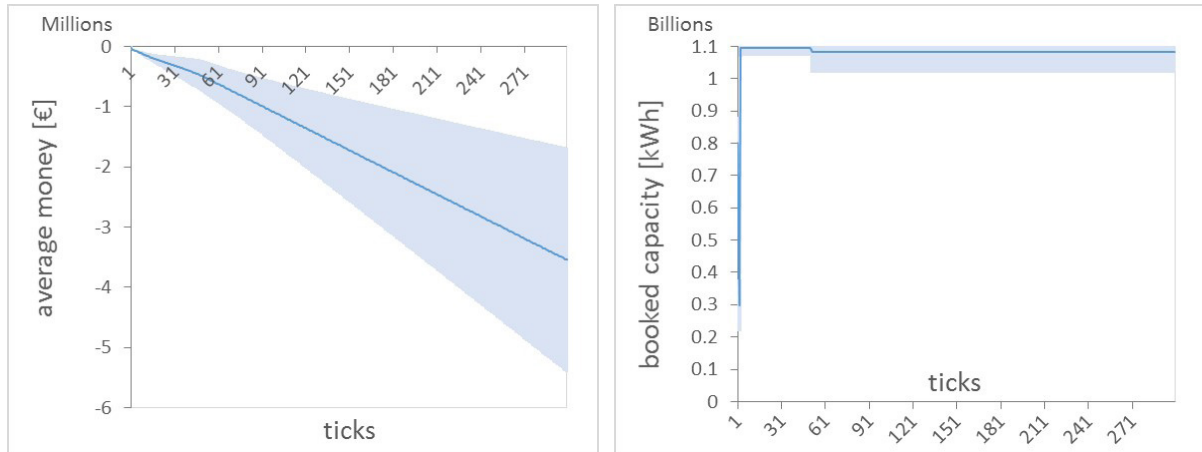
**Figures 1a and 1b – Economic performance and booking behaviour of shippers under scenario 1.**

**Experiment 2.** When the value of capacity is decreased we can see that shippers learn over time to adjust their booking behaviour. There is a trend towards booking less capacity and shippers attempt to avoid penalties. In this experiment the behaviour of shippers is much more chaotic, as a result of the changing gas demand due to exogenous factors such as the weather. Interestingly, while capacity is more expensive, the losses of shippers are lower than they are in the first scenario. This is due to the fact that there is little to no congestion on the border point, allowing shippers to avoid penalties.



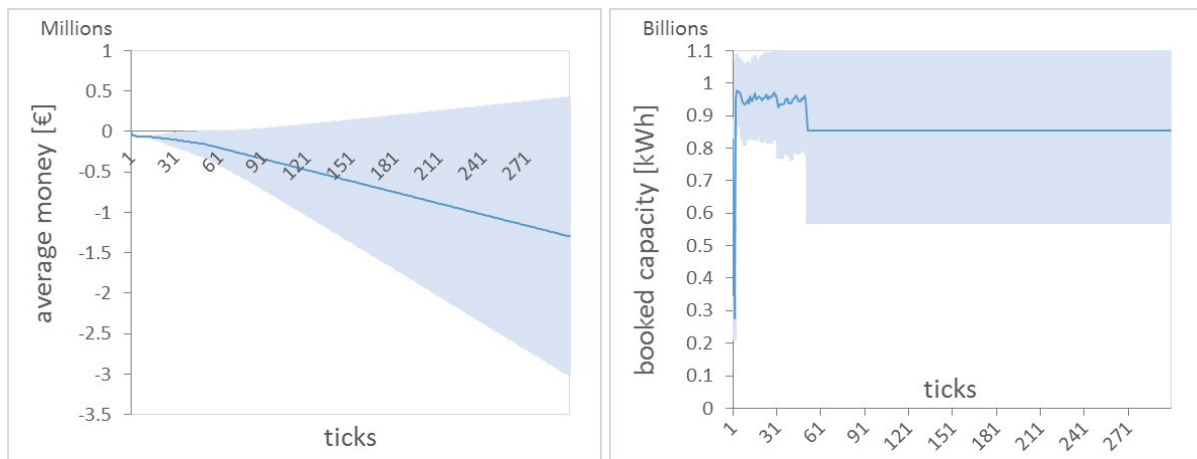
**Figures 2a and 2b – Economic performance and booking behaviour of shippers under scenario 2.**

**Experiment 3.** We observe that an institution to over-book the interconnector capacity emerges even when there are agents making losses. This leads us to believe that there are more shippers who are profiting from over-booking than there are shippers receiving a penalty. The emerging institution actually has an adverse effect in this situation, because it reinforces the over-booking behaviour and eliminates the ability for agents to learn and redistribute resources. The shippers that we have implemented are only self-interested and are unable to assess long-term payoffs. With this current model version, we cannot expect to observe more complex coordination between shippers.



**Figures 3a and 3b – Economic performance and booking behaviour of shippers under scenario 3.**

**Experiment 4.** As expected, an institution emerges under which there is less-overbooking due to the increased capacity price. Similarly to scenario 2 the shippers can avoid penalties in most cases. As a result of the short-term focus of our shipper agents we see that they often arrive at an institution where they book more than they need to avoid the penalty. The learning effect, before the institution emerges, makes them risk-averse due to the high penalty associated with having too little capacity.



**Figures 4a and 4b – Economic performance and booking behaviour of shippers under scenario 4.**

## CONCLUSION

In this paper we investigated the problem of congestion at gas interconnectors. Rather than suggesting further incremental modifications of the European regulations in force to remedy congestions, we took a step back. By considering gas interconnectors as a CPR, we realize that rather than having the EU introduce more detailed regulation, we suggest everyone to wait and see what institutions the shippers allow to emerge to govern and manage interconnector capacity.

To explore the implications of a wait and see approach, we developed a model to simulate the possible emergence of institutions that would coordinate the shippers and help overcome congestion. We simulate 40 shippers at the Dutch and Belgian interconnectors and allow them to autonomously book capacity. Agent can learn over time to improve their behaviour and coordinate with each other to collectively define a new institution in the system. The main simulator indicators are the observed institutions for booking interconnector capacity and shipper profits.

First model results indicate that simple agents are likely to reinforce the currently observed behaviour at interconnectors when they are allowed to coordinate. Their short-term focus leads to the emergence of institutions which are not optimal, and which are hard to get out of. This observation provides a new perspective on the observed over-booking in 2011, because it could be the case that real-world shippers have already coordinated in the past and are stuck in an inefficient institution.

Of course, more research, testing and development of the model is needed, but already we can give the following points to discuss:

- If simple (myopic) agents are able to reproduce the observed behaviour at interconnectors, it would be interesting to explore the institutions that more complex agents allow to emerge.
- The question remains whether TSOs need to implement congestion management measures. Preliminary results indicate that auctions can reduce congestion. This topic deserves more attention with efforts to realistically model capacity auctions.
- It remains unknown why the perceived value of capacity is higher than its current market price. Further research into the driving forces behind the value of interconnector capacity is advised.

## ACKNOWLEDGEMENTS

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# Infrastructure Resilience and Performance



# Service Performance Indicators for Infrastructure Investment

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## ABSTRACT

Infrastructure systems serving modern economies are highly complex, highly interconnected, and often highly interactive. The result is increased complexity in investment decision-making, and increased challenges in prioritising that investment. However, this prioritisation is vital to developing a long-term, sound, robust and achievable pipeline of national infrastructure.

One key to effective, objective and prudent investment prioritisation is understanding the real performance of infrastructure. Many metrics are employed to this end, and many are imposed by governments or regulators, but often these metrics relate only to inputs or outputs in a production process. Whilst these metrics may be useful for delivery agencies, they largely fail to address the real expectations or requirements of infrastructure users — quality of service, safety, reliability, and resilience.

What is required is a set of metrics which address not outputs but outcomes — that is, how well does the infrastructure network meet service needs? This paper reports on a study undertaken at a national level, to identify service needs across a range of infrastructure sectors, to assess service performance metrics in use, and to show how they or other suitable metrics can be used to prioritise investment decisions across sectors and jurisdictions.

**Keywords:** Infrastructure Investment, Performance, Service, Metrics

## THE PROBLEM OF PRIORITISATION

Developed and developing economies depend on effective infrastructure for communication, transport, energy and health. However, infrastructure systems serving modern economies are highly complex, highly interconnected, and often highly interactive. This complexity grows as society's expectations grow, as 'big data' availability grows, as cities become 'smarter', and as system reliability and resilience become more important. The result is increasing complexity in investment decision-making, and increased challenges in prioritising that investment. However, in order to develop a long-term, sound, robust and achievable pipeline of national infrastructure, which grows national productivity while maintaining a prudent and sustainable level of investment, it is exactly this *prioritisation* that is critical.

Governments across the globe recognise this challenge. Government budgets struggle to balance income against growing expense lines for health services, education provision, and other essentials, while debate continues over the level of debt that a nation should contemplate in order to maintain or expand its long-term infrastructure investment. For many nations, this means that the "infrastructure deficit" is growing<sup>1</sup>, while the national budget is constrained

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1 Eg. Infrastructure Australia, *June 2013 National Infrastructure Plan*, p6, at <http://www.infrastructureaustralia.gov.au/coag/index.aspx>

in its ability to respond. Finding a way to prioritise that investment such that it contributes to the greatest possible improvement in national productivity and welfare is therefore critical, but is also complicated and contentious.

Part of the complication is that infrastructure is delivered by a wide range of agencies. State road and rail agencies, national aviation agencies, water corporations, energy networks, and telecommunications corporations all have their own objectives, their own ways of evaluating projects, their own delivery mechanisms, and their own methods of measuring output and value delivered. Each operates to its own technical standards and pricing regimes, each has its own regulatory bodies, each interacts with the private sector in different ways, and each engages with the wider community differently.

How then can a nation take an informed and objective view on national infrastructure priorities, in the midst of such complexity? How can a robust pipeline of investment be planned, maintained, tuned for changing conditions, and delivered? How can the basis of prioritisation be formulated and communicated to multiple stakeholders and communities, who may have conflicting priorities and points of view?

## THE ROLE OF CENTRAL INFRASTRUCTURE AGENCIES

Any robust long-term pipeline of priorities must be based on detailed infrastructure planning. Yet much of this planning is undertaken not at a central or federal level, but by individual agencies responsible for managing State or other networks, whether transport or utilities. These agencies have access to information and resources beyond that which is readily available to central agencies.

In this context, we suggest that there are three critical roles for a central infrastructure agency:

- a. to gather, coordinate, validate and disseminate data that will help agencies determine objectively how well they are meeting national infrastructure needs, and where their challenges and opportunities lie;
- b. to ensure that the best projects filter through proposal and review processes, such that they can be prioritised for investment; and
- c. to coordinate and cross-check that the key national priorities have been fully addressed by the aggregate of agencies' priority projects, and if not, to either adjust prioritisation or provide federal intervention, guidance and funding.

## INFRASTRUCTURE PERFORMANCE, SCORECARDS AND RATINGS

To properly identify needs, and to prioritise those needs, the agency therefore must have a clear knowledge of current infrastructure *performance*. This study was undertaken to assess which performance metrics are being, or should be, employed to measure and report on our infrastructure, across sector and jurisdictional boundaries. The study aimed to identify, where possible, metrics already in use and publicly available, as its intention was to assist agencies in understanding the strengths and weaknesses, and the potential application, of various metrics or benchmarks. In particular, we sought to identify measures of *outcome*, as distinct from *output* or *input*, as our focus was on the *service performance* of infrastructure – how it meets the needs of the end user.

This focus on **service performance** is critical, as agencies will be better equipped to prioritise investment if they have a good understanding of how the outcomes of that investment are valued by the consumer. Similarly, this same understanding can enable a central infrastructure agency to better prioritise investments *across different infrastructure sectors*.

A range of 'Infrastructure Scorecards' has been developed in an attempt to represent holistically the condition of national infrastructure. Engineers Australia produces an annual *Infrastructure Report Card*<sup>2</sup>, and the American Society of Civil Engineers produces a similar appraisal of US infrastructure<sup>3</sup>. More broadly, 'City Rating' systems abound. The Globalisation and World Cities Research Network developed in 1998 a ranking of "world cities"<sup>4</sup>. In 2008, AT Kearney

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2 <http://www.engineersaustralia.org.au/infrastructure-report-card>

3 [www.infrastructurereportcard.org](http://www.infrastructurereportcard.org)

4 Taylor, Peter J, *World City Network: A Global Urban Analysis*, Globalisation and World Cities Research Network (2003)

with others initiated a ranking of global cities<sup>5</sup>. Monocle publishes annually *The Most Liveable Cities Index*<sup>6</sup>, as an assessment of Quality of Life, and the Economist Intelligence Unit produces the *EIU's Global Liveability Ranking and Report*<sup>7</sup>. In an attempt to create some consistency of approach, the International Standards Organisation (ISO) has just released a standard indicating data which should be collected by a city, and the definitions and criteria to be used in collecting and reporting that data<sup>8</sup>. Whilst this is not a mandatory standard, it is a serious attempt to encourage cities to measure their own performance in a way that is consistent and comparable with others. This is a very useful thing to do; however, it assesses city-wide performance, not the service performance of individual water or power networks, or specific segments of a road or rail network. It therefore is not of great help in determining where investment should be prioritised.

To address these challenges, this study takes as its 'exam question' the following:

*What metrics are currently in use to measure infrastructure outcomes or service performance, and how could they be adapted or adjusted to provide a basis for sound infrastructure investment prioritisation across sectors and jurisdictions?*

## APPROACH TO THIS STUDY

The approach taken to this study was to focus on "nationally-significant infrastructure", being transport, energy, communications and water infrastructure in which investment will materially improve national productivity<sup>9</sup>. Directing those investments is normally based on an "investment logic"<sup>10</sup> that links inputs to a set of outputs, which in turn contribute to achieving the desired outcomes and impact. For example, capital investment (input) might be directed towards constructing 10km of national highway (output), which is undertaken to improve travel safety and reliability (outcome) and thereby improve national productivity (impact). Much infrastructure reporting provides inputs and outputs as indicators of performance, but as the OECD has noted:

*"... more spending should not be confused with better outcomes, as the size of [infrastructure sectors] says little about their impacts on welfare ... outputs are often taken as proxies for outcomes"*<sup>11</sup>

We therefore sought to develop a framework of **outcome** indicators across the chosen infrastructure sectors.

This was done by a desk study of information made publicly available by state and federal agencies and network operators. Reference was also made to studies to determine which aspects of infrastructure are valued by users.

Across all infrastructure types, users are primarily concerned with the **quality of the service provided**. The concept of a 'good quality' infrastructure service can be unpacked into several outcomes groupings which are relatively consistent across different types of infrastructure:

- *reliability*: the ability of the infrastructure to meet normal or current demand (eg. proportion of trains running on time, road congestion in response to normal traffic demand)
- *stability*: the consistency of the infrastructure service provided (eg. drops in water pressure, surges in electricity)
- *safety*: the safeness of the infrastructure for those who use it (eg. microbial levels in water, frequency of road accidents)
- *resilience*: the ability of the infrastructure to respond in the event of unusual demand (eg. road congestion in response to unusual event, internet download speeds).

It should be noted that 'efficiency' is not considered as an outcome for the purposes of this framework. Efficiency is a measure of outputs divided by inputs, for example kilometres of road laid per number of hours worked. In this sense,

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5 <http://www.atkearney.com/documents/10192/dfedfc4c-8a62-4162-90e5-2a3f14f0da3a>

6 <http://monocle.com/film/affairs/quality-of-life-survey-2013/>

7 [https://www.eiu.com/public/topical\\_report.aspx?campaignid=Liveability2013](https://www.eiu.com/public/topical_report.aspx?campaignid=Liveability2013)

8 ISO 37120:2014, *Sustainable development of communities -- Indicators for city services and quality of life*.

9 See for example the Infrastructure Australia Act 2008 (No 17, 2008) – Section 3

10 See for example the Investment Logic Map process used by the Department of Treasury and Finance, Victoria at: [www.dtf.vic.gov.au](http://www.dtf.vic.gov.au)

11 Pisu, M., Hoeller, P. and Jourard, I. 2012, *Options for Benchmarking Infrastructure Performance*, OECD Economics Department Working Paper No.956, OECD: Paris. P.5

it does not measure an outcome that is of direct importance to the user — apart from the influence it may have on the price paid to access the infrastructure. It is clearly of importance to those who fund infrastructure, however this is outside the scope of this framework, as a poor efficiency outcome with respect to price would often necessitate a non-infrastructure solution (such as incentives to encourage competition).

## OBSERVATIONS AND FINDINGS

In undertaking the investigation, and reviewing indicators against the framework above, we found a plethora of metrics. As expected, many were input or output measures, particularly of capital invested or quantity of infrastructure constructed. However, across Australia and around the world, there were also a considerable number of *outcome* indicators in use. These are outlined below.

**The water sector** in Australia operates under the National Water Commission's *National Performance Framework*, which identifies 188 indicators and sub-indicators. In the UK the Office of Water (Ofwat) uses a small set of key performance indicators on which utilities must report, and in New Zealand an industry association (Water New Zealand) undertakes performance benchmarking. From this analysis, combined with the findings of Victorian research into customer expectations, we have proposed four key performance indicators for urban water infrastructure.

**The energy sector** analysis focussed on electricity generation, transmission and distribution, and drew upon the Australian Energy Regulator's reporting regime, performance indicators from Australia's largest energy retailers, the UK's Office of Gas and Electricity Markets annual *Transmission and Distribution Reports*, the Annual Report from Contact Energy in New Zealand, and customer satisfaction studies by energy networks and Canstar Blue. From our analysis, we have proposed three key performance indicators for the electricity sector.

**The communications sector** performance is indicated by the Australian Communications and Media Authority (ACMA) in its *Communications Report* and the Government's *Broadband Availability and Quality Report*. International approaches include the UK's Office of Communications *Infrastructure Report* of communications speeds against the threshold minimum performance guaranteed under the Government's Universal Service Commitment on internet access. From our analysis, and review of ACMA's consumer survey on internet service provision, we have proposed four key performance indicators for communications infrastructure.

**The road transport sector** performance is measured at both state and national level, and Austroads (covering Australia and New Zealand) reports annually on 72 indicators in its *National Infrastructure Performance Web Report*. In a similar way, the US National Cooperative Highway Research Program provides a summary of performance indicators, as does Canada's Ministry of Transport Business Plan. Our analysis, combined with a review of transport user priorities identified in the Australian Transport Council's *National Guidelines for Transport System Management in Australia*, and similar guidance from Transport for NSW, has led us to recommend four key performance indicators for road transport infrastructure.

**The freight rail transport sector** study focussed initially on freight rail using Commonwealth-owned interstate freight rail networks. Performance indicators are published by the Australasian Railway Association, the Bureau of Infrastructure, Transport and Regional Economics (BITRE), and the Australian Rail Track Corporation (ARTC). Safety-related indicators are reported by the Australian Transport Safety Bureau. Similar data is measured and reported in the UK by Network Rail and by the Office of Rail Regulation. The latter also undertakes a regular survey of existing and potential freight rail users, and their service priorities. From our review and analysis, we have recommended four key performance indicators for freight rail infrastructure.

**The commuter rail transport sector** reports nationally on safety performance through the Australian Transport Safety Bureau. Beyond that, the sector tends to report by operator, primarily on the proportion of scheduled operations that actually run, and the proportion of scheduled trains that run on-time. Internationally, associations such as CoMET (Community of Metros), Nova, and ISBeRG (International Suburban Rail Benchmarking Group) report similar metrics. Operators variously assess user priorities, and in 2006 the Australian Transport Council undertook an extensive literature review of both stated and revealed user preferences. From our review and analysis, we have recommended five key performance indicators for commuter rail infrastructure.

## CONCLUSIONS, RECOMMENDATIONS AND NEXT STEPS

Our study revealed a very wide range of infrastructure performance metrics in use across Australia and globally. These are employed for varied purposes, and report a considerable span of inputs, outputs, outcomes and impacts. From an infrastructure user's perspective, however, the *outcomes* are of primary interest and importance. This study has therefore focussed on identifying key outcome performance indicators across five sectors, arriving at nineteen such indicators.

These key performance indicators, for the very reason that they capture users' perspectives, also provide critical insights for infrastructure investment agencies at state and national level. Whilst input and output data are important measures of progress within the agency, our national investment must be guided by the outcomes it is delivering for infrastructure users.

The framework we have proposed provides a mechanism which could be used to compare performance across sectors, across jurisdictions, and importantly, between different parts of a network. This makes it an important part of the prioritisation toolkit. Further work is required to enable it to be used by lead agencies to proactively identify areas potentially in need of further investment. This work includes:

- collecting data for each indicator from the relevant sources, at an agreed geographical level;
- quantifying the cost of under-performance in each sector, to enable a cross-sectoral comparison of gaps and needs; and
- depicting the results of the performance management framework in a way that is engaging and that allows for easy identification of under-performing areas within a sector.

In this way, the greatest areas of need, and the greatest opportunities for improving national productivity, could be identified and evaluated in a framework that is meaningful to policy-makers and delivery agencies. This understanding is key to the objective prioritisation of infrastructure investment in Australia and in many other nations.





# Visualisation Tools for Multi-Perspective, Cross-Sector, Long-Term Infrastructure Performance Evaluation

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<http://discovery.ucl.ac.uk/1469292/>

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## ABSTRACT

Across different infrastructure sectors there are systems that help to monitor the current and near-future operation and performance of a particular system. Whilst Supervisory Control and Data Acquisition (SCADA) systems are critical to maintaining acceptable levels of functionality, they do not provide insights over the longer timescales across which strategic investment decisions play out. To understand how individual or multiple, interdependent, infrastructure sectors perform over longer timescales, capacity/demand modelling is required. However, the outputs of such models are often a complex high-dimensionality result-set, and this complexity is further compounded when cross-sector evaluation is required. To maximise utility of such models, tools are required that can process and present key outputs. In this paper we describe the development of prototype tools for infrastructure performance evaluation in relation to different strategic decisions and the complex outputs generated from capacity and demand models of five infrastructure sectors (energy, water, waste water, solid waste, transport) investigated within the UK Infrastructure Transitions Research Consortium (ITRC). By constructing tools that expose various dimensions of the model outputs, a user is able to take greater control over the knowledge discovery process.

**Keywords:** Visualisation, Infrastructure Performance, Cross-sector, Infrastructure Systems, Database

## INTRODUCTION

The evolution of infrastructure systems has resulted in a complex *system-of-systems* that are highly connected and interdependent (Rosato, 2008)<sup>1</sup>. As a result it is a non-trivial task to model and interpret how such a system will evolve and subsequently perform in the future when facing changing demographic, economic, and climatic conditions. Traditionally each infrastructure sector (e.g. energy, transport, waste, water) monitors its own performance, often via targets prescribed by industry regulators such as OFCOM, OFGEM or OFWAT in the UK. For example, OFWAT has outlined water efficiency targets for each privatised UK water supplier, such as Northumbrian or Yorkshire Water, in an attempt to reduce water usage (OFWAT, 2007)<sup>2</sup>. In turn these targets are offered in an attempt to ensure water suppliers can adhere to the fixed prices negotiated every 5 years in the UK water sector (OFWAT, 2008)<sup>3</sup>. The perspectives gained from reviewing such performance indicators or targets are largely focussed on a

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1 Rosato, V. S. (2008). A Complex System's View of Critical Infrastructures,. In D. Helbing, *Managing Complexity: Insights, Concepts, Applications* (pp. 241-260). Springer.

2 OFWAT. (2007). RD 15/07: *Water efficiency targets*. Retrieved 15 05, 2014, from OFWAT: [http://www.ofwat.gov.uk/regulating/ltr\\_rd1507\\_watefftargts](http://www.ofwat.gov.uk/regulating/ltr_rd1507_watefftargts)

3 OFWAT. (2008). *Setting the price limits for 2010-2015: Framework and Approach*. Retrieved 10 03, 2014, from OFWAT: <http://www.ofwat.gov.uk/price/setting-price-limits-2010-2015>

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particular infrastructure sector, and do not allow for evaluation across different sectors or does not provide insight in to the interdependencies between sectors. Equally, such an approach does not allow an analysis of the longer term multi-decadal requirements for infrastructure planning to be addressed; an issue which has been recognised in the UK by the establishment of Infrastructure UK (IUK), (HM Treasury, Infrastructure UK, 2010)<sup>4</sup>, within HM Treasury, and through calls for an independent “National Infrastructure Commission” via Sir John Armitt’s review of UK infrastructure planning (Armitt, 2013)<sup>5</sup>. As such, there is an urgent need for the development of new model paradigms and related analytical tools that enable the evaluation of potential impacts of decisions over the medium to long-term on infrastructure planning and investment (Council for Science and Technology, 2009, Recommendation 5)<sup>6</sup>.

Within the UK, the Infrastructure Transitions Research Consortium (ITRC) has developed a series of capacity and demand models (CDAM) that provide insight into the future performance of key infrastructure sectors utilising projections of future demographic and economic conditions (Zuo, Birkin, & Malleson, 2013)<sup>7</sup> as drivers, and adjustments to model parameters to reflect particular strategic decisions. As a result of executing each model, multi-dimensional data is produced. For decision makers, government agencies, managers of infrastructure assets, and the research community to understand the potential impacts and consequences of taking particular decisions a system to explore and visualise outcomes of different decisions and scenarios is essential (Lempert, 2002)<sup>8</sup>. In this paper we present a series of prototype visualisation tools that in combination will form the basis for an infrastructure performance visualisation and reporting framework. This will be used to evaluate performance from different perspectives with a view to understanding how different decision pathways impact infrastructure performance in the long-term. The tools developed draw on the result-sets of the sector-specific sub-strategies and strategy portfolios investigated in the ITRC capacity and demand models, which in turn employ a number of different economic and demographic scenarios; full details of the design concepts of the ITRC capacity and demand modelling can be found in Otto, et al. 2014<sup>9</sup>.

## INFRASTRUCTURE SECTOR STRATEGIES AND PORTFOLIOS

Whilst decisions that are likely to impact infrastructure in the UK have historically occurred in a relatively ad-hoc manner (Council for Science and Technology, 2009; HM Treasury, Infrastructure UK, 2010)<sup>10,11</sup>, and have been derived from a multitude of complex interactions between infrastructure operators, regulators and government, there is an increasing body of evidence that a more coherent and coordinated approach is required (Tolone, 2009; HM Treasury, Infrastructure UK, 2013)<sup>12,13</sup>. Within ITRC a series of national infrastructure strategy portfolios were developed in order to package together options or interventions that employ different mixtures of regulation, technology choice and

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ofwat.gov.uk/pricereview/pap\_pos\_pr09method080327.pdf

4 HM Treasury, Infrastructure UK. (2010). *Infrastructure UK*. Retrieved 10 03, 2014, from Infrastructure UK: <https://www.gov.uk/government/organisations/infrastructure-uk>

5 Armitt, S. J. (2013). *An independent review of long term infrastructure planning commissioned for Labour’s Policy Review*. Retrieved 10 03, 2014, from Your Britain: [http://www.yourbritain.org.uk/uploads/editor/files/The\\_Armitt\\_Review\\_Final\\_Report.pdf](http://www.yourbritain.org.uk/uploads/editor/files/The_Armitt_Review_Final_Report.pdf)

6 Council for Science and Technology. (2009). *A National Infrastructure for the 21st Century*. Retrieved 10 03, 2014, from Department for Business Innovation and Skills: <http://www.bis.gov.uk/assets/bispartners/cst/docs/files/whats-new/09-1631-national-infrastructure>

7 Zuo, C., Birkin, M., & Malleson, N. (2013). Dynamic Microsimulation Modelling for National Infrastructure Demand in an Uncertain Future. *Geocomputation 2013 Conference Proceedings*. Wuhan, China.

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9,15,17 Otto, A., Hall, J. W., Hickford, A. J., Nicholls, R. J., Alderson, D., Barr, S., et al. (2014). A quantified system-of-systems modeling framework for robust national infrastructure planning. *IEEE Systems*, Accepted.

10 Council for Science and Technology. (2009). *A National Infrastructure for the 21st Century*. Retrieved 10 03, 2014, from Department for Business Innovation and Skills: <http://www.bis.gov.uk/assets/bispartners/cst/docs/files/whats-new/09-1631-national-infrastructure>

11 HM Treasury, Infrastructure UK. (2010). *National Infrastructure Plan*. (2010, 25 10), *National Infrastructure Plan*, Retrieved 10 03, 2014, from National Infrastructure Plan: <https://www.gov.uk/government/publications/national-infrastructure-plan-october-2010>

12 Tolone, W. J. (2009). Interactive visualisations for critical infrastructure analysis. *International Journal of Critical Infrastructure Protection*, 2 (3), 124-134.

13 HM Treasury, Infrastructure UK. (2013). *National Infrastructure Plan*. (2013, 16 04). *National Infrastructure Plan*. Retrieved 10 03, 2014, from National Infrastructure Plan: <https://www.gov.uk/government/collections/national-infrastructure-plan>

investments (Hall et al., 2012; Otto, et al., 2014)<sup>14</sup>. The different mixtures used are represented via a series of sector-specific sub-strategies, with either the capacity or demand within a sector influenced by adjustments to the three aforementioned components in relation to the input capacity-demand model (CDAM) parameters (Tran, et al., 2014)<sup>16</sup>. The process of sub-strategy definition and how they are combined to build a particular strategy portfolio is considered in greater detail in Otto, et al. 2014<sup>17</sup>. Table 1 shows in general terms how the 4 strategy portfolios investigated were constructed with respect to the sector specific sub-strategies (Tran, et al., 2014)<sup>18</sup>. Two initial performance metrics were defined to evaluate and compare the performance of each strategy portfolio. These were, an assessment of environmental performance measured in terms of Carbon Dioxide (CO<sub>2</sub>) emissions from the key sectors, and a calculation of investment. The performance and comparison of the different strategy portfolios was undertaken for 2010, 2030 and 2050. Subsequent visualisation tools for both individual sectors and cross-sector comparison were developed using this initial ITRC CDM set of strategy portfolios and related performance metrics.

**Table 1 – Table depicting the combinations of sector-specific strategies used to generate the cross-sector strategy portfolios.**

	Strategy portfolios →	Minimum Intervention Portfolio [P-MI]	Long-term Capacity Expansion Portfolio [P-CE]	Increasing System Efficiency [P-SE]	New Services and Planning [P-NS]
Sub-strategies ↓					
Energy <sup>‡</sup>		EN0 – Minimal policy intervention	EN2 - Electrification of heat and transport <sup>*</sup>	EN2 - Electrification of heat and transport <sup>**</sup>	EN2 - Electrification of heat and transport <sup>***</sup>
Transport		TR0 – Decline and decay	TR1 – Predict and provide	TR3 – Adapting the fleet	TR6 – Smarter choices
Solid Waste		WE0 – Business as usual	WE1 – High tech	WE3 – Deep green	WE3 – Deep green
Waste Water		WW0 <sup>^</sup> - Current trends	WW0 <sup>+</sup> - Current trends	WW0 <sup>^</sup> - Current trends	WW0 <sup>^</sup> - Current trends
Water		WS0 <sup>^</sup> - Current trends	WS0 <sup>+</sup> - Current trends	WS0 <sup>^</sup> - Current trends	WS0 <sup>^</sup> - Current trends

<sup>‡</sup>**Energy model comprised of two separate models, one demand-side, and one supply-side**

<sup>^</sup>**Central population scenario**

<sup>\*</sup>**High population scenario**

<sup>^</sup>**Low population scenario**

<sup>\*</sup>**with High Nuclear**

<sup>\*\*</sup>**with High Carbon Capture and Storage**

<sup>\*\*\*</sup>**with High Offshore**

## VISUALISING AND COMPARING CROSS-SECTOR PERFORMANCE

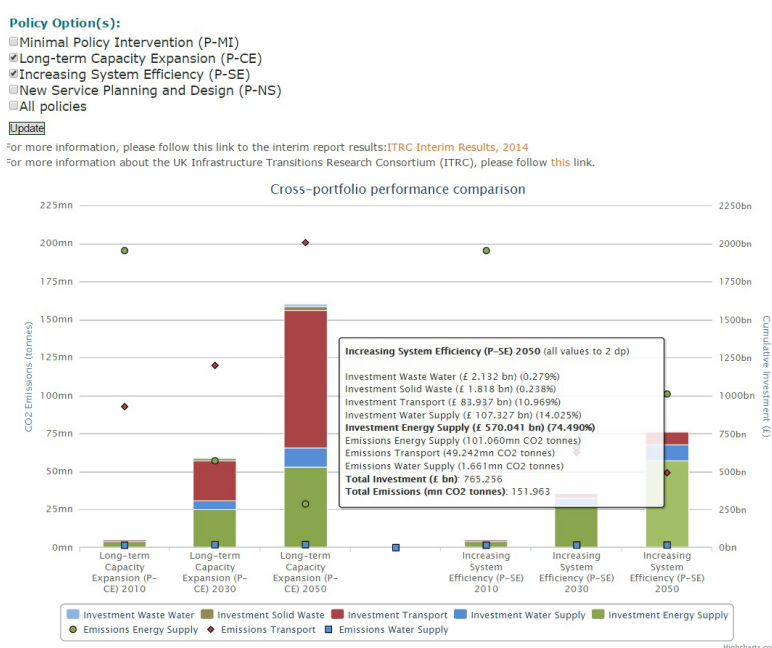
To facilitate the cross-sector exploration of the outputs from executing all the models for the defined sub-strategies (Table 1 rows) that combine to form the strategy portfolios (Table 1 columns), an initial prototype visualisation interface was developed using open-source server-side database technologies, *PostgreSQL* and *PostGIS*, via the use of the Python-powered *Django* web framework coupled with custom client-side *JavaScript* scripts and *Highcharts* library (Figure 1). A user is able to control which strategy portfolios to display via checkboxes, resulting in a POST request to the server-side ITRC database (Barr et al., 2013) to retrieve the relevant data. In the tool, a user can obtain more information on a strategy portfolio by placing the mouse cursor over either the bars representing cumulative investments or the points representing emissions. This invokes a script that dynamically-generates a *data*

14, Hall, J. W., Henriques, J. J., Hickford, A. J., & Nicholls, R. J. (2012). *A Fast Track Analysis of strategies for infrastructure provision in Great Britain: Executive Summary*. Environmental Change Institute. University of Oxford.

16,18 Tran, M., Hall, J. W., Hickford, A. J., Nicholls, R. J., Alderson, D., Barr, S. L., et al. (2014). *National infrastructure assessment: Analysis of options for infrastructure provision in Great Britain, Interim results*. Environmental Change Institute. University of Oxford

label or tooltip that reports the relative contributions from each sector for the selected year (Figure 1). Furthermore, a user is able to decide which sectors they wish to investigate by clicking the appropriate item from the chart legend found beneath the chart. A consistent colour scheme for each sector is employed to more easily determine emissions and investments attributable to each sector.

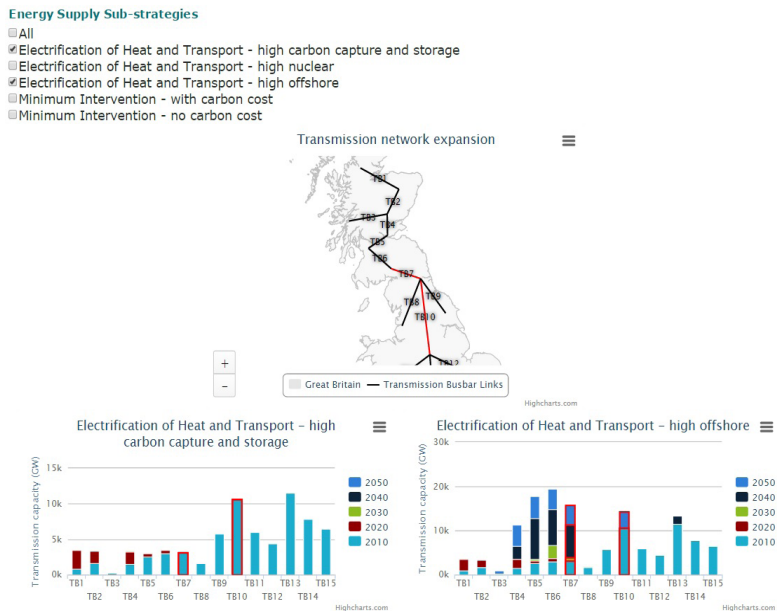
By combining the display of both metrics within the visualisation canvas it allows a user to visually and quantitatively explore the differences between different strategy portfolios both in absolute terms and also in terms of individual sectors within each of the strategy portfolios. This ability allows a user to understand the potential trade-offs involved within and between strategy portfolios in terms of environmental performance via carbon emissions and investment. For example, Figure 1 shows that the Long-term Capacity Expansion (P-CE) strategy portfolio offers high levels of investment, particularly within the transport sector (red) as a result of widespread expansions to the road network, coupled with high levels of carbon emissions, while the Increasing System Efficiency (P-SE) strategy portfolio offers reduced levels of investment alongside significantly lower carbon emissions over the modelled time horizon (Tran, et al., 2014). However, in its current form the visualisation tool via the available metrics cannot give an indication as to the trade-offs between available capacity as a result of differences in investment, an issue that will be addressed in the further development of cross-sector performance metrics.



**Figure 1 - Reporting cumulative investment and CO2 emissions for all evaluated strategy portfolios.**

## SINGLE-SECTOR PERFORMANCE COMPARISON

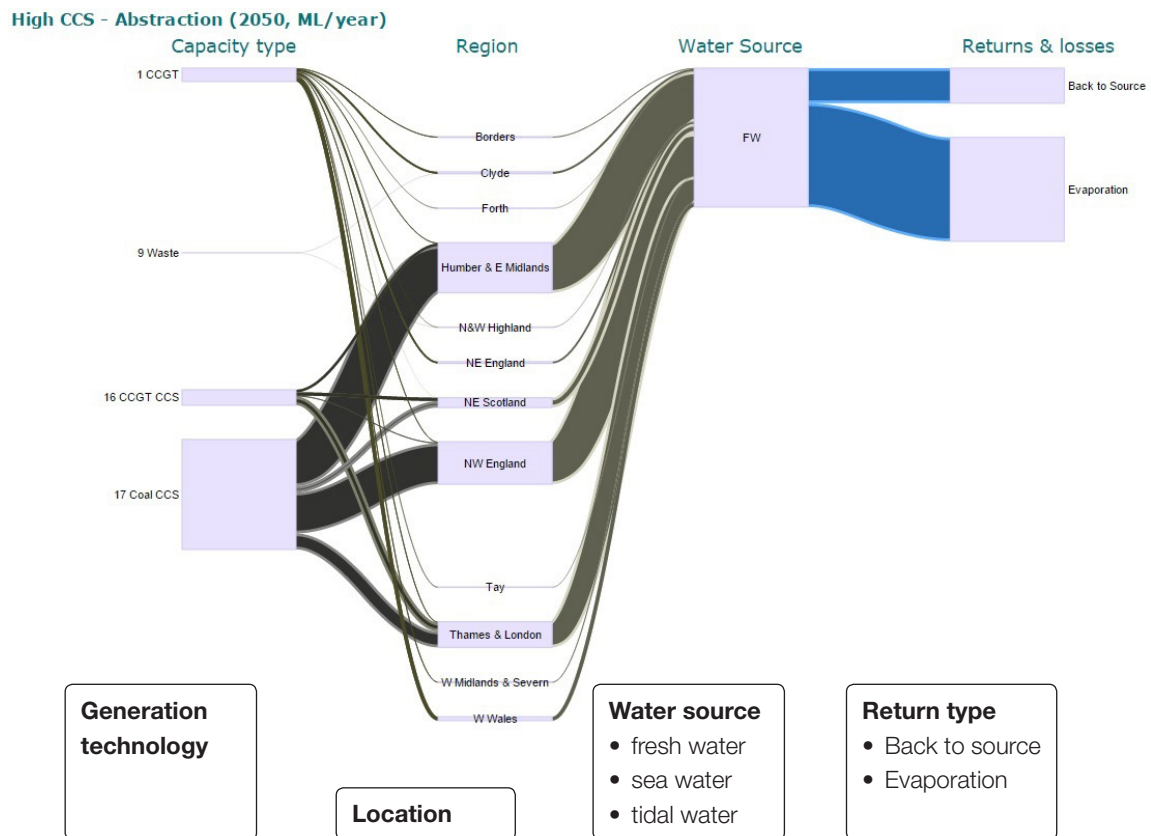
To further expose the modelling outputs of the ITRC CDAM models and to begin to explore ways that individual sectors may be analysed, interrogated, and presented with respect to the strategy portfolios generated, a number of web-based prototype visualisation user interfaces have been developed. Each of these has been designed to extend the static figures that were initially generated for the written report of the CDAM work (Tran, et al., 2014). Figure 2 illustrates an example interface showing the changes in the electricity power transmission network, as modelled within the energy supply CDAM, over time for the different energy supply sub-strategies. A user is able to choose which sub-strategies to display via the checkboxes at the top of the screen, and can choose which of the 5 available 10-year time steps to display via the legend next to each chart. A user is able to retrieve data values from the charts by hovering over the bar of interest, and is also able to select particular busbars links to highlight (red outline) by clicking on the map and holding the *Shift* key (Figure 2).



**Figure 2 – Visualising the energy supply power transmission network expansion for different energy supply sub-strategies over time**

## VISUALISING CROSS-SECTOR INTERDEPENDENCE: COOLING WATER USAGE FROM ELECTRICITY GENERATION

As part of the ITRC CDAM modelling a number of interdependencies between infrastructure sectors were explored by taking the outputs from one particular sector model and using it as inputs within another model in order to specifically investigate the relationship between sectors (Tran, et al., 2014). For example, in order to understand potential changes in water usage as a result of employing alternative mixes of energy generation technologies, a separate model for water usage from energy generation was developed (Byers, Hall, & Amezaga, 2014) that requires energy generation (GWh) and capacity (MW) outputs from the energy supply CDAM disaggregated by generation technology types, year, season, and busbar link. Results from the water usage model were stored in the ITRC database (Barr, et al., 2013) and a suite of open source *JavaScript* libraries were used to develop a visualisation tool that allows users to explore dynamically for different energy sub-strategies the potential impact on water usage from fresh, sea and tidal sources. The tool developed makes use of a Sankey diagram (Bostock, 2012) which expresses visually the relative quantities of different water types used from different energy generation technologies, in different regions in the UK, for different time periods (Figure 3).

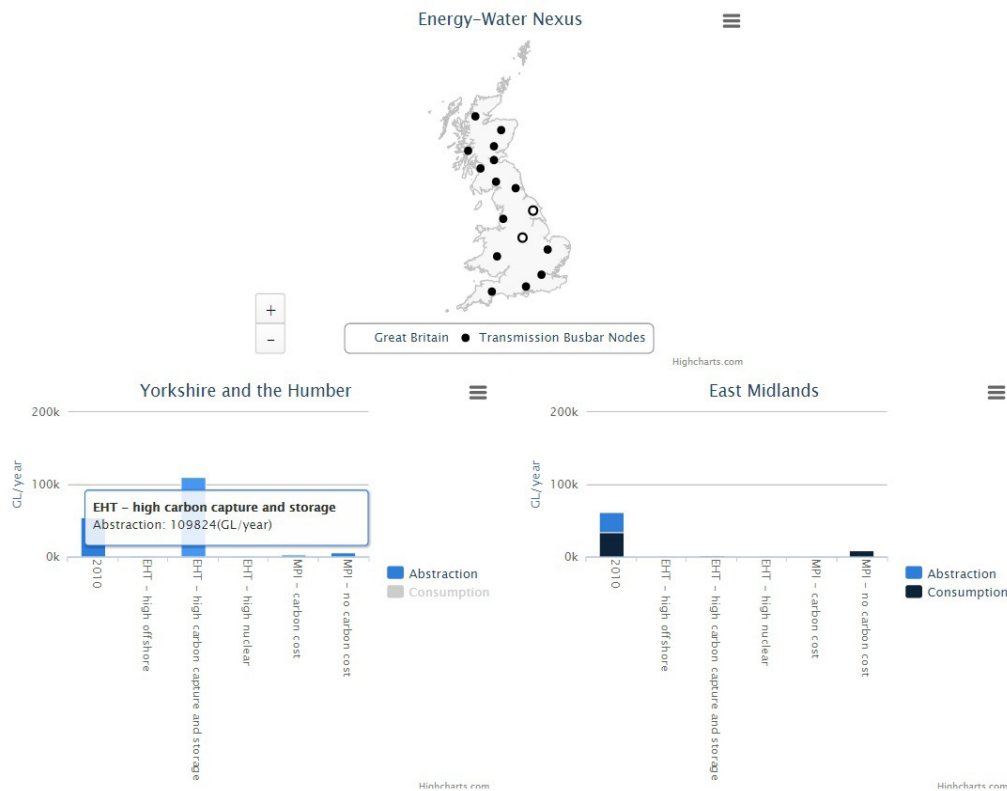


**Figure 3 - Sankey diagram visualisation showing quantity of water usage as a result of different energy generation technology mixes influenced by each energy supply sub-strategy (indicative values).**

To offer an alternative approach to visualise the same data, a further interface was developed (Figure 4). This approach exports the contents of the database tables powering the Sankey diagram shown in Figure 3 to a separate Geographic JavaScript Object Notation (GeoJSON; Butler, et al., 2008)<sup>19</sup> file which is subsequently accessed via a request to the server. Custom JavaScript is used, along with the *Highcharts* and *Highmaps* libraries to build the interface. A user is able to choose what data to display by *Ctrl*-selecting multiple locations on the map to retrieve different combinations of charts beneath. The charts show the quantity of water abstraction and consumption for the base year 2010, as well as for all energy supply sub-strategies in 2050. The sub-strategies are reflected in the categories across the x-axis. Inspection of Figure 4 shows a comparison of the abstraction and consumption water levels for Yorkshire and the Humber, and the East Midlands regions of the UK. By using this tool, and by allowing a user to control what regions of interest to display it is possible to determine where alternative energy generation mixes (as defined by the different energy supply strategies evaluated) are going to have the greatest impact on fresh water usage. In this case, it is apparent that levels of freshwater abstraction and consumption for Yorkshire and the Humber are much greater in 2050 under the Electrification of Heat and Transport (with high carbon capture and storage) strategy, compared to other strategies for that region, and compared to the East Midlands region across all strategies. An important aspect of this tool is that a user is able to decide which geographic regions to compare at any one time, and is able to retrieve data values for these directly, without having to refer to the original data tables generated from the CDAM modelling.

<sup>19</sup> Butler, H., Daly, M., Doyle, A., Gillies, S., Schaub, T., & Schmidt, C. (2008). *The GeoJSON Format Specification*. Retrieved 05 02, 2014, from geoJSON.org: <http://geojson.org/>





**Figure 4 - Visualising water usage from energy generation under different energy supply sub-strategies, over time. This example is for freshwater abstraction and consumption only.**

## FUTURE WORK

The ITRC project has initiated an ambitious programme of capacity and demand modelling of infrastructure sectors and their interdependencies. To date our ability to interrogate, analyse, and present the outputs of such models has been limited. In order to maximise the utility of modelling dedicated visualisation systems are required that can directly query the model outputs via the ITRC database to extract, synthesise and present relevant sub-sets of results for decision making purposes. The tools presented in this work are an initial start on developing such a software framework. In future, however, a much broader and detailed set of analytical middleware is required that acts as a broker between the model outputs in the ITRC database and the web-based visualisation interfaces. The model outputs will be generated in a coordinated fashion via the use of the integrated system-of-systems modelling framework currently in development that will enable all infrastructure sector models to be executed together and the results subsequently explored. This will enable more strategies representing particular decisions on infrastructure for a wider range of demographic and economic scenarios to be evaluated. A user will be able to view different cross-sector or sector-specific visualisations of the modelled outputs and subsequently export the images and data for publication in reports, or for further investigation. Furthermore, additional performance metrics, alongside investment and CO<sub>2</sub> emissions, related to capacity utilisation and total service delivery will be developed and included within the extended visualisation and reporting framework.

## CONCLUSION

Through the use of computer models representing five key infrastructure sectors within the UK (energy, water, waste water, solid waste, transport) evaluations of the potential impacts of different decision pathways taken regarding infrastructure have been performed; the interim results of which are available in Tran, et al., 2014<sup>20</sup>. Due to the highly complex systems being modelled, the resultant data is also highly complex with multiple dimensions. Through the use of database technologies and scripting and JavaScript libraries, ITRC has produced a set of prototype visualisation tools that will enable users to review and explore the outputs from these computer models. Through the use of these technologies, directly coupled to model output data, the currency of each visualisation can be maintained as new data becomes available, giving prospective users more opportunity to discover new insights and interact with new outputs (Fox & Hendler, 2011)<sup>21</sup>. For example, as new strategy portfolios of strategic decisions are formulated and tested, the results can be made available via web-based interfaces, such as those presented in this paper. The prototypes developed will be extended as part of ITRC CDAM modelling that will develop an ITRC *system-of-systems* modelling framework.

The authors would like to acknowledge funding from the Engineering and Physical Sciences Research Council (EPSRC) grant EP/I01344X/1 to the Infrastructure Transitions Research Consortium (ITRC), and the respective authors' host institutions of Newcastle University, University of Oxford and Southampton University.

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# Assessing Risks to Inform Resilience: a Criticality Assessment of the British Railway Network

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<http://discovery.ucl.ac.uk/1469293/>

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## ABSTRACT

National infrastructures are constantly at risk from extreme weather events and random shocks that induce widespread failures across such systems. For example, the vulnerability of Britain's national-scale rail infrastructure has been highlighted during extreme floods, and it seems likely that the levels of risk faced by transport infrastructures more generally will increase in future years. Given the importance of rail infrastructure, there is a clear need for an improved understanding of the risks which it faces. Such a risk assessment would aim to identify the relative criticality of the network elements which different risk events are likely to affect, leading towards better risk management and resilience investment decisions. This paper provides a methodology to meet this need, by analysing the systemic risk to Britain's rail infrastructure from a range of disruptive events. It first considers the range of events and processes which have the potential to disrupt operation of the rail network. Alongside this, a procedure is developed for assessing the relative criticality of different nodes and edges on the network based on the passenger traffic they carry. Two case study risk types (floods and traction system failures) are used to demonstrate how criticality assessment can identify those parts of the rail network which are most at risk of causing substantial disruption to rail traffic, and therefore are most critical to maintaining national mobility. The paper concludes by considering the implications of this analysis for investment decisions and the potential for transferring this methodology to other spatial or economic contexts.

**Keywords:** Resilience, Risk Assessment, Railway

## BACKGROUND AND OVERVIEW:

Coastal flooding in early 2014 brought the issue of infrastructure risk into the media spotlight, when the only rail link to a large area of South-West England was severed for several months after tracks and their protecting sea wall were washed away by a winter storm. Attention was focused on the question of whether or not it was desirable for transport networks to be reliant on single 'critical' network edges (links), particularly when such edges are exposed to a high level of risk. The floods also led to a more general debate on the level of risk from and resilience to coastal flooding across the UK rail network, set against the background of continuing climate change which suggests that the frequency of coastal flooding events will increase over the 21<sup>st</sup> century. While coastal flooding has the potential to cause serious problems, it is not certain that it is necessarily the most serious risk factor facing Britain's railway infrastructure or that the edges affected (and therefore potentially targeted for investment to increase resilience) are in fact the most critical edges on the network.

The relative criticality of different network edges depends both on current patterns of rail services and rail travel and on future demographic changes to these patterns. There are also clear interdependencies with energy infrastructure,

without which mobility at current levels would be impossible. Research has shown that the most likely demographic future for the UK will involve sustained population growth, potentially to over double the current level<sup>1</sup>. While evidence suggests that growth in mobility per capita may be levelling off amongst some socio-economic groups<sup>2</sup>, it still seems likely that the growing population of Britain will expect to enjoy at least equivalent levels of mobility to those available to British residents today. This means transport infrastructure systems will need to accommodate much greater aggregate travel volumes than is currently the case.

There are though significant resource implications of this growth in travel, as it has the potential to conflict with the urgent requirement to reduce transport-related carbon emissions, which made up 27% of the UK total in 2011 (up from 18% in 1990)<sup>3</sup>. In order to meet emissions targets it will be necessary to substantially reduce transport's carbon emissions by shifting travellers to the most environmentally-friendly modes possible for particular journeys. Despite predicted fuel efficiency gains for road<sup>4</sup> and air<sup>5</sup> transport, rail is still expected to maintain an environmental advantage, meaning that mode shift to rail should be encouraged. However, while such mode shift to rail could help to meet the needs of a larger population using fewer resources, this will mean placing more stress and more economic 'responsibility' on the existing railway infrastructure. In a situation where the rail network is responsible for a greater proportion of national mobility, major asset failures such as those seen in Devon in early 2014 will have a correspondingly greater economic and social impact. Breakdowns of critical infrastructures disrupt essential services, which have serious consequences including severe economic damage, grave social disruptions or even large-scale loss of life<sup>6,7,8</sup>. There is thus a pressing need for an improved understanding of the risks which face the rail network and of the relative criticality and substitutability of the edges and nodes which these risk events would impact on. This paper provides a methodology to meet this need, by analysing the systemic risk to Britain's rail infrastructure from a range of disruptive events.

## RISKS FACING THE RAIL NETWORK

Risks to the rail system are defined as events or processes which have the potential to render certain edges or nodes on the rail network partially or fully inoperable. They may take place at a range of spatial and temporal scales, and both the magnitude and the duration of their impacts can vary widely. While hydrological risks such as coastal, river and groundwater flooding have enjoyed a high priority in recent months, they are just one part of a wide-ranging set of environmental risks which can also include heatwaves (causing track buckling), problems caused by ice or snowfall, and landslips and slope failures caused by either saturation or drought. Structural failure of elements of the rail infrastructure can result from the poor quality of construction or maintenance of particular assets, and this can relate both to large scale structures such as tunnels and viaducts and to smaller components such as rails (with the derailment at Hatfield in 2000 caused by a broken rail being a notorious example of the latter). Operating systems such as signals or points are also prone to occasional failures, and while the 'fail-safe' nature of such systems means that these failures are unlikely to cause accidents, they can still cause significant short-term disruption to operations, as can train failures. Human actions (both intentional and accidental) can also lead to disruption, for example as a result of bridge strikes and level crossing collisions (both examples of road user failures impacting on the rail system), suicides and terrorist attacks. While extensive research has been carried out to quantify the level of many of these risks, the wide range of risk events combined with the variation in risk likelihood over space means that assessment of the aggregated risk of disruption for a particular node or edge can be very complex.

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1 Tran, M. et al. National Infrastructure Assessment: Analysis of Options for Infrastructure Provision in Great Britain. Environmental Change Institute, University of Oxford (2014).

2 Le Vine, S., Jones, P. On the move: making sense of car and train travel trends in Britain, RAC Foundation (2012).

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8 ICE. The State of the Nation: Defending Critical Infrastructure. Institution of Civil Engineers, London, UK (2009).

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## ASSESSING RELATIVE IMPORTANCE OF EDGES AND NODES

Just as the likelihood of risk occurrence varies hugely over space, the impact of risk occurrence also varies substantially from place to place, particularly with regard to the total disruption caused to the operation of the rail network and therefore to national mobility. For example, with the British rail infrastructure a risk event which halts all rail operations on a branch line in the Scottish Highlands will have a much smaller disruptive impact than an event of similar magnitude which affects a major commuter route into London. It should be noted that the volume of traffic on a particular route is not the only determinant of aggregate disruption, as in a dense network where diversionary routes are available the loss of a particular link will have a much smaller impact than it would if that edge formed the only route between two large traffic generators/attractors.

In order to assess the total impact of risk events in particular locations, a methodology has been developed to estimate railway network flows to a high level of spatial disaggregation. Flows are estimated at nodes (stations or junctions) and edges (tracks) through which we can infer the relative importance of certain travel patterns over others, leading towards a network criticality assessment. In this study the relative importance of the railway network assets (nodes and edges) is evaluated in terms of the daily usage of the network by passengers travelling along different routes. We have built an origin-destination trip assignment model for Britain's railway network in order to develop estimates for network vulnerability due to any external shock impacts. Later in the vulnerability assessment being done here we are interested in quantifying the disruptive impacts on passenger travel due to removal of affected stations, junctions or track sections.

This railway trip assignment model uses two datasets, namely: (i) The Office of Rail Regulation's (ORR) station usage dataset, which provides details of the annual number of passengers entering, exiting and interchanging at all railway stations in Britain<sup>9</sup>, and (ii) timetable data from the Association of Train Operating Companies (ATOC), which gives full details of routing and calling points for all passenger trains operating on the British rail network<sup>10</sup>. From these datasets the trip assignment model calculates the *daily number of passenger trips* between stations (or junctions) along specific routes (tracks) using the following steps:

1. From the train timetable data we select a representative weekly schedule and calculate the *daily number of trains at each station* divided into number of trains originating, intermediate or terminating at the station.
2. Using the station usage data and the step 1 estimates, we calculate the *daily number of passengers using stations* by converting the annual estimates into weekly estimates and then assigning these estimates to particular days in proportion to daily train frequencies. We perform separate calculations for *passenger entries plus interchanges*, and *passenger exits plus interchanges*.
3. Each train schedule in the timetable data indicates the *trip information* for a particular train. For each trip in the timetable we estimate all the station pairs where passengers board and alight (origin-destination (O-D) pairs).
4. The daily station usage estimates (step 2) have to be disaggregated into flows along specific paths. We define a *trip attractiveness factor* for each entry station, which is the product of the number of trains along the path and the volume of passengers at the exit (plus interchange) stations along the path. A path with a higher trip attractiveness factor will attract more passengers from the entry stations. At each entry station we convert the station usage estimates into *trip entry estimates* by dividing in proportion to the trip attractiveness factor.
5. Once we have *trip entry estimates* we calculate the *trip exit estimates*, which give the number of exits at each O-D pair along a path. We assume that along a path the numbers of passengers getting off at stations are in direct proportion to the station's usage.
6. The methodology used in steps 4 and 5 guarantees that for a chosen path the sum of trip entry estimates at all stations is equal to the sum of trip exit estimates at all stations. Hence the flow is conserved for each trip assignment.
7. The final outcome of the calculations results in estimates of the number of the *passenger-trips between O-D station pairs* along specific routes on the rail network.

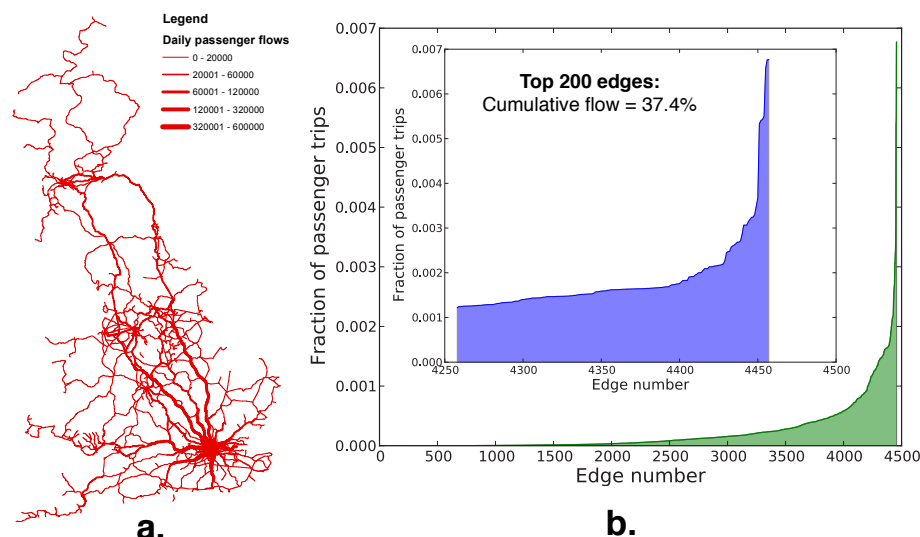
Figure 1(a) illustrates the results of the trip assignment analysis, showing the size of the daily passenger flows (for an average working weekday) across the British rail network. The railway network is comprised of 2539 stations, 1420

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9 ORR. Office of Rail Regulation: Estimates of Station Usage. UK. Available at: <http://www.rail-reg.gov.uk/server/show/nav.1529> (2013).

10 ATOC. Association of Train Operating Companies: Timetable data. UK. Available at: <http://data.atoc.org/> (2013).

junctions and 4457 tracks (edges). These results indicate the aggregated daily travel patterns for the railway network and can be used to assess the relative importance or criticality of individual stations, junction or track sections in the railway network. The relative criticality of different edges is shown in Figure 1(b), where the different edges are ranked based on the fraction of total passenger trips assigned to them. Figure 1(a) provides a spatial description of the network criticality and Figure 1(b) result shows that a relatively small number of edges (mainly located in and around London) have very large flows compared to the rest of the network.



**Figure 1: (a) Results of trip assignment analysis showing estimates of daily number of passenger trips across individual railway network edges on the GB rail network. (b) Distribution of the passenger flows (expressed as fractions of total flows) showing the relative importance of a small number of edges.**

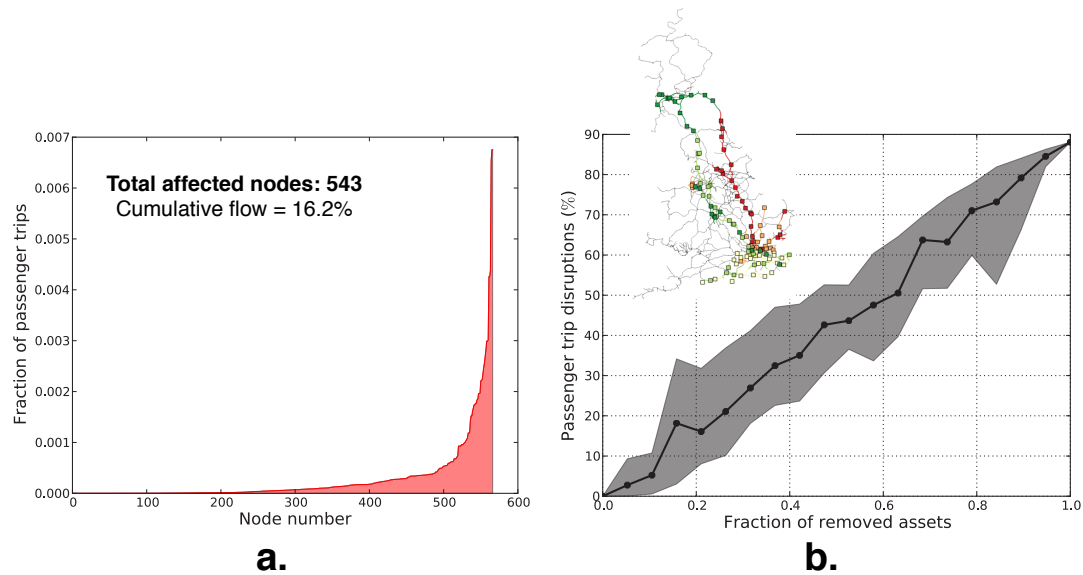
## ASSESSING RISK TO LINKS AND NODES

Using the Section 3 criticality assessment results for different nodes and edges in the railway network we can understand the possible failures that induce the greatest risks to the railway network. As discussed in Section 2 there are multiple failure scenarios that induce risks on the railway network. In the current analysis we explore two possible risk scenarios for the railway network: (i) flooding of stations and junctions, and (ii) failures of the energy supply system that provides traction electricity for specific routes.

For flood vulnerability assessment we have used the National Flood Risk Assessment (NaFRA) flood likelihood map for England and Wales<sup>11</sup> (Environment Agency, 2009), which provides information on the estimated likelihood of flooding to areas of land within the flood plain of an extreme flood (0.1 per cent or 1 in 1000 chance of fluvial and/or tidal flooding in any year). The analysis shows that 543 out of 3959 nodes in the rail network lie in areas where there is some likelihood of flooding during a 1 in 1000 year flood event. Figure 2(a) shows the distribution of the passenger trips (expressed as fractions of the total network trips) through the nodes and their associated edges. Compared with Figure 1(b), the result indicates that some of the very high flow network routes are at risk of flooding and hence most vulnerable. For risk planning and improved network resilience appropriate flood defences or other resources can be allocated towards these high flow routes.

Figure 2(b) shows the energy supply system that provides traction electricity for specific routes. It consists of 125 substations (shown as nodes in the inset Figure 2(b)). The result in Figure 2(b) shows multiple passenger trip disruption outcomes when certain fractions of the traction substations are considered failed (or removed), thereby cutting off the electricity supply to the rail network. Most of the traction systems are located along routes where the majority of the passenger flows occur, which results in almost 90% of trips lost if the entire electric traction system shuts down.

11 Environment Agency. Flooding in England: A National Assessment of Flood Risk. Bristol, UK (2009).



**Figure 2: (a) The distribution of the passenger trips at risk due to nodes (and corresponding edges) that are vulnerable to 1 in 1000 year flood event, and (b) Vulnerability of the overall rail network due to traction system (shown in the inset figure) failures.**

## IMPLICATIONS

This paper has demonstrated how the measure of infrastructure criticality developed here allows identification of those links and nodes which are most vulnerable to a range of risks, and which therefore have the greatest potential to adversely affect the railway network's ability to enable the effective functioning of the systems with which it shares interdependencies. When extended to cover all risk categories it could therefore be used as a tool to assess where investment in increased resilience should be focused, whether through measures to reduce the likelihood of risk events occurring, to mitigate the effects of such risks when they do occur, or to provide diversionary routes to increase the resilience of the rail network to disruption. It could also help to identify which categories of risk have the greatest overall impact on railway network vulnerability, and this may in turn have implications for policy in related areas. It should be noted that the risks (and therefore the criticality levels) identified here will not remain constant over time, but will change in relation to both internal factors, such as rail electrification and centralised control systems) and external factors such as climate change and changing socio-demographic and economic patterns. While the methodology as described here has been developed specifically for the rail network in Great Britain, it could be applied both in other spatial contexts and to other infrastructure systems. In future research the methodology will be applied to multiple infrastructure networks to capture interdependence between rail and other infrastructure systems.

## ACKNOWLEDGEMENTS

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# Infrastructure Interdependence





# Towards a Common Language of Infrastructure Interdependency

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<http://discovery.ucl.ac.uk/1469380/>

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## ABSTRACT

Infrastructure systems can exist interdependently with one another either by design, necessity or evolution. There is evidence that interdependencies can be the source of emergent benefits and hazards, and therefore there is value in their identification and management. Achieving this requires collaboration and communication between infrastructure stakeholders across all relevant sectors.

Recognising, developing and sharing multiple understandings of infrastructure interdependency and dependency will facilitate a wide range of multi-disciplinary and cross-sectorial work and support productive stakeholder dialogues. This paper therefore aims to initiate discussion around the nature of infrastructure interdependency and dependency in order to establish the basis of a useful, coherent and complete conceptual taxonomy. It sets out an approach for locating this taxonomy and language within a framework of commonplace stakeholder viewpoints.

The paper looks at the potential structural arrangements of infrastructure interdependencies before exploring the qualitative ways in which the relationships can be characterised. This builds on the existing body of knowledge as well as experience through case studies in developing an Interdependency Planning and Management Framework for Infrastructure.

**Keywords:** Interdependency, Resilience, System Architecture

## SUBTITLE REQUIRED

Infrastructure systems can exist interdependently with one another either by design, by necessity or through evolution. There is widespread evidence that interdependence can be the source of emergent benefits and hazards, and therefore there is value in its identification and management<sup>1</sup>. Achieving this requires collaboration and communication between infrastructure stakeholders across all relevant sectors. Collaboration can develop Situational Awareness, that is to say a holistic knowledge of the infrastructure landscape and therefore potential interdependencies.

As a result of the perceived vulnerabilities and opportunities which emerge from infrastructure interdependency, there is an increased interest in modelling and understanding them<sup>2</sup>.

There are many methods for modelling the interdependency between infrastructure elements, each serving a

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

2 HM Treasury & Infrastructure UK. National Infrastructure Plan 2011. (2011).

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specific purpose and providing a different conception of what interdependency means in relation to infrastructure. Some differing conceptions of infrastructure interdependency can be attributed to the multiple viewpoints of the stakeholders responsible for commissioning, financing, planning, designing, building, operating and using infrastructure. For example, there was a significant increase in research into infrastructure interdependencies following the Oklahoma City bombing in 1995<sup>3</sup>, primarily as a result of Presidential Decision Directive 63<sup>4</sup> which stressed the importance of *infrastructure interdependency* in terms of national vulnerability. This influenced a focus on the vulnerability emergent from interdependency. The resultant modelling tools focussed on understanding those risks, often as discrete from understanding the benefits of interdependency.

Without a reflection on the meaning of infrastructure interdependency, and without the means to describe it completely and consistently, there is a danger that one particular understanding of infrastructure interdependency, for example in terms of producing vulnerability; one particular modelling approach, for example network theory; or one particular type of interdependency, for example the physical transfer of resources; become dominant at the expense of others.

The complete, holistic view of a system can rarely be effectively captured by one single model or modelling approach. Instead it is necessary to have a meta-model or a framework which brings together all models which represent different aspects and views of the system into one coherent and internally consistent architecture, as advocated by Zachmann<sup>5</sup> and Kruchten<sup>6</sup> and used in architectural frameworks in many domains (e.g. DoDAF<sup>7</sup> or TRAK<sup>8</sup>). In formulating a '4+1' view architecture, Kruchten shows how to represent concurrently and coherently four viewpoints on a complex software development programme, comprising 1) logical, 2) process, 3) development and 4) physical views, each represented and best-served by a different modelling approach. These are complemented by a fifth end-user view. These system architectures, in which multiple perspectives are developed for the same underlying system, have the advantage of providing an efficient and effective means of communicating with multiple stakeholders.

In a similar way, the language of infrastructure interdependency and any associated taxonomy needs to recognise the likelihood that different stakeholders will have differing perspectives on a network of infrastructure and on the associated interdependencies. The language and taxonomy therefore needs to provide a means of relating the shared understanding of infrastructure interdependencies to the interests of the different stakeholders. For example, an engineering perspective may tend to focus on physical interactions and information flows between infrastructure systems and use these to identify issues of network resilience. While, no doubt concerned by issues of resilience, an investor in infrastructure is also likely to take an interest in any opportunities to generate additional value through the exploitation of infrastructure interdependency.

Recognising, developing and sharing multiple understandings of *infrastructure interdependency and dependency* will facilitate a wide range of future multi-disciplinary and cross-sectorial work and support productive cross-sector stakeholder dialogues. This paper aims to initiate a discussion around the nature of infrastructure interdependency and dependency in order to establish the basis of a useful, coherent and complete conceptual taxonomy. It also sets out an approach for locating this taxonomy and language within a framework of commonplace stakeholder viewpoints.

There are many ways in which the interdependency within and between infrastructure networks can be modelled. For example, previous reviews<sup>9,10,11</sup> have identified qualitative and semi-qualitative models including: Network and Graph Theory; topological models; Petri-nets; Input-Output models; Agent Based models; spatial and time-series analysis; matrix representations and hierarchical risk models.

Building these models can lead to a discussion of interdependency types with which to characterise the edges connecting the nodes in the system and therefore they help in establishing the beginnings of an interdependency taxonomy. If the different types of interdependency are not explicitly considered in the early stages of a project,

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3 Heller, M. in Front. Eng. Reports Leading-Edge Eng. from 2001 NAE Symp. Front. Eng. 138 (National Academies Press, 2002)

4 The Clinton Administration. Presidential Directive 63 (PDD-63): Policy on Critical Infrastructure Protection. (1998).

5 Zachman, J. A. A framework for information systems architecture. IBM Syst. J. 26, 276–292 (1987).

6 Kruchten, P. Architectural Blueprints - The "4+1" View Model of Software Architecture. IEEE Softw. 12, 42–50 (1995).

7 Department of Defense. Department of Defense Architecture Framework Version 2.0 (2009)

8 TRAK Steering Group and UK Department for Transport. TRAK Enterprise Architecture Framework (2013)

9 Pederson, P., Dudenhofer, D., Hartley, S. & Permann, M. Critical Infrastructure Interdependency Modeling: A Survey of U.S. and International Research. (2006).

10 Bloomfield, R., Salako, K., Wright, D., Chozos, N. & Nobles, P. Infrastructure interdependency analysis: an introductory research review. (2009).

11 Ouyang, M. Review on modeling and simulation of interdependent critical infrastructure systems. Reliab. Eng. Syst. Saf. 121, 43–60 (2014).

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and each modelling approach specialises in a particular type of interdependency, then the choice of model can unintentionally narrow the view of what constitutes interdependency. Ultimately this can increase the risk of temptation, “if the only tool you have is a hammer, to treat everything as if it were a nail”<sup>12</sup>.

It is proposed therefore that there is a renewed need to reflect on the characteristics of interdependency; the modelling approaches which best provide insight into each, and the way in which these modelling approaches can be brought together into a coherent architecture framework which allows us to represent the totality of interdependency. The paper begins by examining the three most commonly discussed characteristics; *directionality*, *order* and *typology*, before proposing a wider set of characteristics with which infrastructure interdependency can be described.

## DIRECTIONALITY

Infrastructure interdependency has been described as a distinctly **bidirectional** relationship<sup>13</sup> and elsewhere in such a way that includes bidirectional and **non-reciprocal dependency** in the form of an influence from one element on another<sup>9,14</sup>. Eusgeld et al.<sup>15,16</sup> differentiate between these as ‘input’ and ‘mutual’ interdependency types. It has been argued that these bidirectional relationships exist at the macro level, whereas dependencies are more common at the component level<sup>17</sup>.

## ORDER

Discussions of the fundamental definition of infrastructure interdependency and its modelling have also led to the distinction between **first**, **second** and **third** order dependencies<sup>13,17</sup> having been previously proposed as an important part of a characterisation framework<sup>18</sup>. A **first order dependency** is where system A is directly dependent on system B, and **second order dependency** is where system A is indirectly dependent on system B via A's first order dependency on a third infrastructure which is itself directly dependent on B. These indirect effects can lead to feedback loops where the second order dependency means A affects B which then affects A<sup>19</sup>. This implies that second order dependencies are interdependencies. **Third order dependencies** introduce a further intermediary system.

## TYPE

There have been several attempts to characterise interdependency into several descriptive types alternatively referred to as the nature of the interdependency. One of the earliest and most frequently cited taxonomies was proposed by Rinaldi et al.<sup>13</sup>:

- **Physical** (a physical output from one system is a necessary input to another)
- **Cyber** (information produced by a system affects the operation of another)
- **Geographic** (two or more systems are considered to be co-located in physical space)
- **Logical** (a mechanism that could be organisational or social).

These reflect four earlier interdependency typologies for product design matrices proposed by Pimmler and

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12 Maslow, A. H. The Psychology of Science. (1966).

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

14 HM Treasury & Infrastructure UK. National Infrastructure Plan 2011. (2011).

15 Eusgeld, I., Nan, C. & Dietz, S. “System-of-systems” approach for interdependent critical infrastructures. Reliab. Eng. Syst. Saf. 96, 679–686 (2011).

16 Briš, R., Eusgeld, I., Nan, C. & Dietz, S. “System-of-systems” approach for interdependent critical infrastructures. Reliab. Eng. Syst. Saf. 96, 679–686 (2011).

17 Johansson, J. & Hassel, H. An approach for modelling interdependent infrastructures in the context of vulnerability analysis. Reliab. Eng. Syst. Saf. 95, 1335–1344 (20).

18 McDaniels, T., Chang, S., Peterson, K., Mikow, J. & Reed, D. Empirical Framework for Characterizing Infrastructure Failure Interdependencies. J. Infrastruct. Syst. 13, 175–184 (2007).

19 Little, R. G. Controlling Cascading Failure: Understanding the Vulnerabilities of Interconnected Infrastructures. J. Urban Technol. 9, 9–123 (2002).

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Eppinger<sup>20</sup>: **Materials, Energy, Information** and **Spatial**. Zimmerman<sup>21,22</sup>, again looking specifically at infrastructure interdependency only differentiates between two types **Functional** and **Spatial**, while others<sup>17</sup> use **Functional** and **Geographic** (where functional covers physical, cyber and logical). Pederson et al.<sup>9</sup> use an expanded version of an earlier taxonomy<sup>23</sup> which splits Logical interdependencies into two further groups: **Policy/Procedural** and **Societal**.

The distinction of **physical, cyber** and **logical** interdependencies is also used by Satumtira and Duenas-Osorio in their review of the area of infrastructure interdependency<sup>24</sup>. The UK's 2011 National Infrastructure Plan<sup>2</sup> outlines three forms of interdependencies (p90):

- **Geographic co-location**
- **Shared use (of equipment or resource)**
- **Reliance on another network's function.**

While this aligns with the split into geographic and functional, shared use expands on the previous conception of physical interdependencies. A Frontier Economics Report<sup>1</sup> implements a definition of interdependency proposed by O'Rourke<sup>25</sup>, which suggests that it results from **physical proximity** or **operational interaction**, reflecting the two-factor split into spatial and functional interdependency. They use this to develop an economic framework within which to consider interdependency, which proposes three forms: **physical, digital**, and **organisational** (e.g. shared ownership or oversight).

The process of defining the nature of interdependency has proved to be a challenging one<sup>24</sup>. A recent analysis<sup>11</sup> of the taxonomies of Rinaldi et al.<sup>13</sup>, Zimmerman<sup>21</sup>, Dudenhoeffer et al.<sup>23</sup>, Wallace et al.<sup>26</sup> and Zhang and Peeta<sup>27</sup> concluded that "some interdependency examples in practice cannot be definitely categorized by some classifications", and only the classification proposed by Rinaldi et al<sup>13</sup> covered all ten real-world interdependency examples analysed.

While at one level of operation these dimensions may be sufficient to characterise the interdependency between two infrastructure systems, there are others that could be important, particularly in relation to specific modelling approaches. For example, the degree of coupling (from tight to loose) between systems may affect the way in which effects propagate<sup>19</sup> invoking Perrow's<sup>28</sup> classification of systems. Sector specific metrics can also be used such as the relative duration of a power outage in relation to the disruption it causes to the function of other systems<sup>22</sup>.

In planning and managing infrastructure interdependencies, both for resilience and efficiency, it is also necessary to consider the ways in which the interdependencies have impact and can be impacted. The case studies reported previously<sup>29</sup> resulted in the introduction of a number of additional characteristics for describing infrastructure interdependency discussed below.

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20 Pimmler, T. & Eppinger, S. Integration analysis of product decompositions. in ASME 6th Int. Conf. Des. Theory Methodol. (1994).

21 Zimmerman, R. Social Implications of Infrastructure Network Interactions. J. Urban Technol. 8, 97–119 (2001).

22 Zimmerman, R. & Restrepo, C. E. The next step: quantifying infrastructure interdependencies to improve security. Int. J. Crit. Infrastructures 2, (2006).

23 Dudenhoeffer, D., Pernann, M. & Manic, M. CIMS: A Framework for Infrastructure Interdependency Modeling and Analysis. in Proc. 2006 Winter Simul. Conf. 478–485 (IEEE, 2006).

24 Satumtira, G. & Duenas-Osorio, L. in Sustain. Resilient Crit. Infrastruct. Syst. Simulation, Model. Intell. Eng. (Gopalakrishnan, K. & Peeta, S.) 300 (Springer, 20).

25 O'Rourke, T. D. Critical Infrastructure, Interdependencies, and Resilience. Bridg. 37, (2007).

26 Wallace WA, Mendonça D, Lee EE, Mitchell JE, Chow JH. Managing Disruptions to Critical Interdependent Infrastructure in the Context of the 2001 World Trade Centre Attack. In: Monday JL, editor. Beyond Sept. 11th An Acc. Post-Disaster Res., (2003)

27 Zhang, P. & Peeta, S. A generalized modeling framework to analyze interdependencies among infrastructure systems. Transp. Res. Part B Methodol. 45, 553–579 (2011).

28 Perrow, C. Normal Accidents. (Basic Books, 1984).

29 Rosenberg, G. & Carhart, N. J. A Systems-based Approach to Creating Value from Infrastructure Interdependencies. in Int. Symp. Next Gener. Infrastruct. (2013).

## FUNCTIONALITY

It has previously mentioned that infrastructure interdependencies can be thought of as either functional or spatial<sup>14,21,30</sup>, but it is proposed that this is an import distinction separate from the typology. In terms of vulnerability analysis, functional dependency between two elements can be of utmost importance, but in terms of opportunities and efficiencies, the creation of non-functional interdependencies can be significant. For example, the ElecLink Channel Tunnel Interconnector is said to create a geographic interdependency saving in the region of £60m compared to laying a seabed cable<sup>1</sup>. The Channel Tunnel Rail link does not depend on the electricity interconnector for it to function, and the interconnector does not depend on the functioning of the rail link.

## NECESSITY

Strongly related to identifying whether an interdependency is based on a functional requirement is the distinction between an interdependency which already exists and is **necessary** or a situation where a relationship exists which is not essential to a system's operation, but in which there is the **potential** for the interaction to be exploited to provide additional benefits such as enhancing efficiency or resilience. There is some overlap between a necessary interdependency and a functional one, but the need to include this as a specific category arose from work looking to identify beneficial interdependency opportunities in three UK case studies<sup>29</sup>.

## OUTCOME

The identified interdependencies also need to be classified as to whether they primarily offer additional opportunity to **benefit** or whether they result in an increase in negative risks or **dis-benefit**. If it is beneficial then there may be a reason to utilise an existing interdependency and leverage it for additional value or alternatively create it if there is the potential to do so. If it is hazardous, there may be a reason to mitigate or prevent the interdependency.

## LIFE-CYCLE IMPACT STAGE

This refers to the chronological phase of the infrastructure's life cycle during which the impact of the interdependency is of most importance. Some interdependencies only have an impact during the **Planning** or **Construction** phase, others are important during **Operation** or at the infrastructure element's '**End of Life**'. Additionally, some interdependencies are *only* relevant under particular **Scenarios** (such as during accidental failure or during extreme weather events). These categories also arose during the research of three UK case studies<sup>29</sup>.

## GEOGRAPHIC SCALE

Identifying whether the interdependency exists on a **local**, **regional**, **national** or **international** scale may be important, as may characterising where the impact of the interdependency lies<sup>18 31</sup>.

Table 1 compiles a checklist of interdependency categories which has been drawn from the wide range of literature describing and modelling interdependency referenced and discussed above. While all of these criteria are intended to simplify the categorisation process, there remain practical complexities. For example, assessing whether a network of infrastructure systems, taken as a whole, possess the sufficient and necessary capabilities to realise the cumulative benefits of a desirable interdependency.

A rich and shared through-life understanding of the diverse aspects of infrastructure interdependency, and an appreciation for which modelling tools best represent each of those aspects, are the first steps to creating a framework to integrate toolsets and provide a more comprehensive picture of the interdependencies in the infrastructure 'system of systems'. This has implications for the design of infrastructure assets and their integration in the wider network of a nation's infrastructure, by helping to minimise unforeseen vulnerabilities and maximise opportunity management for valuable emergent economic and social benefits that might otherwise be missed.

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30 Zimmerman, R. & Restrepo, C. E. The next step: quantifying infrastructure interdependencies to improve security. *Int. J. Crit. Infrastructures* 2, (2006).

31 Peerenboom, J. P. Infrastructure Interdependencies: Overview of Concepts and Terminology. in *Natl. Sci. Foundation. Sci. Technol. Policy Workshop on Crit. Infrastructure. Needs in Interdisciplinary Research and. Graduate. Training.* (2001).

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A review by Satumtira and Duenas-Osorio<sup>24</sup> of 162 published papers on infrastructure interdependency modelling identified over 40 different approaches, with three in particular being much more widely used than the others. Around 22% of the papers employed Network and Graph Theory based approaches, and around the same for Input-Output based approaches. A further % used Agent Based Modelling, while the remaining 46% used one or a mixture of the many other techniques. A more recent study<sup>11</sup> highlighted how each of these techniques addresses each interdependency type, for example, they concluded that Input-Output modelling, does not effectively capture geographic or logical interdependencies.

**Table 1: Infrastructure interdependency characterisation checklist**

		Identified Interdependency
TYPE	Physical	
	Digital	
	Geographic	
	Organisational	
ORDER	First Order	
	Second Order	
	Higher Order	
FUNCTION	Functional	
	Non-Functional	
NECESSITY	Necessary	
	Optional	
OUTCOME	Benefit	
	Dis-benefit	
LIFE-CYCLE IMPACT STAGE	Planning	
	Construction	
	Operation	
	Scenario	
GEOGRAPHIC SCALE	Project	
	Local	
	National	
	International	

Work for Engineering the Future<sup>32,33</sup> which investigated the interdependencies between future UK infrastructure projects and policies<sup>34</sup> found that while 47% of the identified interdependencies could be classified as physical, 26% were logical and 13% geographic. This is not a criticism of the ability of any particular technique, but it is an argument for the need for a suite of modelling approaches, and a framework which brings them together, to truly understand all dimensions of interdependency.

In conclusion, we believe that bringing together the terminology used for the description of infrastructure interdependency, as described in this paper, is an important stage in the establishment of a common language for characterising and discussing infrastructure interdependency across infrastructure sectors and amongst different academic disciplines. It is hoped that this will initiate further discussion on the nature of infrastructure interdependency and ultimately aid in facilitating cross-sector discussions. Most importantly perhaps, it highlights the need for a framework which brings together all of the individually powerful modelling approaches in a consistent and mutually beneficial way, such that the totality of interdependency within the infrastructure system-of-systems can be made visible for the reduction of vulnerability and the exploitation of additional benefits. Without a common language with which to describe all aspects of interdependency there is a danger that an important piece of the puzzle will be overlooked.

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

33 Engineering the Future. Infrastructure Interdependencies Timelines. (2013).

34 Engineering the Future. UK Infrastructure Timelines. (2011).

# Adaptation and Resilience of Interdependent Infrastructure Systems: a Complex Systems Perspective

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<http://discovery.ucl.ac.uk/1469381/>

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## ABSTRACT

The effects of disruption upon one or more components in interdependent infrastructure systems and the ability of the system to return to normal operations, is investigated in this paper. This addresses the concept of resilience, and examines the trade-off between redundancy and efficiency, as well as the adaptive ability of a system to respond to disruptions and continue to operate, albeit not necessarily as it did initially.

**Keywords:** Complex Systems, Inter-disciplinary, Adaptive, Resilient, Interdependent

## INFRASTRUCTURE SYSTEMS

Infrastructure systems have been built traditionally for the long-run as exemplified by the Victorian's visionary infrastructures. Regardless of the funder and their motives (such as social and economic well-being) there is an embedded often explicit assumption of the investments worthwhile nature based on some cost-benefit that will arise contingent upon the use made of the infrastructure. This most often implies that the system will need to be uninterrupted and undisturbed otherwise benefits delivery would be compromised. It is not surprising therefore, that infrastructure systems have been kept separate and isolated as far as possible using controls to ensure benefits delivery. These controls are evidenced by legislation, regulation, functional departments and organizations (e.g. electricity, water), disciplinary (academic) specialization and industrial (and professional) groups. These controls act as negative feedback to ensure a status quo in the infrastructure system creating inertia and leads to sweating of assets and avoidance of adaptation.

Lives in the 21<sup>st</sup> century are however very far from static and unchanging. Indeed they highlight the very nature of interdependencies in infrastructure systems often driven by the innovation of new technologies and integration of services. The services extracted from infrastructure, are at least for the domestic market, converge at the consumer level. Examples, facilitated by new technologies, include information on the move (ICT and transport convergence), increasing use of electric and hybrid vehicles (energy and transport) and on demand hot water (energy and water). Integrating devices, such as sat navs, electric car batteries, and combi-boilers, join up multiple infrastructure systems.



However at the infrastructure system and sub-system levels, there is even greater interdependency<sup>1, 2, 3, 4</sup> such as electricity production dependent on water and ICT, with transport dependent on energy and ICT, and with water treatment dependent on transport and waste.

These interdependencies create connected networks not only during the operation of the systems, but also in their build and de-commissioning phases.

## PATTERNS OF INTERDEPENDENCY

Two key issues are evident as a result of these interdependencies. First, is that as interdependencies become more closely coupled through the dynamics of use, inertia sets in, there will be an increased probability of greater impact of a disruption, especially in cases of single point of failure. For example, use of rail transport for long-distance commuting can be disrupted by power outages. However business continuity is an organizational matter and is not usually addressed at small scale, e.g. domestic environments, nor between meso and large scale infrastructure systems. Second, is that interdependency may operate without the knowledge of one or other infrastructure provider until a disruption occurs. Novel uses of infrastructure emerge to meet demands, such as the use of railway defences against flood, and digital communications to circumvent traffic issues.

Big data technologies which capture infrastructure use and condition data in real time and detect patterns of use across infrastructure systems, can 1. highlight points of conversion in infrastructure systems which are vulnerabilities, and 2. help transform knowledge about adaptation. They can inform scientific discovery of resilient dynamical structures, and provide evidence for management of risk and steering future change. This information would be cross-cutting, e.g. such as demand forecasting, and has the potential to reduce the effect of disruptions to infrastructure, and to those in the organizations and supply chains providing these services. Diagnostic information can also be tracked, because in complex systems the areas of impact are often far removed from the sources of the problem, for example a blocked water main may create floods in unexpected places.

This approach is especially important because the issues are exacerbated by contextual factors, such as increasing, aging and affluent population and in particular urbanization, globalization and interconnected economies, changes in weather patterns (such as stronger winds, heavier and prolonged rain-fall, larger tides and extremes of temperature), and also the risk and reality of terrorism and security attack. These contextual factors exacerbate the pressure on interdependent infrastructures as more people are affected and conditions make it difficult to achieve a return to normal operation services.

## SUSTAINABLE DEVELOPMENT, ADAPTATION AND NORMATIVE FUTURES

A further significant context is the need for sustainable development and preservation of resources and the environment. Following the United Nations 2005 World Summit<sup>5</sup>, sustainable development was defined as the interdependent and mutually reinforcing pillars of economic development, social development and environmental protection.

Coupled with sustainable development is a fundamental desire to create adaptable infrastructure systems which are adaptable in response to changing demand and contextual circumstances. Adaptive development is the institutional capacity to cope with change<sup>6</sup>. It is about survival and changing parts of systems so that they function better with

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1 Heller, M., (2001). Interdependencies in Civil Infrastructure Systems. *The Bridge*, Vol. 31, No. 4, pp. 9-15.

2 Rinaldi, S. M., Peerenboom, J. P. and Kelly, T. K. (2001). Identifying, Understanding, and Analyzing Critical Infrastructure Interdependencies. *IEEE Control Systems Magazine*, Vol. 21, No. 6, pp. 11-25.

3 Dunn, M., (2005). The socio-political dimensions of critical information infrastructure protection (CIIP). *International Journal of Critical Infrastructures*, Vol. 1, No. 2/3, pp. 258-268.

4 O'Rourke, T. D., (2007). Critical Infrastructure, Interdependencies, and Resilience. *The Bridge*, Vol. 37, No. 1, pp. 22-29.

5 United Nations (2005), *United Nations World Summit Outcome*, Sixtieth session – Items 48 and 121 of the provisional agenda (A/60/150), available online at [www.un.org/News/Press/docs/2005/05/20050516.unsummit.asp](http://www.un.org/News/Press/docs/2005/05/20050516.unsummit.asp)

6 Marten, G. (2001) *Human Ecology: Basic Concepts for Sustainable Development*, Earthscan, London, UK

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interacting systems, and create capacity to deal with disruptions. Adaptive development requires regular assessment and corrective action<sup>6</sup>. Ashby<sup>7</sup> suggests that adaptability is enhanced among the system's components if there is a modest degree of interaction among the system's components. In what Ashby terms, a fully joined system, a perturbation in one variable requires adjustment in all other variables of the system, making adaptation improbable<sup>8</sup>. Perrow<sup>9</sup> makes a similar argument when analysing the possibility of "normal" accidents in complex, tightly coupled systems. Tightly coupled firms can not engage in exploration without foregoing the benefits of exploitation. In addition, we are entering an era of climate change and uncertainty – it is no longer tenable to manage for the mean we need to "manage for the variance", as unpredictability in weather patterns become the norm – potentially hugely significant for future urban planning and design<sup>10</sup>.

It follows that a transformative teleological position<sup>11</sup> is needed to steer interdependent systems towards normative futures which can be shaped and re-shaped along with the infrastructure systems which enable them. We cannot know the extent to which the future is recognizable today, nor how we will perceive our dependency on infrastructure systems. And everyone's perceptions of sustainability, adaptability and resilient systems is unique, since perceptions are value-laden, change over time, and in response to needs; a pluralistic epistemology must prevail which embraces difference and inter-disciplinarity and importantly acknowledges the limitations of absolute analysis<sup>12</sup>.

## RESILIENCE ASSESSMENT

Resilience is defined as "the capacity for an enterprise to survive, adapt and grow in the face of turbulent change"<sup>13</sup>. This is a concept that has been prevalent in understanding the way in which natural systems respond to perturbation and change, since the 1970's with a focus on "functions"<sup>14</sup> or a narrower emphasis on return to "pre-disturbance" state<sup>15</sup>. This is still subject of much debate, with recent work demonstrating that there is both "helpful" and "unhelpful" resilience – the latter keeping a system in an undesirable state once a threshold or tipping point has been crossed<sup>16</sup>.

Systems are resilient if they are able to continue functioning despite occasional and severe disturbances. Methods to achieve resilience include 1. Redundancy: duplication and diversification which replace parts that go wrong, and (in natural systems) species which have overlapping roles and niches, e.g. multiple forms of power generation serving overlapping parts of a city, and 2. Low dependence on human inputs which is desirable since it reduces interference with resilience. Resilience is desirable but requires extra cost and effort and conflicts with global economic pressures to increase efficiency and related low operating costs essential for survival in modern firms<sup>6</sup>. Resilience is not to be confused with reliability which is defined as the probability of a network remaining functional during a disruption<sup>17</sup>.

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7 Ashby, W. R. (1960), *Design for a Brain*, John Wiley & Sons, New York.

8 Glassman, R. B. (1973), Persistence and Loose Coupling in Living Systems, *Behavioural Science*, vol. 18, pp. 83-98.

9 Perrow, C. (1984), *Normal Accidents: Living with High-Risk Technologies*, Basic Books, New York.

10 Braun, B. P. (2014), A new urban dispositif? Governing life in an age of climate change, *Environment and Planning D: Society and Space*, vol. 32, pp. 49 – 64.

11 Stacey, R.D., Griffin, D., and Shaw, P. (2000), *Complexity and Management – Fad or Radical challenge to systems thinking?* Routledge, London.

12 Johansen, I. L. and Rausand, M. (2014), *Defining complexity for risk assessment of sociotechnical systems: A conceptual framework*, Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability, pp 228: 272. DOI: 10.1177/1748006X13517378

13 Fiksel, J. (2006), Sustainability and Resilience: Toward a Systems Approach, *Sustainability: Science Practice and Policy*, vol. 2, no. 2, pp. 14-21. See page 16 for citation.

14 Holling, C.S. (1973), Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics* vol. 4, pp. 1-23.

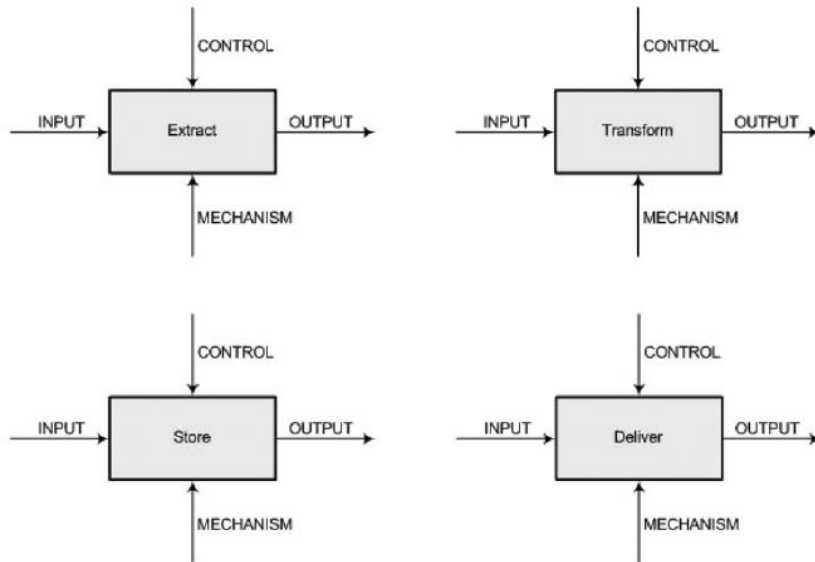
15 Pimm, S.L. (1984), The complexity and stability of ecosystems, *Nature*, vol. 307, pp. 321-326.

16 Standish, R.J., Hobbs, R.J., Mayfield, M.M., Bestelmeyer, B.T., Suding, K.N., Loretta L. Battaglia, L.L., Eviner, V., Hawkes, C.V., Temperton, V.M., Cramer, V.A., Harris, J.A., Funk, J.L., Thomas, P.A.. (2014) Resilience in ecology: Abstraction, distraction, or where the action is? *Biological Conservation*, vol. 177, pp. 43 – 51.

17 Adenso-Diaz, B., Mena, C., García-Carbajal, S. and Liechty, M. (2012), The Impact of Supply Network Characteristics on Reliability, *Supply Chain Management*, vol. 17, no. 3, pp. 263-276.

## AN AGENT BASED MODEL ASSESSING RESILIENCE OF INTERDEPENDENT INFRASTRUCTURES

An agent based model is defined using a conversion point ontology<sup>18</sup>. This ontology defines each component of an infrastructure system in terms of the inputs to the component (such as the various resources: grey water, coal, etc.), the controls (such as regulations, cultural norms), the mechanisms (such as the technology used, its capacity, normal operating minima and maxima, its related efficiency, and the skills required for the conversion), and the outputs (including waste, emissions, by-products, and primarily useful outputs, such as heat, power, mobility).



**Figure 1: Key activities/services underpinning conversion points<sup>14</sup>**

The ontology allows us to capture interdependencies, whereby the output from one conversion is available to another conversion through a distribution channel which itself is another conversion point (and consumes time, and other resources, and generates losses through the inefficiency of the process). The ontology will work either as a push (supply) system or as a pull (demand) system.

Use big data technologies we collect production and consumption data of all infrastructures within a defined boundary, and using records of real-time feeds we simulate disturbances to the infrastructure systems. This asset data is collected from infrastructure operators, such as Highways Agency, Network Rail, WPD, Anglian Water and EON.

Resilience is indicated by the system's ability to provide essential or desired services (or "functions") through alternative means in the modeled infrastructure system. That is, the adaptive capability of the system is tested. Model outputs are tested using measures of resilience including: temporal and spatial indicators of slowing down, trend analysis and shiftograms<sup>19</sup>, ball and cup model (recovery time, autocorrelation, variance and skewness<sup>20</sup>) and Critical Slowing Down and transcritical bifurcation<sup>21</sup>. Network theory is used to identify closed loops, e.g. where component A depends on B, and B depends on C, and C depends on A, and to analyse the different network topologies, node centralities, holes, etc. in order to create understanding of the resilience in respect to the networks' topologies.

Tests of full or partial disruptions to one or more points in the infrastructure system are carried out, simulating various types of inter-dependencies are made including geographical and cyber<sup>2</sup>. The use of genetic algorithms to identify the optimal configurations are determined by iterative running of systems difference scenarios of use, e.g. increasing trends in particular directions over time.

18 Varga, L, Grubic, T, Greening, P, Varga, S, Camci, F, Dolan, T (2014) Characterizing conversion points and complex infrastructure systems: Creating a system representation for agent-based modeling, *Complexity*, Vol. 19, pp. 30-43. DOI: 10.1002/cplx.21521

19 Lindegren, M, Dakos, V., Gröger, J., Gårdmark, A., Kornilovs, G., Otto, S., Möllmann, C. (2012). *Early Detection of Ecosystem Regime Shifts: A Multiple Method Evaluation for Management Application*, PLOS One, Vol. 7 No. 7.

20 Dakos, V., Kéfi, S., Rietkerk, M., van Nes, E., Scheffer, M. (2011). *Slowing Down in Spatially Patterned Ecosystems at the Brink of Collapse*. *The American Naturalist*, Vol. 177, No. 6, pp. E153-E166. <http://www.jstor.org/stable/10.1086/659945>

21 Chisholma R., Filotas, E., (2009) Critical slowing down as an indicator of transitions in two-species models, *Journal of Theoretical Biolog*, Vol. 257, pp. 142-149

## EXPECTED RESULTS AND DISCUSSION

Based on earlier and smaller scale results together with the proposed enhancements developed above, we expect to find the following results:

As the system of systems becomes less diverse and inter-dependencies increase, we expect to see more frequent occurrence and more prolonged time before recovery after disruption, in essence a “critical slowing down” found in natural systems as they approach threshold/transition points<sup>22</sup>, suggesting worsening resilience; vice versa, with greater diversity and less inter-dependence, we expect to find greater resilience but less overall usage of available capacity; that is efficiency might be greater with newer technology, but it may take longer to achieve pay-back on investment.

We expect to find those points (including distribution channels) in the system which have greatest dynamical centrality, that is, frequency of flows (since we are treating all infrastructure systems as having continuous (not batch) flows. These points come under pressure regardless of which points in the system are disrupted and require alternative points or sub-systems to generate adaptive capacity.

The topology type of each system’s network is expected to make a difference to resilience with scale-free networks being most resilient. However it is difficult to predict what will emerge as a result of the interdependence of mixed topologies across the three key infrastructure systems (e.g. hierarchical for energy, random for water, and scale free for transport).

Finally we expect that trends such as population increase or urbanization will drive unanticipated and paradoxical outcomes: e.g. slowing down the flow of resources by reducing capacity will increase system throughput. However as flow is severely curtailed we expect alternative technologies to develop in other infrastructure systems to take up demand, e.g. road congestion driving increased telecommunications traffic, local energy provision (meso CHP), and the increased deployment of “hybrid biological/engineered” systems comprising hard and biological components as part of the “Green Infrastructure” of cities<sup>23</sup>. We also anticipate that intelligent autonomous technologies (demanding no or little skills of the user) to increase which will self-organize the system to reduce congestion, improve resilience and avoid waste, including user time.

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22 Dakos, V., Carpenter, S.R., Brock, W.A., Ellison, A.M., Guttal, V., et al (2012) Methods for Detecting Early Warnings of Critical Transitions in Time Series Illustrated Using Simulated Ecological Data, *PLoS ONE*, Vol. 7 No. 7., doi:10.1371/journal.pone.0041010

23 CABI Space (2010) Urban green nation: building the evidence base, *UK Commission for Architecture and the Built Environment*, London.



# Integrated Infrastructure Modelling — Managing Interdependencies with a Generic Approach

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<http://discovery.ucl.ac.uk/1469382/>

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## ABSTRACT

Infrastructure provision is a highly challenging task, especially when accounting for climate change mitigation and adaptation needs. Efforts of making infrastructure more efficient and flexible result in an increasing number of sensitive infrastructure interdependencies. This enforces an integrated infrastructure assessment for planning purposes, in contrast to the traditional independent infrastructure-sector modelling.

For the unification of the existing infrastructure-sector models, we propose the implementation of a generic communication interface, which allows the separate sector-models to communicate at the necessarily disaggregate level in order to account for interdependencies appropriately. This approach allows for infrastructure provision modelling under one unified umbrella in a minimally invasive way, while conserving crucial individualities of the separate models. This is achieved through a generic network description, in which we solve the resource allocation through a pragmatic network-flow algorithm that resembles market and consumer behaviour. The developed framework establishes the basis for fully integrated infrastructure evaluation and hence cross-sectorial infrastructure investment decision making — a crucial tool in times of tight governmental budgets.

**Keywords:** Infrastructure Interdependencies, Generic Modelling, Cross-Sectorial Investment Optimization

## INTRODUCTION

Infrastructure interdependencies are gaining increased attention due to multiple incidents of catastrophic cascading failures of complex infrastructure networks in recent years<sup>1</sup>. While this forces us to investigate the robustness of the topology of our infrastructure networks, it also sheds light on the increasing relevance of infrastructure interdependencies in all other aspects of infrastructure provision.

With the need of climate change mitigation and adaptation we see more efficient and flexible measures of infrastructure provision, to use resources more efficiently and to be able to react to unexpected changes of external driving forces, like climate or global economic trends. Since the behaviour of the socio-economically driven adaptive system of infrastructure-systems is dependent on external driving forces, the choice of service provision might yield widely different amplitudes of the feedbacks between the individual infrastructure systems, depending on changes in the driving forces.

This eradicates the static supply arrangements that traditionally allowed us to account for interdependencies at a highly aggregate level. Instead, we have to account for them at a much more disaggregate level, determined by the dynamics of actual infrastructure provision. The loss of the static situation hence requires more elaborate infrastructure forecasting

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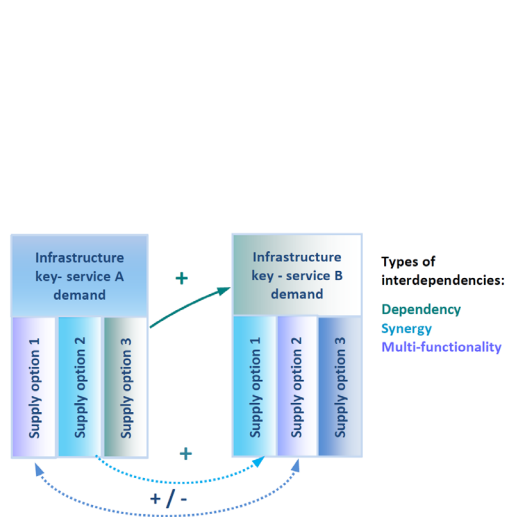
1 Eusgeld, I., Nan, C., & Dietz, S. 'System-of-systems' approach for interdependent critical infrastructures. *Reliab. Eng. Syst. Saf.* **96**(6), 679–686 (2011). Little, R. Controlling cascading failure: understanding the vulnerabilities of interconnected infrastructures. *J. Urban Technol.* **9**(1), 109–123 (2002).

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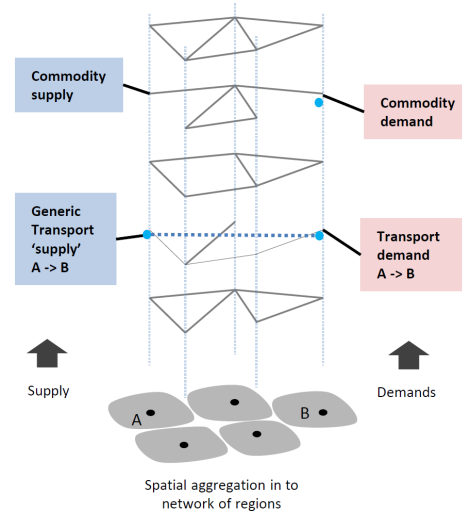
and planning, moving away from deterministic long-term planning to an increased focus on provision strategies, which do not define the actual investments upfront, but the rules according to which investment decisions are being taken in response to unpredictable changes in the external driving factors.

In times of tight governmental budgets this variability and unpredictability in the planning sphere implies that a cross-sectorial optimization of infrastructure investments would be highly valuable to maximize their utility for economic growth and societal wellbeing in general.

In this study we propose a unified generic infrastructure model, drawing upon the existing results on integrated infrastructure investment optimization<sup>2</sup> and studies on generic description of interdependent infrastructure systems<sup>3</sup>. By casting only the information essentially relevant to infrastructure provision and interdependencies in a generic way, we provide an interface for model-communication at an appropriately disaggregate level, to account for interdependencies. By this we create a generic network-based modelling setting capable of accounting for crucial sector-specific details.



**Figure 1. Generic schematics of key-infrastructure systems and their interdependencies.** An infrastructure system is serving a key-service demand through supply options. The actual provision of a service can have a positive or negative feedback on either the demand for another infrastructure capacity of another supply option.



**Figure 2. Emergence of the generic network and key-service classification.** Spatial aggregation enables a generic description of the state of the system and leads to a natural emergence of a generic network structure. With reference to this generic network, key-services are classified into two types: commodity and transport, depending on whether the respective demands arise local or for a connection.

## GENERIC APPROACH

An integrated infrastructure model has to account for all those infrastructure services that are providing essential, i.e. at a given moment in time irreplaceable, inputs to all that a society does – the so called key-services: energy (in various forms, e.g. electricity, space-heating, fuel etc.), fresh water, transportation, communication and waste treatment (solid waste, sewage, greenhouse gas emissions etc.).

In consultation of previous accounts of infrastructure interdependencies<sup>3,4</sup>, we characterize relevant infrastructure interdependencies as visualised in the top of figure 1. A simple dependency is given, if the service provision in one infrastructure system causes a key-service (or network-service) demand in another infrastructure system. In the case of a synergy the provision of one service enables the provision of another service, i.e. increases the respective supply capacity, while in the case of a multi-functionality, the opposite is the case, i.e. the actual service provision decreases the supply capacity of the dependent supply option.

<sup>2</sup> Nozick, L.K. et al. Assessing the Performance of Interdependent Infrastructures and Optimizing Investments. *Proceedings of the 37th Hawaii International Conference on System Sciences – 2004* **C**, 1–7 (2004). Ibanez, E. & McCalley, J.D. Multiobjective evolutionary algorithm for long-term planning of the national energy and transportation systems. *Energy Syst.* **2**(2), 151–169 (2011).

<sup>3</sup> Lee, E.E., Mitchell, J.E. & Wallace, W.a. Restoration of Services in Interdependent Infrastructure Systems: A Network Flows Approach. *IEEE Trans. Syst. Man Cybern. Part C* **37**(6), 1303–1317 (2007). Zhang, P. & Peeta, S. A generalized modeling framework to analyze interdependencies among infrastructure systems. *Transp. Res. Part B* **45**, 553–579 (2011).

To account for the relevant interdependencies uniformly, we introduce a generic description of demand and supply as depicted in figure 2, by spatial aggregation over regions, to derive a consistent set of state-of-the-system variables, such like population density, economic activity, as well as the state of the infrastructure systems themselves. This spatial aggregation naturally induces the formation of a generic network of spatial nodes representing regions and of arcs representing connections between regions in infrastructure distribution networks. All information about the underlying system and the infrastructure itself is being accounted for in this setting in respective aggregation and not on the level of individual assets.

Most key-services are fulfilled by the provision of some sort of commodity through a respective transmission network. In these cases the demand for these *commodity-type* key-services arises locally, irrespective of the origin of the commodity, since the commodity flow units are indistinguishable. In case of transport and communication services we find that the actual key-service is to provide a connection for transportation of some flow good (i.e. passengers, goods or information), between two points in space. Hence, the key-service demand for these *transport-type* key-services is a demand for a specific connection.

At each point in time, resources of supply have to be allocated sensibly to prevailing demands. In the case of commodity-type infrastructure systems, the generic network description offers the natural setting to model this task as a network-flow problem. The allocation is hence modelled as a flow of service-units between respective sources and sinks of the generic network, i.e. the commodity generation nodes and the commodity key-service demand nodes.

To include transport-type infrastructure systems into this generic setting, we define artificial transportation generation nodes for each transport demand at the spatial node of the transport-connection origin, as indicated in figure 2. When treating every single transport demand as being only satisfiable by a specific commodity (e.g. personal transport from region A to B), then the allocation of transport services to demands can be modelled as a multi-commodity flow on the respective generic transportation network<sup>4</sup>. This allows us to treat transport type systems identical to commodity type infrastructure networks, under the generalization of allowing for multiple-commodity flows.

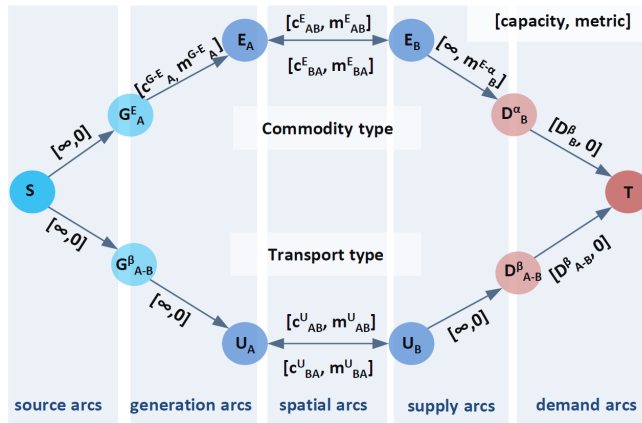


Figure 3. Extended network for the allocation algorithm. S: ultimate source; T: ultimate sink; G: generation; D: demand; A,B: regions;  $\partial, \beta$ : key services; E,U: distribution networks.

## SERVICE ALLOCATION AND ACCOUNTING FOR INTERDEPENDENCIES

The actual service allocation algorithm is being performed on an artificially extended network as shown in figure 3, where generation and transmission assets, as well as demands for key-services are represented through the capacities of suitable edges of the artificial network. To derive an optimal, but yet pragmatic and realistic solution, each edge can have a metric parameter, which is a weighted sum of all relevant supply factors, such as service provision cost and environmental impact. The solution to the allocation problem is found by iteratively optimizing the supply for individual key-service demands and then allocating existing resources in a fair share amongst all demands.

All three forms of interdependencies defined earlier take the generic form in this setting that flows through edges induce changes of capacities in other edges of the extended network. In an outer iteration of the above described algorithm, the interdependency effects are being updated and the flow optimization accordingly refined. Direct dependencies add onto the already existing capacity of demand arcs, while synergies add to the capacities of the edge corresponding to the affected generation or transmission asset. Finally, in the case of multiuse, the capacities of multiple arcs are linked in a way that in each interdependency update, the total shared capacity is allocated to the affected assets in a respective share of relative usage of these edges.

4 Ahuja, R.K. et al. Network flows: Theory, Algorithms and Applications. Prentice Hall (1993)

## CROSS SECTORIAL OPTIMIZATION

In times of tight governmental budgets and needs of climate change mitigation, we need to be able to optimize infrastructure investments in direct cross-sectorial comparison. Our generic description of infrastructure service generation and allocation allows us to define generic performance indicators.

Straight forward examples include the *total metric* of the allocation flows, i.e. a measure of how favourable the total solution is. Likewise, the *collective demand margin*, which is the ratio by which key-service demands can be simultaneously up-scaled and still catered for with supply, is a useful measure to judge the resilience of the overall system to cope with unforeseen demand peaks. Based on such generic performance indicators, investment decisions can then be made in line with generic decision rules, captured in strategies.

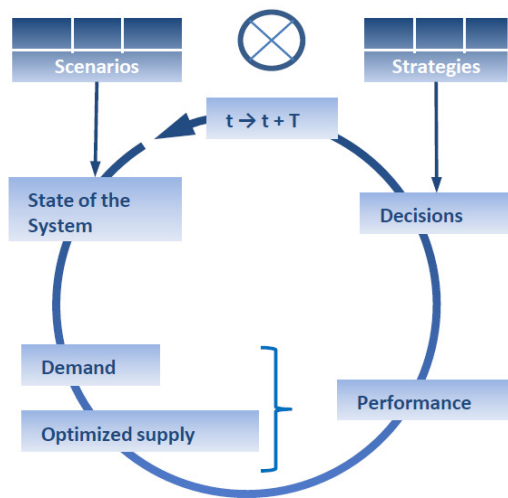


Figure 4. Schematics of the dynamic simulation cycle.

## FULLY INTEGRATED SIMULATION SETTING

Finally, in our fully-integrated infrastructure forecasting model setting the driving forces determining the development of infrastructure provision and key-service demand are subject to uncertainty and hence are creating a set of possible scenarios for the development of key-infrastructure and the availability of supply. The demand for key-services is determined as functions of the state-of-the-system parameters and the external influences captured in the scenarios. The functions determining demand and supply and are highly specific for each infrastructure system and are provided by the individual sectorial models.

With the above described matching algorithm the model setting will then determine the optimized resource allocation in every time-step of the simulation, given as *allocation flows of service provision*. The performance of the key-infrastructure system is then a function of initial demand and found allocation flows. These results then feed into the decision-making, which is performed according to the rules captured in a chosen strategy. Finally, an evolutionary step implements the time development of the state-of-the-system, including population and infrastructure ageing, implementation of infrastructure investments, updating of economic performance etc. The simulation of all given strategies under all specified scenarios will result in a performance landscape of strategies and scenarios, which allows to find the ‘fittest’ strategy of all investigated ones.

## CONCLUSION AND OUTLOOK

In conclusion, we have mapped out a simple, but effective scheme how to cast infrastructure models in order to be able to unify them, allowing to account for interdependencies in the realm of planning purposes and cross-sectorial infrastructure optimization. A case study demonstrating the potential of this framework, when accounting for the impact of interdependencies for planning purposes and hence their consequences for investments, is under way.



# A Systems-Based Approach to the Identification of User/Infrastructure Interdependencies as a Precursor to Identifying Opportunities to Improve Infrastructure Project Value/Cost Ratios

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<http://discovery.ucl.ac.uk/1469383/>

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## ABSTRACT

The bulk of the investment needed for infrastructure renewal in the United Kingdom will have to come from private sector investors, who will require attractive value/cost ratios. Government recognises infrastructure interdependencies can help deliver these, but returns remain uncertain. New business models are required to overcome this problem, which take account of enterprise-centred infrastructure interdependencies (interdependencies between social and economic enterprises and the infrastructures they use). The complex and closely coupled nature of enterprise and infrastructure systems can stand in the way of identifying these interdependencies; however, model-based systems engineering techniques offer a framework for dealing with this complexity. This paper describes research that the iBUILD project is doing to develop a methodology for modelling the interdependencies between infrastructure and the enterprises that use it, as a precursor to identifying opportunities to improve infrastructure project value/cost ratios. The methodology involves: identifying the suite of policy, strategy and operational documents relating to the enterprise-of-interest; eliciting system data from the documents and integrating it to create an enterprise system model; and, generating N2 diagrams from the model to identify the interdependencies.

**Keywords:** Infrastructure Interdependency, Model-Based Systems Engineering, Enterprise Value

## INTRODUCTION

The United Kingdom's (UK's) infrastructure is in need of significant investment<sup>1</sup>, which might benefit from the opportunities afforded by interdependencies between the various infrastructure systems, although such interdependencies also bring risks. The UK Government has recognised the potential to encourage private investment through improvements in infrastructure project value/cost ratios<sup>1</sup>. In spite of these opportunities, it remains difficult for investors to be sure of an adequate return on their investment, or that they will capture their fair share of the value their investment helped to generate. New business models are required to help overcome these problems.

The iBUILD research consortium, with funding from the UK Engineering and Physical Sciences Research Council (EPSRC) and the Economic and Social Research Council (ESRC), is studying the development of new infrastructure business models to support local infrastructure delivery<sup>1</sup>. It is pursuing three research themes: the business of interdependence; re-thinking infrastructure value; and, issues of scale in local delivery. These are being brought together in a number of integrative case studies that have been co-created with commercial and public project partners.

The new business models must take account not only of infrastructure-centred interdependencies (interdependencies

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1 HM Treasury, 2011, 'National Infrastructure Plan 2011', Her Majesty's Treasury and Infrastructure UK, PU1208, The Stationery Office,

between infrastructures themselves), but also user-centred interdependencies (interdependencies between users and the infrastructures that support them). This paper describes *iBUILD*'s development of a methodology for modelling the interdependencies between users and infrastructure as a necessary precursor to identifying opportunities to improve infrastructure project value/cost ratios. The methodology is based on model-based systems engineering (MBSE) techniques and involves: identifying the suite of policy, strategy and operational documents relating to the activity-of-interest; eliciting system data from the documents and integrating it using CORE 9, a powerful system modelling tool produced by Vitech Corporation, to create an activity system model; and, finally, generating N<sup>2</sup> diagrams from the model to identify the interdependencies.

## INFRASTRUCTURE INTERDEPENDENCE

Infrastructure interdependence is the term commonly used to refer to both dependencies and interdependencies between infrastructures. This is a somewhat limited viewpoint, because it fails to acknowledge that infrastructure is not an end in itself, but is created to facilitate the activities that generate value for civilised society. The 'real' value of infrastructure arises from the various uses to which it is put.

A new viewpoint therefore, is required: one that identifies the interdependencies between infrastructure and the value that users generate with it – in short, a 'user-centred' viewpoint.

From this viewpoint it will be easier to see how any given infrastructure contributes to user value generation, and easier to allocate, and hence capture, that value for the relevant infrastructure, thus resulting in improvements to the value/cost ratio.

## 'BROADBAND FOR THE RURAL NORTH' (B4RN): AN EXAMPLE OF 'USER-CENTRED' INFRASTRUCTURE

The UK Government is rolling out 'Next Generation Broadband' (NGB), but current infrastructure-centred business models do not support installation in remote, rural areas.

To overcome this problem, a community company (B4RN) has been established to undertake the supply, installation and operation of a full fibre network, starting with eight rural parishes in the north-west of England<sup>2</sup>. It uses a novel business model to improve value/cost ratios. Cost reduction is achieved by: laying optical fibre cables across land owned by members of the co-operative, rather than in the public highway; members carrying out much of the installation work themselves; and, members who invest in the scheme receiving tax relief through the Government's Enterprise Investment Scheme. Value capture comes from members having access to the benefits arising from access to online services. It is difficult to make an objective assessment of monetary value for some of the services, such as access to a variety of news and entertainment services, but that does not matter because people are very good at making 'fuzzy' assessments of value, which they convert into a willingness to make a monetary payment for access. B4RN is, therefore, an example of the benefit that can come from adopting a user-centred viewpoint.

## IDENTIFYING INTERDEPENDENCIES: A MODEL-BASED SYSTEMS ENGINEERING APPROACH

The interfaces between users and the infrastructures they use are often complex, which makes it difficult to identify user/infrastructure interdependencies. Creating models of user-centred systems can help overcome this problem. However, current methods of interdependence modelling rely on the input of domain experts, with the risk of subjective and variable outputs. *iBUILD* is exploring the feasibility of using a model-based systems engineering (MBSE) methodology, developed on an earlier EPSRC-funded project<sup>3</sup>, to create objective and repeatable models of existing user/infrastructure systems.

MBSE is defined as the "formalised application of modelling to support (system development)"<sup>4</sup> – it joins modelling

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2 Forde, B., 2013, 'Broadband for the Rural North Limited: Business Plan v5.2', Broadband for the Rural North Limited, Lancaster, United Kingdom.

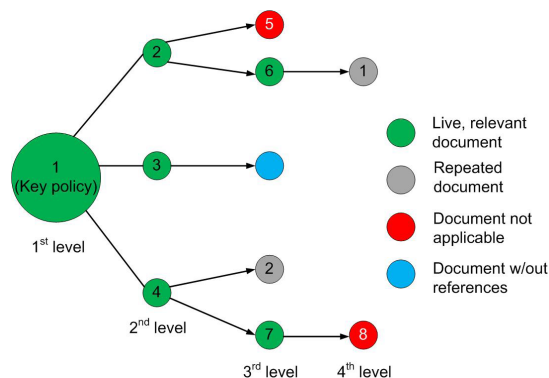
3 Bouch, C., Roberts, C., 2013, 'Developing System Models to Help Great Britain's Railways Embrace Innovative Technologies with Confidence', Proceedings of the Institution of Mechanical Engineers Part F: Journal of Rail and Rapid Transport, Volume 227, Number 6, p. 677-684, Sage Publications, London, United Kingdom.

4 INCOSE, 2007, 'Systems Engineering Vision 2020', INCOSE-TP-2004-004-02 version/revision 2.03, INCOSE, San Diego, CA, USA.

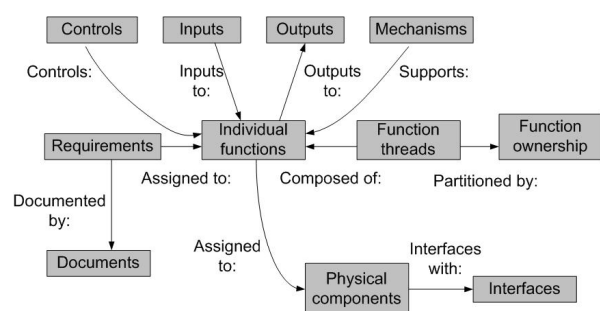
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with systems engineering techniques to create an integrated view of the system of interest<sup>5</sup>. Within MBSE, *iBUILD* is using a so-called ‘middle-out’ approach to create models of existing user-centred systems, which requires: clear definition of the system boundary; elicitation of system data, ideally from an objective source; and integration of those data to create the model.

The *iBUILD* modelling methodology defines the boundary of the system of interest in terms of the suite of related policy, strategy and operational/procedural documents, identified using the repeatable search method shown indicatively in the diagram of Figure 1. The process starts with high-level policy documents and works down through increasing levels of detail to user operating processes and procedures. The National Infrastructure Plan 2013<sup>6</sup>, which was used as the starting point (referred to as ‘key policy’ document in Figure 1), makes reference to a number of documents, shown in the diagram as second level references; those documents in turn have references (third level references), and so on to produce an expanding tree diagram. The diagram does not, however, branch indefinitely: some documents start to repeat (shown grey), some do not have any references (shown blue) and some are deemed not relevant to the system of interest (shown red). The process continues until the circle at the end of every branch is grey, blue or red. The documents signified by the green circles then form the suite of documents for the system.



**Figure 1: Indicative Diagram of the Document Search Method**



**Figure 2: Indicative Diagram of an Entity-Attribute-Relationship Database Schema**

Data integration and model creation is achieved using CORE 9<sup>7</sup>. Essentially, CORE 9 is an entity/relationship/attribute database, where the system entities (functions, components, data items, etc.), together with their attributes, are linked together by relationships. System data elicitation involves reading through the documents identified by the search method and picking out the entities that taken together describe a system. The entities include: requirements, which describe what the system should do; functions, which describe what the system does; components, which are the physical parts of the system; and items, which include flows of information between functions and components. A high-level outline of the CORE 9 schema is shown in Figure 2.

## EXAMPLE OF USER/INFRASTRUCTURE SYSTEM MODEL: HYPOTHETICAL PORT

Work is currently underway to develop user/infrastructure system models using the methodology described above. Two iterations of the document search process, with the National Infrastructure Plan 2013<sup>6</sup> as the key policy document, have identified 107 relevant reference documents. System data are being elicited from these and integrated using CORE 9, but work has not yet advanced to the stage where a complete model has been developed. In the light of this, a hypothetical, outline model for a maritime port system has been created to illustrate how models will be able to assist with identification of user/infrastructure interdependencies.

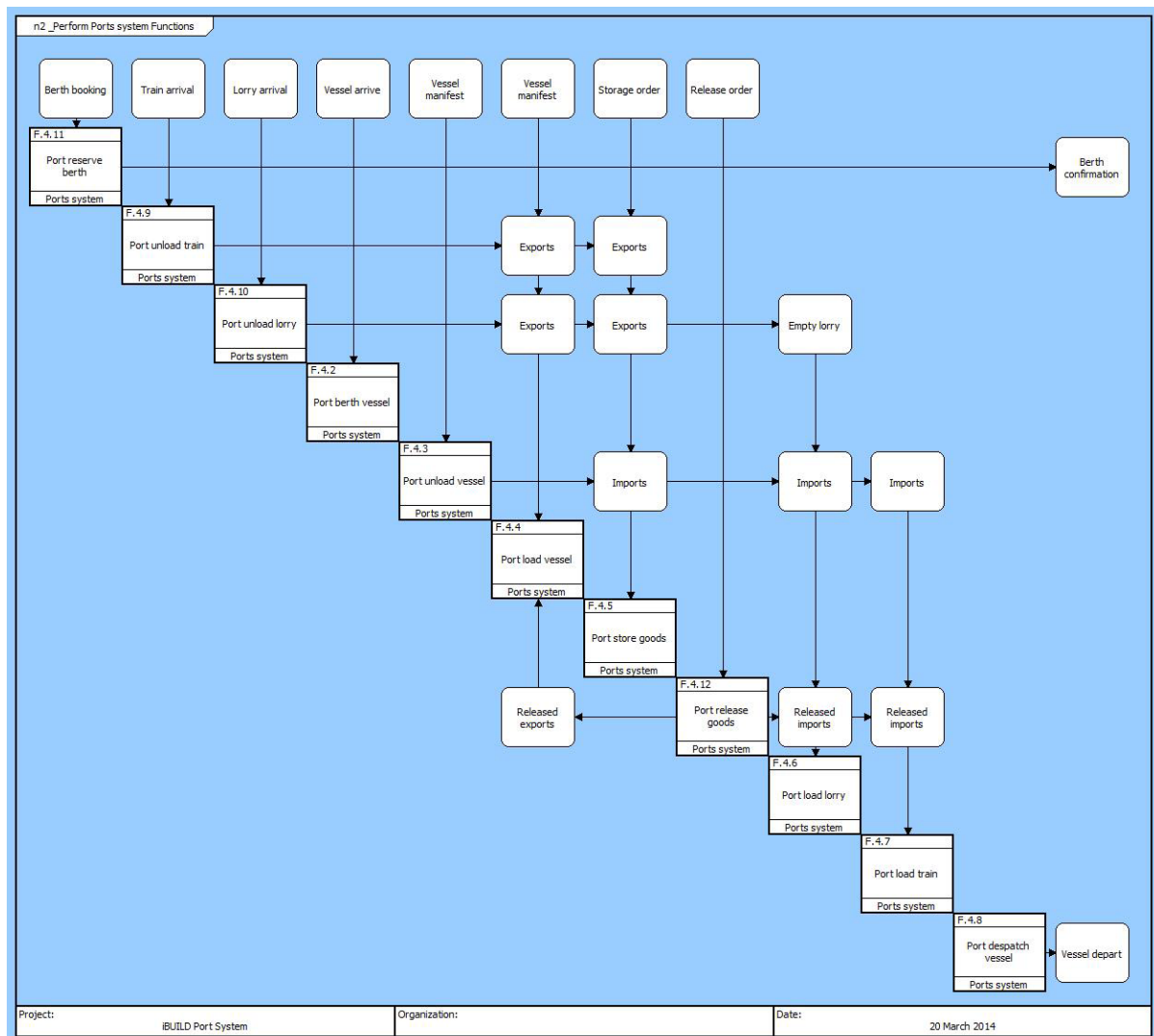
The diagram in Figure 3 shows an assumed set of high level functions describing the operation of the port. The functions are shown on the diagonal running from top left to bottom right. All other boxes on the diagram show events (event boxes)

<sup>5</sup> Long, D., Scott, Z., 2011, ‘A Primer for Model-Based Systems Engineering’, 2nd Edition, pp 14, Vitech Corporation, Blacksburg, VA, USA

<sup>6</sup> HM Treasury, 2013, ‘National Infrastructure Plan 2013’, PU1576, Her Majesty’s Treasury, London, United Kingdom.

<sup>7</sup> Vitech, 2012, ‘CORE® Delivers Project Success Through Integrated Modelling’, <http://www.vitechcorp.com/products/core.shtml>, accessed 29th August 2012.

that trigger the functions: for example, in the top left, arrival of the train triggers the function 'Port unload train'. The event boxes also indicate interdependencies between the port and its supporting infrastructure: for example, the train arrival event indicates that there is an interdependence between the port and the railway system. Similarly, the 'berth booking' and 'berth confirmation' events indicate interdependencies between the port and the ICT system. These are, perhaps, obvious examples, which could be identified without the help of a model; however, as the model is developed to greater levels of detail and complexity, it will help to identify interdependencies that might otherwise have remained hidden.



**Figure 3: N<sup>2</sup> Diagram for a Hypothetical Port with Principal Functions and Related Interdependencies**

## CONCLUSIONS

This paper shows in outline that model-based systems engineering can be used to identify interdependencies between users and their supporting infrastructure. It suggests a repeatable method for identifying the suite of documents describing the system of interest. Moreover, it shows how objective data elicited from the documents can be integrated using CORE 9 to create a system model. The N<sup>2</sup> diagram derived from the model can help to identify the interdependencies.

Work is underway to develop further the model-based systems engineering approach and prove its efficacy. A current *iBUILD* case study concerns local business opportunities deriving from the arrival of the new high-speed train line (HS2) into Birmingham – business functions define (broadly-interpreted) infrastructure needs, hence opportunities to create and capture additional (again broadly-interpreted) value from their interdependencies, both now and into the far future, and thus propose novel business models that will deliver local and regional infrastructure to the greatest benefit to all. This is thus an 'enabler' in the complex, multiply-conflicting future city agendas.

# The Role of Futureproofing in the Management of Infrastructural Assets

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## ABSTRACT

Ensuring long-term value from infrastructure is essential for a sustainable economy. In this context, futureproofing involves addressing two broad issues:

- i. Ensuring the ability of infrastructure to be resilient to unexpected or uncontrollable events e.g. extreme weather events; and
- ii. Ensuring the ability to adapt to required changes in structure and / or operations of the infrastructure in the future e.g. expansion of capacity, change in usage mode or volumes.

Increasingly, in their respective roles, infrastructure designers/builders and owners/operators are being required to develop strategies for *futureproofing* as part of the life cycle planning for key assets and systems that make up infrastructure.

In this paper, we report on a preliminary set of studies aimed at exploring the following issues related to infrastructure / infrastructure systems:

- What is intended by the futureproofing of infrastructural assets?
- Why and when to futureproof critical infrastructure?
- How can infrastructure assets and systems be prepared for uncertain futures?
- How can futureproofing be incorporated into asset management practice?

In order to seek answers to the above questions, the Cambridge Centre for Smart Infrastructure and Construction (CSIC) has conducted two industrial workshops bringing together leading practitioners in the UK infrastructure and construction sectors, along with government policy makers. This paper provides an initial summary of the findings from the workshops (part presentation, part working sessions), and proposes a simple framework for linking futureproofing into broader asset management considerations.

To begin, an overview of futureproofing and motivate the need for futureproofing infrastructure assets is provided. Following this, an approach to futureproofing infrastructure portfolios is presented that organisations in the infrastructure sector can use. Key barriers to futureproofing are also presented before examining the ISO 55001 asset management standard to highlight the interplay between futureproofing and infrastructural asset management. Finally, different ways by which an effective futureproofing strategy can enhance the value of infrastructure are examined.

**Keywords:** Infrastructure, Futureproofing, Asset Management, Resilience, Change Management Capability

## WHAT IS INFRASTRUCTURAL FUTUREPROOFING?

For the purposes of this study infrastructure futureproofing has been defined as “the process of making provision for future developments, needs or events that impact on particular infrastructure through its current planning, design, construction or asset management processes”.

Having examined the different industrial motivations for futureproofing in an infrastructure context, there are two distinct considerations:

- i. *Infrastructural Resilience*: By this we refer to the resilience of critical infrastructure in the face of unexpected / uncontrollable events and circumstances. This might include ability to withstand climate change variations, flooding events or even terrorist actions.
- ii. *Change Management Capability*: Here we refer to the capability of critical infrastructure to adapt or respond to changing needs, uses or capacities. Examples of futureproofing in this context might include easier reuse of substructure elements and buried structures, allowing infrastructure life to be extended, such as by ‘bolting on extra lanes on a bridge’, or by building more floors on an existing building.

## WHY IS CONSIDERATION OF FUTUREPROOFING NECESSARY?

There is significant evidence emerging that consideration of the future needs of infrastructure is the only responsible path to follow in the development and maintenance of infrastructure. Such consideration may conclude that a ‘no action’ response is the most cost effective long term strategy – e.g. in the acceptance that some assets may need to be sacrificed under particular flood scenarios – but we differentiate here between no consideration and no action. The latter is a conscious decision based on an economic /social / strategic analysis of the role of the selected asset. The following paragraphs outline some of the evolving debates around the need for managing future scenarios for critical infrastructure carefully and thoroughly.

The UK national infrastructural assets generally have long operational lifetimes and majority of the UK’s existing infrastructure was originally built in the 19<sup>th</sup> century e.g. London’s sewerage system and Royal Albert Bridge over the River Tamar<sup>1</sup>. Unplanned and uncontrolled user driven future changes to infrastructure and infrastructure systems are also required to be made during operations e.g. design changes, adaptability / capacity changes, and need changes. The consequences of such disruptions and changes are huge over long infrastructure life cycles, which lead to futureproofing considerations. Increase in population also adds to the infrastructure capacity issues over long life cycles.

Not only is infrastructure required to last longer, but recently there has been increase in disruptive extreme events due to climate changes e.g. heavy snowfalls in the UK in 2010 affected transport infrastructure particularly rail and airports. A number of road bridges collapsed and the road and rail networks were disrupted during 2009-2014 as a result of severe flooding. Key climate change impacts are identified as increased flooding (fluvial, tidal and pluvial or surface water), high temperatures (extreme weather events) and increased water scarcity<sup>2,3</sup>. Extreme weather (e.g. heavy rainfall pluvial flooding, wind storms, snow, and ice) also poses construction risks. Flooding also causes operational risks. High ambient temperatures affect rolling stock and railway tracks as well as passenger comfort.

Hurricanes, earthquakes, drought threats and resource scarcity are among other disruptions to infrastructure or infrastructure systems due to long term climate change effects. This means that such infrastructure needs to be maintained for the long term with future climate changes in mind i.e. making it resilient and more adaptable, key challenges identified by DEFRA as for climate resilient infrastructure<sup>1</sup>.

Other reasons to consider futureproofing include the following: wider social, economic and environmental benefits are particularly important for infrastructure with high vulnerability and lower capacity to respond to risks (Atkins, UCL and DFID 2012); interconnected risk topologies are key for energy intensive infrastructure with significant carbon footprint, major climate hazards, regional support systems such as water and food systems, and multiple risks e.g. risks of

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1 DEFRA (2011) “Climate Resilient Infrastructure: Preparing for a Changing Climate”, pp 1-76, available from [www.defra.gov.uk/environment/climate/sectors/infrastructure-companies/](http://www.defra.gov.uk/environment/climate/sectors/infrastructure-companies/).

2 RSSB (2011) “Operations and Management: Adapting to extreme climate change (TRaCCA), Phase 3 report – Tomorrow’s railway and climate change adaptation (T925 Report)

3 Paris, R. (2011) “Crossrail-Climate Change Adaptation”, Crossrail presentation.

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disaster, earth quakes<sup>4</sup>; *foresights projections for solutions for future infrastructure* can change over long time periods and may include considering flexible structures, having sustainable resources, reactive facades, and smart systems<sup>5</sup>.

This growing set of drivers for a more formal and considered approach to managing the future of critical infrastructure is discussed in the following section.

## AN APPROACH TO FUTUREPROOFING OF INFRASTRUCTURE

As part of the outputs from the series of workshops relating to infrastructural futureproofing, a simple *approach to futureproofing of infrastructure* has been developed. This approach (which could possibly become a framework) is intended to be applicable to a portfolio of an infrastructure e.g. a county's bridges portfolio consisting of 100s of different types of bridges. The approach is presented in Figure 1, and considers the following:

### Requirements Analysis

In order to identify and understand user needs and the requirements of business and external parties, stakeholder and PESTLE (Political, Economic, Social, Technological, Legal, and Environmental) analyses are conducted. Stakeholder examples include public, asset owners, asset operators, asset maintainers, organisations e.g. utility companies, regulatory bodies, interdependent and mutually benefited companies, UK Government, Infrastructure UK, treasury, investors, and the media. The PESTLE analysis will answer questions related to key political drivers of relevance, important economic factors, treasury rules and budget availability, main societal and cultural aspects, current technological imperatives, changes and innovations, current and impending legislation and environmental considerations affecting the infrastructure.

### Futureproofing Considerations

There are a number of futureproofing considerations that need to be considered for long term sustainability of infrastructure. These range from developing meaningful and implementable criteria, strategies, technological solutions, options appraisal, information continuity, anticipated asset life, supporting lifecycle models, risks of not futureproofing, future scenarios, impact and criticality of infrastructure or infrastructure systems and elements.

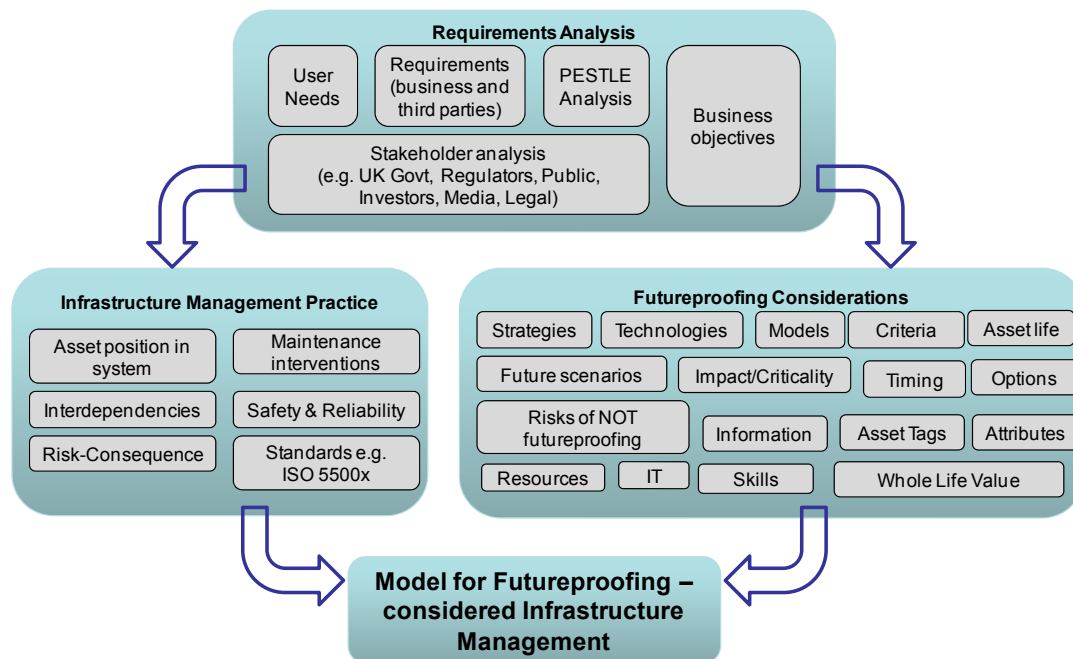
The following set of *criteria* is proposed for considering infrastructure futureproofing requirements, strategies and solutions:

- Resilience – *ability to withstand shocks and recover quickly;*
- Adaptability – *ability to be readily adapted or reconfigured if understanding of risks or requirements change;*
- Replaceability – *ability to be replaced during or at the end of life or use;*
- Reusability – *ability to be reused or extended if no longer required for original purpose; and*
- Self-reinforceability – *ability to work with, rather than against natural processes*
- Organisations would need to consider above mentioned futureproofing elements as well as any additional set of futureproofing considerations in their strategies to plan, design, construct and maintain.
- The following questions are also relevant while considering criteria:
  - *Quality* – What is the quality criteria for infrastructure; and how to measure, monitor and sustain the quality?
  - *Value* – What is the value in optimising and updating the infrastructure?
  - *Time* – How long to optimise and update for?
  - *Performance* – What is the definition of infrastructure performance? How to measure, monitor and sustain it?
  - *Lifecycle* – Which are the key lifecycle stages for the infrastructure?
  - *Risk* – What are the key risks to futureproofing infrastructure and assets?
  - *Criticality* – What is the criticality of various elements of the infrastructure and assets?
  - *Strategies* – Which strategies are relevant in futureproofing the infrastructure?
  - *Technologies* – Which technologies are relevant in futureproofing the infrastructure?
  - *Information* – What types of information are required to support futureproofing decisions? Are those information types collected, maintained, updated and made available for reuse throughout the lifecycle (and even beyond in some cases)?

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4 Atkins, UCL and DFID (2012) "Futureproofing Cities – Risks and opportunities for inclusive urban growth in developing countries", London, 20 November.

5 Hargrave, J. (2013) "It's Alive! – Can you imagine the urban building of the future?", ARUP Foresight & Innovation, London, January 2013, pp 1-12.



**Figure 1: An approach to futureproofing of infrastructure portfolio**

### Infrastructure Management Practice

Infrastructure management practice is analysed so that the outputs of futureproofing considerations could be integrated. Key related questions follow:

- *Interdependencies* – How different assets comprising the infrastructure are interdependent?
- *Asset Position in System* – What are different systems providing functionalities of the infrastructure? What are the asset positions in those systems?
- *Standards* – Which standards are (being) implemented e.g. PAS 55, ISO 55001:2014, and BS 1192-3? What are the key lessons learnt from their implementation? What are the key interfaces?
- *Safety & reliability* – How safe and reliable is the infrastructure? What are the threats and challenges?
- *Risk-Consequences* – What are the risks prone to the infrastructure and assets? What are the consequences of these risks? What is the priority mechanism?
- *Maintenance interventions* – What are various maintenance intervention schemes in place to maintain the infrastructure and the assets in the systems?

### Model for futureproofing-considered infrastructure management

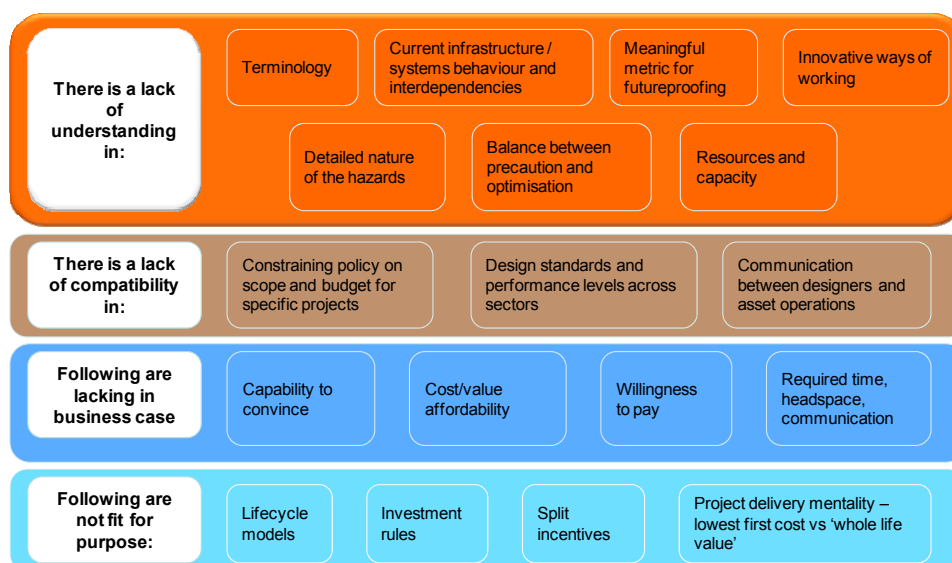
A model for futureproofing-considered infrastructure management can be formed based upon the current practice and futureproofing considerations. This model considers the following:

- *Diagnosis* – Defines or explains the nature of the challenge in integrating futureproofing with asset management practice;
- *Policies* - Guiding policies to achieve a futureproofing-considered infrastructure management;
- *Strategies* - Containing action plans to integrate futureproofing considerations with asset management practice based upon futureproofing goals, the diagnosis and the guiding policies;
- *Tactics* – Coming up with futureproofing integration tactics, where opportunities arise, that will support the long-term action plans; and
- *Operations* – Keeping a ‘value of futureproofing-considered infrastructure management’ check on all operations to ensure their alignment with the futureproofing goals.



## KEY BARRIERS TO INFRASTRUCTURE FUTUREPROOFING

Barriers exist to wide adoption of futureproofing. Figure 2 provides a categorisation of key barriers to infrastructure futureproofing (i.e. a lack of understanding and a lack of compatibility in some areas, inadequate business plan, and current asset management practice that is not fit for purpose) with key elements noted in each of the categories.



**Figure 2: Key barriers to infrastructure futureproofing**

## HOW TO INTEGRATE FUTUREPROOFING INTO ASSET MANAGEMENT PRACTICE?

Treating futureproofing as a standalone requirement leads to marginalisation of the issue and ultimately becoming an add-on consideration. Hence, it is important that the futureproofing concepts are aligned with asset management practice and standards. Here we simply identify some issues associated with integrating futureproofing into a broader infrastructural asset management agenda.

The integration can be supported by understanding and taking care of the stakeholder requirements early on and, to fully to deliver long-lasting infrastructure, and understanding the impact of futureproofing over life cycle. Establishing and implementing futureproofing criteria across asset life cycle stages will also help integration. Planning for change earlier on and managing change in operations is key while allowing for future growth across life cycle stages. Adopting standardized approaches to futureproofing in asset management practice will also help in integration, where Government input can be critical, through legal and regulatory standards and guidance.

Recently released asset management standard, ISO 55001:2014, considers the long term but does not specifically mention futureproofing concepts, its value and integration into asset management practice<sup>6</sup> (ISO 2014). However, there are possible links of futureproofing to ISO 55001. The following clauses of ISO 55001 could be extended to include requirements for futureproofing:

- Clause 4.1 (Understanding the organization and its context) and Clause 4.2 (Understanding the needs and expectations of stakeholders) can include futureproofing requirements and futureproofing criteria.
- Clause 6.1 (Actions to address risks and opportunities) can include futureproofing requirements and long term risks and opportunities.
- Clause 6.2 (Asset management objectives and plans to achieve them) can include futureproofing criteria and a model for futureproofing-considered infrastructure management.

Within the workshops run by CSIC, the value of futureproofing as part of asset life cycle management was also considered, which will be discussed in the following.

6 ISO (2014) "ISO 55001: Asset Management -- Management systems -- Requirements", 9 January 2014.

## VALUE OF FUTUREPROOFING OVER ASSET LIFE CYCLE

Futureproofing creates most value when considered during earlier asset lifecycle stages. For long term decisions, it is also important to know at what stage in the life cycle of an asset a futureproofing strategy provides the biggest value. From the CSIC futureproofing workshops, it is learnt that the asset lifecycle stages in order of accruing most value include: Operate, Maintain, Renew, Upgrade, Decommission/Reuse, Requirements, Build, Design, Installation, and Planning. Table 1 provides summary results on accruing value of futureproofing in asset management life cycle.

**Table 1: Accruing value of futureproofing in asset life cycle**

Lifecycle stages	What should organisations do?	Accrued Value
Requirements & Plan	<ul style="list-style-type: none"> <li>- Place firm limits on asset life</li> <li>- Specify future in requirements</li> </ul>	<ul style="list-style-type: none"> <li>- Greater certainty/more answers/more long term options</li> <li>- Attractive financial proposition</li> <li>- Greater R.O.R.</li> </ul>
Design, Build & Install	<ul style="list-style-type: none"> <li>- Add capacities, functionalities, redundancies to assets</li> <li>- Tailor design to asset life</li> </ul>	Negligible value gain during this stage
Operate	Configure to meet demand & technologies	<ul style="list-style-type: none"> <li>- Reliable performance of infrastructure</li> <li>- Cheaper infrastructure operations</li> </ul>
Maintain / Renew / Upgrade	<ul style="list-style-type: none"> <li>- Predict &amp; prevent failures</li> <li>- Predict maintenance interventions</li> </ul>	<ul style="list-style-type: none"> <li>- Less reactive maintenance</li> <li>- Safer planning &amp; scheduling</li> </ul>
Decommission / Reuse	<ul style="list-style-type: none"> <li>- Improve ability to decommission safely and in an environmental friendly way</li> <li>- Extract / extend maximum effective life (evidence based)</li> </ul>	Greater residual value

## CONCLUSIONS

The following conclusions can be drawn from the research presented in this paper:

- Infrastructure futureproofing is a concern for asset managers.
- A meaningful framework, criteria or metric for futureproofing are not formally embedded into existing options appraisal processes but are needed for effective and long term infrastructural asset management.
- Key futureproofing criteria are based on resilience, adaptability, replaceability, reusability and self-reinforcing concepts.
- Barriers exist to wide adoption of futureproofing.
- A possible infrastructure futureproofing framework has been proposed in this paper for further development.

The proposed futureproofing framework has not been tried in many industrial settings. Therefore, it is recommended to translate the framework into an actionable tool and develop a process for prioritisation of considerations for wider asset portfolios. It is also recommended to assess the applicability of the futureproofing approach to non-infrastructure asset portfolios.

## ACKNOWLEDGEMENTS

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# A Socio-technical Analysis of Interdependent Infrastructures among the Built Environment, Energy, and Transportation Systems at the Navy Yard and the Philadelphia Metropolitan Region, USA

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<http://discovery.ucl.ac.uk/1469385/>

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## ABSTRACT

This paper reports on a research initiative that explores the interdependencies of the system of systems — the built environment, energy, and transportation — related to the redevelopment of The Navy Yard in Philadelphia and the Philadelphia Metropolitan Region. The overarching goal of the project is a clearer understanding of the dynamics of multi-scale interactions and interdependencies of systems of sociotechnical systems that will be useful to system practitioners. The understanding and the subsequent planning and design of sociotechnical systems are “wicked” problems and one characteristic is there is no definitive formulation. One of the main findings or lessons learned of the work reported for the understanding of interdependencies of infrastructure is the identification of what are the problems or challenges because for wicked problems “[t]he formulation of the problem is the problem!”

We find that systems practitioners have an overarching concern of a fragmented regional policy and decision making process. Four main themes of 1. Vulnerability of aging infrastructure, 2. Integration of emerging technology into existing infrastructure, 3. Lifestyle and value changes, and 4. Financial innovations were identified as challenges. Continuing research work explores three possible infrastructure projects for further study as well as the development of a high-level systems of systems model. The principle outcome is the initiation of a planning process so that the system practitioners will learn to better understand the connections among related sociotechnical systems and the constellation of problems they face not within their immediate scope of responsibility yet influences the operations of their systems.

**Keywords:** Interdependent Infrastructure, Socio-Technical Systems Analysis, Scenario Planning, Risk Management, Strategic Investment

## INTRODUCTION

This paper reports on a research initiative that explores the interdependencies of the system of systems – the built environment, energy, and transportation – related to the redevelopment of The Navy Yard in Philadelphia and the Philadelphia Metropolitan Region. The overarching goal of the project is a clearer understanding of the dynamics of multi-scale interactions and interdependencies of systems of sociotechnical systems that will be useful to system practitioners<sup>1</sup>. The understanding and the subsequent planning and design of sociotechnical systems are “wicked” problems and one characteristic is there is no definitive formulation<sup>2</sup>. One of the main findings or lessons learned of

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1 Rouse, W. & Bodner, D.A. Multi-Level Modeling of Complex Socio-Technical Systems. Center for Complex Systems & Enterprises. Report No. CCSE-2013-01 (2013).

2 Rittel, H. W. J. & Webber, M. M. Dilemmas in a General Theory of Planning. *Policy Sci.* **4**:155-169 (1972).

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the work reported for the understanding of interdependencies of infrastructure is the identification of what are the problems or challenges because for wicked problems “[t]he formulation of the problem *is* the problem<sup>2</sup>!”

A challenge is to understand why stakeholders may have different interpretations or “mental models” of how infrastructure sociotechnical systems function, even for supposedly the same systems, which is valuable knowledge for understanding “whole” systems of systems functioning. The knowledge generated then serves to inform the construction and evaluation of sociotechnical theory as well as to inform the practice of strategic infrastructure decision making and implementation in the public and private sectors. The initiative is reliant on collaboration with system practitioners in the development of models, simulations, and scenarios of the many system and component interactions. It is through collaboration with system practitioners that “an image of the problem and of the solution emerges gradually among the participants, as a product of incessant judgment, subject to critical argument” and is distinctly different from the conventional or “first generation” systems engineering approach<sup>2</sup>.

The principle outcome of the analysis is not a static strategic plan. It is the initiation of a planning process so that the system practitioners will learn to better understand the connections among related sociotechnical systems and develop an expanded understanding of the constellation of problems they face that is not within their immediate scope of responsibility yet influences the operations of their systems. In engaging with systems practitioners and potentially influencing and engineering the sociotechnical systems, one faces the question about the validity and veracity of the knowledge generated<sup>3</sup>. In other words, how is systems knowledge considered scientific knowledge and why? What constitutes scientific knowledge of a system when one is intervening in the behavior of sociotechnical systems? “What is an application and when is theory a waste of time<sup>4</sup>?” How can the scientific knowledge be used to create systems innovations that will make the systems resilient, secure, environmentally responsible, economically competitive, and socially acceptable<sup>5,6</sup> ? On the one hand, to what extent is the design and evolution of sociotechnical infrastructure systems a “wicked” problem and as such, there are limits to what is scientifically knowable<sup>2</sup>? On the other hand, are there concepts and methods that can represent and model a sociotechnical system of systems, including interventions, such that one may gain insight into the possible ways the systems may change over time<sup>7</sup>?

The increasing interdependencies of the systems generate many direct and even more indirect risks that are not well understood so that communication among the multiple stakeholders is essential to insure a fair and reasonable representation of perspectives. The aim is that systems practice drives the development of the research and theory to insure that the outcomes are management and policy relevant so that one needs a new way of thinking about and understanding the interdependencies of large-scale, complex, interdependent, infrastructure systems<sup>8</sup>. In the development of a new way to think through and formulate the problems, however, there are at least three types of errors one may make:

Type I Error: Detecting a problem when there isn’t one.

Type II Error: Not detecting a problem when there is one.

Type III Error: Solving the wrong problem<sup>9</sup>.

“Most research on decision making focuses on how problems are solved [. . . not] *which problems* are solved and how alternatives are generated for problem solving. These are fundamental activities underlying effective problem solving. Clearly, if we spend our time solving the wrong problems or if we restrict attention to an inferior set of alternative solutions, then no matter how effective our problem-solving procedures may be, the outcome will be

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3 Oreskes, N., Shrader-Frechette, K. & Belitz, K. 1996. Verification, Validation, and Confirmation of Numerical Models in the Earth Sciences. *Science* **263**: 641-646.

4 Shubik, M. What is an Application and When is Theory a Waste of Time? *Management Sci.* **33**: 1511-1522 (1987).

5 de Weck, Olivier, Roos, D. & Magee, C.L. *Engineering Systems: Meeting Human Needs in a Complex Technological World*. Cambridge, MA: The MIT Press (2011).

6 Barami, B. Infrastructure Resiliency: A Risk-Based Framework. Excerpt of white paper. John A. Volpe National Transportation Systems Center, U.S. Department of Transportation (2013).

7 Batty, M. *The New Science of Cities*. Cambridge, Massachusetts: The MIT Press (2013).

8 Tran, M., Hall, J., Hickford, A., Nicholls, R., Alderson, D., Barr, S., Baruah, P., Beavan, R., Birkin, M., Blainey, S., Byers, E., Chaudry, M., Curtis, T., Ebrahimi, R., Eyre, N., Hiteva, R., Jenkins, N., Jones, C., Kilsby, C., Leathard, A., Manning, L., Otto, A., Oughton, E., Powrie, W., Preston, J., Qadrdan, M., Thoun, C., Tyler, P., Watson, J., Watson, G. and Zuo, C. National infrastructure assessment: Analysis of options for infrastructure provision in Great Britain, Interim results. Environmental Change Institute, University of Oxford (2014).

poor<sup>9</sup>". The research reported in this paper has expanded the understanding what may be the right problems to address and suggests a future research strategy to explore further the problem space.

## THE NAVY YARD AND PHILADELPHIA REGION

The Navy Yard in Philadelphia is a 1,200 acre facility that, until the early 1990s, was a U.S. Navy ship building facility, which began operation at its current location during the American Civil War<sup>10</sup>. The Navy Yard traces its origin to the first naval shipbuilding facility of the United States founded at the beginning of the country. In the early 1990s, the Base Realignment and Closure Commission recommended its closing. The U.S. Navy still has facilities at The Navy Yard, notably the Naval Ship Systems Engineering Station (NAVSEA) and Naval Inactive Ship Maintenance Facility. The Philadelphia Industrial Development Corporation (PIDC) manages the site for the City of Philadelphia. The Navy Yard serves as home to the Department of Energy, Consortium for Building Energy Innovation (CBEI). The research at CBEI served as a starting point for exploring the interdependencies of infrastructure systems in the larger region.

## SCENARIO PLANNING SCOPING MEETING AND SYSTEMS WORKSHOP

On September 19, 2013, a half day scenario planning scoping meeting was held at the Navy Yard CBEI with a select group of infrastructure system planners and practitioners. The participants represented the regional transit organization, the national passenger rail service, the management company that operates the Navy Yard buildings and grounds, the regional planning commission, and a local chamber of commerce organization in addition to Penn State engineering faculty. One aim of the meeting was to build upon existing scenario analysis and planning work related to the region<sup>11,12,13,14,15,16,17</sup>.

Also participating in the scoping meeting were Dr. Paulien Herder, Dr. Theo Toonen, and Dr. Jeroen van den Hoven from TU-Delft, who are part of an EU-wide Next Generation Infrastructures project and Dr. Banning Garrett, one of the contributors to the United States National Intelligence Council's *Global Trends 2030* report<sup>18</sup>. The main purpose of the scoping meeting was to identify problems, questions, and issues related to developing a next generation built environment-transportation infrastructure system focused on The Navy Yard and the Philadelphia region, but also to recognize the region's relationship to global trends and to learn from related infrastructure work in Europe. An expected outcome of this meeting was a preliminary, applied engineering systems research and education agenda for a follow-up workshop to be held in 2014 on interdependent infrastructure.

An overarching concern expressed at the September meeting was the fragmentation of the decision and policymaking processes of the different stakeholders that govern, operate, and invest in the infrastructure. Four main themes emerged from the September discussion: 1. vulnerability of aging infrastructure, 2. integration of emerging technology into existing infrastructure, 3. lifestyle and value changes influencing infrastructure demand and use, and 4. financial innovations needed to fund infrastructure re-development including workforce education. In listening to the participants' concerns, the use of computational models appeared as the next step beyond qualitative scenarios

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9 Kleindorfer, P. R., Kunreuther, H. C. & Schoemaker, P.J.H. *Decision Sciences: An Integrated Perspective*. Cambridge: Cambridge University Press (1993).

10 PIDC (Philadelphia Industrial Development Corporation <http://www.pidcphila.com/>) (2014).

11 Amtrak. The Amtrak Vision for the Northeast Corridor, (2012).

12 Delaware Valley Regional Planning Commission. Making the Land Use Connection: Regional What-If Scenario Analysis. September. Delaware Valley Regional Planning Commission (2008).

13 Delaware Valley Regional Planning Commission. Making the Land Use Connection: Regional What-If Scenario Analysis. September. Delaware Valley Regional Planning Commission (2008).

14 Delaware Valley Regional Planning Commission. Connections 2040: Plan for Greater Philadelphia. July. Delaware Valley Regional Planning Commission (2013).

15 Economy League of Philadelphia. *2026: Future Histories of Greater Philadelphia*. Philadelphia, Pennsylvania: Economy League of Philadelphia (2011).

16 Fusco, B. The Future of Scenario Planning. Delaware Valley Regional Planning Commission. White Paper, March (2014).

17 Robert A. M. Stern Architects. The Navy Yard Master Plan Update (2013).

18 Burrows, M. *Global Trends 2030: Alternative Worlds*. Washington, DC: National Intelligence Council (2012).

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to gain a deeper understanding of the critical interdependencies among systems. These models should contribute to effective decision making for the management of risks and the evaluation of public-private investments to achieve resiliency, sustainability, competitiveness, security, and social acceptability.

A follow-up systems workshop was held April 3, 2014 with the goal to identify variables, parameters, constraints, and the data needed to model accurately the interdependencies of complex, adaptive socio-technical infrastructure systems. The workshop included a representative of the regional electric power transmission organization as well as participants from the Pennsylvania State Police responsible for critical infrastructure intelligence and protection, and Dr. Asta Zelenkauskaitė from Drexel University. Dr. Kevin Stamber from Sandia National Laboratories presented on complex, adaptive systems of systems (CASoS) projects that the laboratory had conducted, some of which were already performed on “smart grids” for electricity distribution at the Navy Yard and national petroleum supply chain vulnerabilities<sup>19</sup>. Other participants included General James E. Cartwright, the 8<sup>th</sup> Vice Chairman of the US Joint Chiefs of Staff, who led a discussion on the interactions among cyber and physical systems and the challenges that enterprises face integrating emerging technologies into a wide diversity of systems in an attempt to increase overall performance. Mr. Bob Prieto, Senior Vice President of Fluor and author of *Strategic Program Management*<sup>20</sup>; Dr. Janet Barlow, Director of the Centre for Technologies for Sustainable Built Environments, University of Reading, UK.; and Dr. Marc Weiss, Chairman of Global Urban Development discussed different aspects of infrastructure interdependencies to provide, as in the September scoping meeting, a broader perspective to understand the infrastructure challenges of the Philadelphia region.

Three possible projects were suggested at the workshop and call for further investigation:

1. A need to assess new public transportation connections to areas of the region that are already experiencing renewal and growth, particularly University City - Navy Yard - 30<sup>th</sup> Street Station.
2. A need to assess energy supply and demand at the Navy Yard and region to understand the implications of current and projected economic growth rates, which would include future energy capacity needs, options, and risks. A modeling project would also assess the implications of increased energy supply from natural gas for the development of new manufacturing and the competitiveness of unique regional assets, such as food refrigeration.
3. A need to assess the implications and risks of extremes in weather to existing and future infrastructure and model a strategy for infrastructure renewal and protection accounting for the lessons observed from super storm Sandy. Specifically, the modeling would identify the vulnerabilities and implications for cascading system failures among the built environment, energy systems, and transportation infrastructure and consider the linkages to other critical infrastructure such as water, food, communication, and public health.

Each of the three possible projects has economic, environmental stewardship, and security dimensions that interact. There are variables of aging infrastructure, emerging technologies, stakeholder-customer values and behavior changes, and alternative mechanisms for public-private financing among the systems as well as interdependencies that may not be entirely clear generating risks as well as opportunities. During the summer of 2014, we will be coordinating with Sandia National Laboratories on developing models to explore the three projects for further research. We have also begun to engage The Mayor of Philadelphia's Office of Sustainability to assess the implications and risks of extremes in weather to the Navy Yard and the Philadelphia region in relationship to the City's climate adaptation strategy.

## DISCUSSION AND FUTURE RESEARCH

The Navy Yard project has begun to explore the systems of systems problem space related to the resiliency, security, sustainability, and competitiveness of the Philadelphia Metro Region and there are many fundamental questions to ask. What defines the resiliency, security, sustainability, and competitiveness of a region? How do different infrastructure sociotechnical systems contribute to resiliency, security, sustainability, and competitiveness? How is the resiliency, security, sustainability, and competitiveness of one region related to another? Although this project focuses on the Philadelphia Metro Region, we recognize that the Philadelphia Metro Region is an intrinsic part of the larger

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19 Brown, T. J., R. J. Glass, R.J., Beyeler, W. E., Ames, A. L, Linebarger, J. M., & Maffitt, S. L. Complex Adaptive System of Systems (CASoS) Engineering Applications Version 1.0. Sand Report 2011-8032. (October 2011).

20 Prieto, B. *Strategic Program Management*. McLean, Virginia: Construction Management Association of American (2008).



U.S. mid-Atlantic corridor and that the knowledge generated will have broader practical implications for the larger region. Events external to the region, such as the widening of the Panama Canal will influence the region through increased commerce, will also need to be considered. This will require an enlarged collaborative research effort with multiple stakeholders of critical infrastructure that operate under different socio-technical constraints throughout the mid-Atlantic region.

Three general questions have guided the research. First, what are the challenges that systems practitioners face from their point of view? Second, what is the relationship between sociotechnical systems theory and practice generally with lessons specifically applied to this case? Third, how does sociotechnical systems theory inform systems practice and how may practice improve theory? These questions are asked to understand how infrastructure sociotechnical systems are interdependent, which is central to the evaluation of investment in a particular infrastructure project that may influence the performance of systems of systems across a range of expected outcomes, such as resiliency, competitiveness, sustainability, and social acceptability. Understanding the interdependencies of infrastructure is also essential to avoid cost and schedule overruns as well as canceled projects<sup>21,22,23</sup>.

The overarching concern of a fragmented regional policy and decision making process and the four theme areas of 1. vulnerability of aging infrastructure, 2. integration of emerging technology into existing infrastructure, 3. lifestyle and value changes, and 4. financial innovations were identified as challenges through the scenario scoping meeting. Consequently, a main outcome of the follow-on systems workshop was the identification of three possible projects for further study that reflect the challenges expressed in the scoping meeting.

Since the April 2014 systems workshop, we have discussed the findings with our colleagues at Sandia National Laboratories and regional participants about how to proceed with a systems modeling activity. As of July 2014 we are evaluating which of the three possible research projects would yield the greatest expected benefits for the resources expended and that include the value of future real options for follow-on research and development<sup>24,25 26</sup>. Three related activities will also inform the modeling process. The first is the development of the South Eastern Pennsylvania Transportation Authority (SEPTA) strategic business plan. The second is the Delaware Valley Regional Planning Commission's September 2014 launch of a public participation website and meetings on the driving forces and game changers that may influence transportation in the region. The third is the Mayor's Office of Sustainability effort to develop a climate adaptation plan for infrastructure.

Our future research strategy is to leverage existing modeling efforts for energy, transportation, the built environment, and land-use planning, which includes a recently completed Sandia study on the implementation of smart grid technology at The Navy Yard, to evaluate future technology investments across a range of criteria. The metrics are to be determined. As part of the research, we are in the process of developing a high level sociotechnical systems influence diagram that will enable us to get a "bird's eye" so we can see in a general way the interdependencies of the social and technical systems related to the three possible projects.

We initiated this project with the idea of developing a "strategic conversation" through scenario planning among system practitioners and planners to identify challenges to regional systems and better understand how the systems functioned and depended upon one another<sup>26</sup>. The challenge of designing and evolving infrastructure systems is a "wicked" problem such that stakeholders need to engage in a "discipline of systematic thinking" to better understand which problems to address and to better understand the associated risks<sup>27</sup>. Engaging in "reasoned imagination is thus an important part of risk assessment because it implies, first, anticipating by systematic analysis scenarios that have not happened yet, and second, recognizing and communicating these unusual signals<sup>28</sup>".

Scenario and sociotechnical systems analysis can also make intelligible policy processes that are not necessary the

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22 Merrow, E. W. *Industrial Megaprojects*. Hoboken, New Jersey: John Wiley & Sons (2011).

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27 Buchanan, R. Wicked Problems in Design Thinking. *Design Issues* **8**: 5-22 (1992).

28 Paté-Cornell, E. On "Black Swans" and "Perfect Storms": Risk Analysis and Management When Statistics Are Not Enough. *Risk Anal.* **32**: 1823-1833 (2012).

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outcome of a well-ordered, “rational” decision process<sup>29</sup>. A better understanding of the policy making process is needed because, “we are attempting to build systems that are beyond our ability to intellectually manage; increased complexity of all types makes it difficult for designers to consider all the potential systems states or for operators to handle all normal and abnormal situations and disturbances safely and effectively. In fact, complexity can be defined as intellectually unmanageability”<sup>30</sup>. How one understands and communicates what one knows and does not know about complex sociotechnical systems of system problems is also an ethical issue. According to Churchman “whoever attempts to tame a part of a wicked problem, but not the whole, is morally wrong.” “Look, I’ve not tamed the whole problem, just the growl; the beast is still as wicked as ever”<sup>31</sup>.

## ACKNOWLEDGEMENTS

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# Carbon Capture Clustering: the Case for Coordinated Approaches to Address Freshwater Use Concerns

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<http://discovery.ucl.ac.uk/1469386/>

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## ABSTRACT

Carbon capture and storage (CCS) will be a key technology for reducing emissions from fossil-fuelled electricity generation. The UK is developing demonstration plants and UK Government strategy proposes the clustering of CCS facilities, having identified significant cost-savings from shared pipeline infrastructure. However, cooling water use from CCS power plants are almost double those of conventional plants. There are concerns about the volumes of freshwater used and vulnerability to low river flows, particularly in areas identified for CCS clusters. Two innovative approaches may reduce water use in CCS clusters by exploiting synergies with other infrastructures; district heating and municipal wastewater. Our analysis indicates that cooling water reductions from district heating may be feasible in the northwest, but less likely in Yorkshire. We also find that across the UK there are numerous, sufficiently large wastewater treatment plants capable of providing alternative cooling water sources for large power plants. Feasibility of these promising options will be highly contextual, require detailed analysis and may face economic and regulatory barriers. Historically, ad-hoc development of energy infrastructure has struggled to exploit such synergies, but may now be facilitated by the clustering of CCS facilities.

**Keywords:** Water-Energy Nexus, Cooling Water, Carbon Capture and Storage, Combined Heat and Power, Wastewater

## INTRODUCTION

The societal challenge of reducing greenhouse gas (GHG) emissions to mitigate anthropogenic global warming has led to focussed research efforts on technological systems to sequester GHGs from fossil-fuelled electricity generation, known as carbon capture and storage (CCS). Thermoelectric generation (coal, gas, nuclear) currently accounts for 80% of global electricity production<sup>1</sup> and the majority of this capacity is reliant on cooling water for safe and efficient operation. Recent studies across the world have highlighted concerns about the cooling water requirements for

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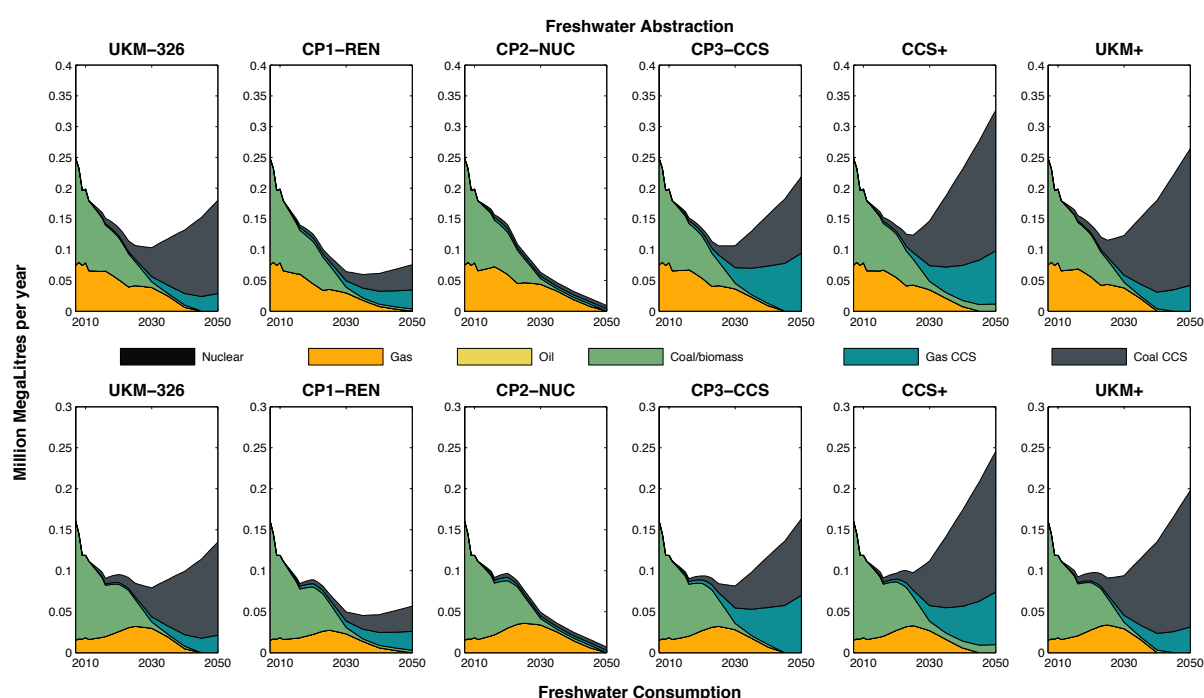
<sup>1</sup> International Energy Agency. IEA Energy Statistics - Electricity for World. (2009). at <[http://www.iea.org/stats/electricitydata.asp?COUNTRY\\_CODE=29](http://www.iea.org/stats/electricitydata.asp?COUNTRY_CODE=29)>

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fossil-fuelled electricity generation with carbon capture and storage.<sup>2,3,4,5,6,7,8</sup>

Whilst only in demonstration phases, carbon capture and storage systems appended to fossil-fuelled generation place parasitic loads on the power plant in order to sequester the carbon before it is emitted to the atmosphere. This results in not only a reduction in production efficiency but also in increased waste heat and hence cooling demands<sup>8,9,10</sup> Three drivers make this a critical issue worth exploring further. Firstly, wide-scale deployment of CCS in global electricity production is integral to achieving the stabilisation of global average temperature increases below 4°C, and particularly at 2°C<sup>6</sup>. Secondly, the impacts of climate change, population growth, urbanisation and rising affluence will likely increase industrial and agricultural demands and also water scarcity in many parts of the world. Thirdly, the increased water-intensity of CCS-enabled electricity production and the clustering of CCS facilities will compound the pressure on localised water resources. In this paper we elaborate on these pressures with a focus on CCS development in the UK and discuss two innovative opportunities to reduce freshwater requirements from CCS generation: the use of combined heat and power to reduce cooling demands and the use of wastewater as an alternative cooling water source.

## FUTURE DEMANDS FOR COOLING WATER FROM CARBON CAPTURE



**Figure 1. Abstraction and consumption of freshwater, split by generation technology for six energy pathways from 2007-2050. (CC-BY) 2**

The study by Byers, Hall and Amezcaga<sup>2</sup> calculated the current and projected cooling water use of six low-carbon

<sup>2</sup> Byers, E. A., Hall, J. W. & Amezcaga, J. M. Electricity generation and cooling water use: UK pathways to 2050. *Glob. Environ. Chang.* 25, 16–30 (2014).

<sup>3</sup> Macknick, J., Sattler, S., Averyt, K., Clemmer, S. & Rogers, J. The water implications of generating electricity: water use across the United States based on different electricity pathways through 2050. *Environ. Res. Lett.* 7, 045803 (2012).

<sup>4</sup> Naughton, M., Darton, R. C. & Fung, F. Could Climate Change Limit Water Availability for Coal-fired Electricity Generation with Carbon Capture and Storage? A UK Case Study. *Energy Environ.* 23, (2012).

<sup>5</sup> Hadian, S. & Madani, K. The Water Demand of Energy: Implications for Sustainable Energy Policy Development. *Sustainability* 5, 4674–4687 (2013).

<sup>6</sup> World Energy Council. *Water for Energy*. (World Energy Council, 2010).

<sup>7</sup> IEA. *Technology Roadmap: Carbon capture and storage*. *Energy Technol. Perspect.* (2013).

<sup>8</sup> International Energy Agency. in *World Energy Outlook 2012* (IEA, 2012).

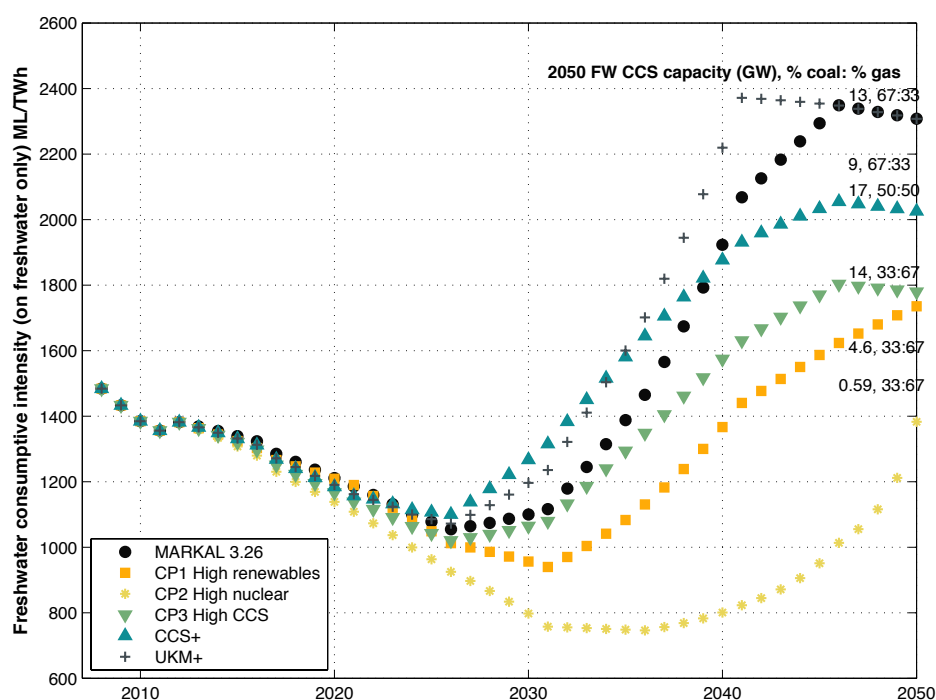
<sup>9</sup> Zhai, H., Rubin, E. S. & Versteeg, P. L. Water use at pulverized coal power plants with postcombustion carbon capture and storage. *Environ. Sci. Technol.* 45, 2479–85 (2011).

<sup>10</sup> Zhai, H. & Rubin, E. S. Performance and cost of wet and dry cooling systems for pulverized coal power plants with and without carbon capture and storage. *Energy Policy* 38, 5653–5660 (2010).

energy pathways from 2010 to 2050 for the UK. Four of the six pathways form the basis of the UK Government's 'Carbon Plan'<sup>11</sup> with the aim of meeting the UK Climate Change Act 2008 targets for an 80% reduction in Greenhouse Gas emissions (on 1990 levels) by 2050.

Of the six pathways, those with high levels of CCS penetration (CP3-CCS, CCS+, UKM+) result in freshwater consumption in 2050 that exceed 2010 levels by 37-107% (Figure 1). The research also reports the rise in consumptive freshwater-use intensity driven by the more water-intensive CCS generation. The trend is towards power stations that are, on average, twice as water-intensive as the current stock (Figure 2). The study also notes that up to 2025, freshwater use actually declines due to the EU Large Combustion Plant Directive and delays in the commercialisation of CCS. This trend only reverses from 2025 onwards as the penetration of CCS increases.

Similar results have been produced<sup>12, 13</sup> using similar energy pathways that built on the work of Byers et al.,<sup>2</sup> by disaggregating the demands on a regional basis. A large majority of elevated freshwater demands occur in regions with significant CCS capacity, namely the northwest, Thames and Yorkshire/Humber and East Midlands areas. This is expected to occur due to the clustering of CCS facilities in order to reduce the costs of pipeline infrastructure, as directed by the Department for Energy and Climate Change (DECC) CCS Roadmap<sup>14</sup>.



**Figure 2. Average freshwater intensity (ML/GWh) of thermoelectric generation decreases due to closure of more inefficient plants under the LCPD, but then rises again with the introduction of CCS capacity from 2025 onwards. Pathways with more coal are more water intensive.**

## BENEFITS AND CONCERNS OF CCS CLUSTERING

The case for the clustering of CCS facilities is driven by a few interconnected issues: the legacy of power generation sites, industry and water availability; proximity to the coast and CO<sub>2</sub> storage sites; and subsequently the economic advantages of clustering infrastructure. Potential clusters in the UK were identified in the government's CCS Roadmap, in Scotland, Yorkshire & Humber, Teesside and near the East Irish Sea (the north west) given that

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12 Tran, M. et al. *National infrastructure assessment: Analysis of options for infrastructure provision in Great Britain*. (Environmental Change Institute, University of Oxford, UK, 2014).

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concentrations of power generation and industry are also close to storage locations offshore<sup>14</sup>. Amongst other recommendations, the CCS Cost Reduction Task Force concludes that the costs of CCS can be reduced through investment in large CO<sub>2</sub> clusters and investment in large shared pipelines<sup>15</sup>. From demonstration to more widescale development, it is estimated that transport and storage costs can be reduced by two-thirds when shared pipelines have high utilisation and clusters are supplying CO<sub>2</sub> to clusters of storage sites. To date the identification of clusters has led to more coordinated work such as for the Thames estuary<sup>16</sup>, the Don Valley<sup>17</sup> and the Tees Valley<sup>18</sup> projects.

The size of these clusters is important in determining what potential impacts may arise. The E.ON Thames estuary cluster study identified 10 major power generation sites with total annual emissions potential of 27.9 MtCO<sub>2</sub>/yr, whilst 67% of the northeast's emissions could be captured from just 6 sites in the Tees valley. When evaluating the available water resources, the Environment Agency will need to consider carefully the aforementioned increased water-use intensity of CCS facilities, dependent on the proportion of emissions captured from the site. In the first stages of CCS development only 25-50% of emissions will be captured. However, this proportion will increase in the future, for both new and existing facilities. Hence, power plant operators may come across difficulties in obtaining further abstraction licences when seeking to expand the CCS facilities at a plant.

## INNOVATIONS FOR REDUCING THE WATER INTENSITY OF CCS CLUSTERS

### Combined heat and power to reduce cooling demands

Further use of combined heat and power (CHP) may be well suited to CCS clusters. CHP is the process of removing the waste heat from power generation and providing it for use by another user, usually domestic or industrial. The clustering of CHP plants with CCS facilities presents technical challenges such as the availability of space, but also synergistic opportunities. Industrial facilities can make use of waste heat, otherwise heat can be transported for district heating, with the costs shared amongst power stations. Such implementation however would require significant strategic direction and inclusion at the beginning of the design cycle. Uptake of district heating in the UK to date has been low compared to other parts of Europe, contributing less than 2% of heat demand. With the right conditions, including government incentives, it is thought this could contribute up to 14%<sup>19 18</sup>. Subsequently, DECC have developed a “national heat map for England” which shows the intensity of heating demand across the country<sup>20, 21</sup>. Inspection indicates that the use of CHP on CCS could be economical in the northwest, but less likely in the Yorkshire, Humber, east Midlands and north east areas (Figure 2).

The seasonal variation of heat demand (unless industrial) complicates economic implementation of CHP in the UK. Nonetheless it is not hard to imagine that a well designed industrial ecosystem could turn the threat of localised high-intensity water demands into a reliable source of heat that shares infrastructure costs not just for CO<sub>2</sub> pipelines but also heat transport.

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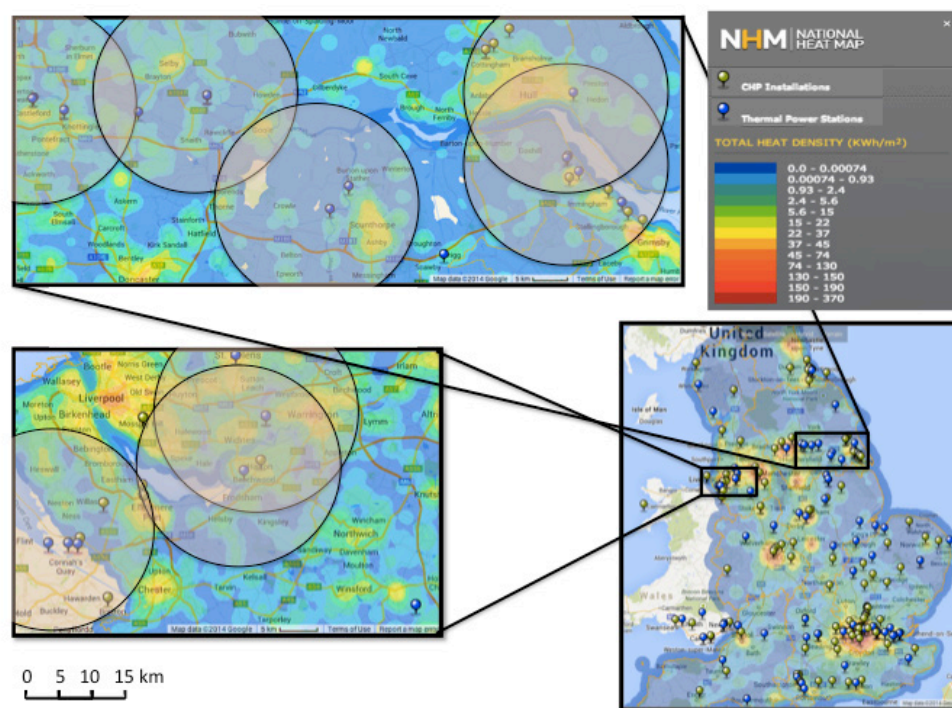
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**Figure 2. Screenshots of the National Heat Map from DECC<sup>19</sup>. Blue markers indicate current power stations, green markers are current CHP schemes. The heat demand intensity is indicated by the shaded colours. Shaded circles indicate radii of 15km from power stations from which heat could be economically transported.**

### Wastewater as an alternative cooling water source

The second opportunity is the use of treated wastewater as a cooling water source in closed loop wet cooling towers. As of 2007, over 50 power plants in the U.S. used wastewater, mostly for cooling but also boiler feed water in some cases<sup>21</sup>. There is a growing body of technical research in this area coming from the U.S. that has been pilot and field-tested<sup>22,23,24,25,26,27,28,29</sup>. Municipal wastewater is even used for cooling at the Palo Verde nuclear power plant, the largest in the U.S., providing a reliable cooling water source in Arizona whilst increasing revenue for the local water company<sup>30</sup>. In the UK, both the 363 MW coal (soon to be mothballed) and 834 MW CCGT Uskmouth power stations also pioneer the use of treated wastewater for their boiler feed water, but not for cooling<sup>31</sup>.

Further challenges of using wastewater include contaminants and nutrients in the water, condenser tube fouling,

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28 Walker, M. E. et al. *Utilization of municipal wastewater for cooling in thermoelectric power plants: Evaluation of the combined cost of makeup water treatment and increased condenser fouling*. *Energy* **60**, 139–147 (2013).

29 Ciferno, J., Aljoe, W. W. & Dzombak, D. A. *Tertiary Treatment Versus Expanded Chemical Regimen for Recirculating Water Quality Management*. *Use Treat. Munic. Wastewater as Power Plant Cool. Syst. Makeup Water* (National Energy Technology Laboratory, USDOE, 2009).

30 Rodriguez, D. J., Delgado, A., Delaquil, P. & Sohns, A. *Thirsty Energy*. *Water Pap.* (World Bank, 2013).

31 Power Engineering. *Siemens hands over 834 MW Uskmouth CCGT in UK to DONG Energy*. *Power Eng.* (2010).

increased risk of Legionnaire's disease, proximity to wastewater sources and increasing competition for sources of treated wastewater<sup>27</sup>. In some UK rivers, wastewater makes up a considerable proportion of the river flows and maintains the environmental integrity. Reducing municipal wastewater returns could also increase the occurrence of low flows. Conversely this may be welcomed by wastewater treatment companies who are finding it increasingly difficult to meet effluent quality regulations in low flows due to lack of dilution. A further non-technical barrier could be Ofwat, the economic regulator for the water sector, who have prevented investment in areas outside the core business, such as renewables electricity generation<sup>32 32</sup>.

Successful integration between wastewater and electricity production will be highly contextual and location specific. Given the right incentives, wastewater for cooling presents an innovative opportunity for the UK's wastewater system, which in some places is over 100 years old. We estimate that a sewage treatment works capable of serving one million people at full capacity is of sufficient size to provide a reliable cooling water flow of approximately 1 m<sup>3</sup>/s assuming that 60% of the supply volume is discharged. This would be sufficient for large power stations operating at full load: an 800 MW<sub>e</sub> coal+CCS plant, or almost a 2,000 MW<sub>e</sub> gas CCGT+CCS plant, if using closed loop wet tower cooling. For current capacity without CCS, the potential would be a further 90% higher. There are approximately 25 wastewater treatment plants with this capacity of 1 million people, a further 90 that can serve 300,000 people, and even four plants with capacity in the order of 3-4 million people. More detailed studies evaluating technological, geographic economic and regulatory feasibility, as has been done in the U.S.,<sup>25,33</sup> are highly recommended for the UK.

## CONCLUSIONS

Current policy, technologic, economic and geographic circumstances suggest that the clustering of CCS-enabled power stations is likely to occur in the UK. The increased water-use intensity of CCS technology coupled with this clustering also presents concerns for both the water and energy security of the UK. High cooling water demands from the sector will be more vulnerable, and may possibly contribute, to localised water scarcity which can be expected to increase with both population growth and climate change.

The two suggestions of using combined heat and power to utilise waste heat and using wastewater as a cooling water source are both technically feasible and already implemented in a variety of contexts across the world. The barriers to their implementation in the UK lie within wider constraints of economic viability and the need for better integration of power stations within their wider environments. Both opportunities would require early involvement at the design stage and probably public-private partnerships for local integration. The nature of CCS infrastructure development in clusters also requires similar planning and implementation, thus consideration of the potential to use CHP or wastewater is recommended.

Preliminary analysis suggests that the potential feasibility of CHP systems is greater in the northwest than the Humber/East Midlands regions, due to higher concentration of heating demands and closer proximity of the power stations. This is likely to also be the case for wastewater availability. However, industrial developments in the Humber area may provide concentrated demands and sources of heat and wastewater, respectively. If clustered CCS developments occur in these two areas, as is expected, sharp increases in the demands for cooling water will occur. Greater use of CHP and wastewater for cooling has the potential to reduce the pressures on freshwater resources, and thus the feasibility of these opportunities should be investigated in detail, at the earliest stage possible.

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# A New Model for Evaluating the Future Options of Integrating Ground Source Heat Pumps in Building Construction

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<http://discovery.ucl.ac.uk/1469387/>

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## ABSTRACT

Decision-making for effective infrastructure integration is challenging because the performances of long-lasting objects often depends on conditions which are either outside the control of the designer or difficult to foresee at the design stage. In this paper we examine a new approach to estimating the range of cost-effective solutions for integrating the construction/retrofit of two or more different types of infrastructure. Infrastructure integration has many perceived benefits, but also faces serious new challenges and doubts from practitioners, particularly in sectors with complex construction process, long asset lives, uncertain cost parameters, and slow and unwieldy decision-making, such as is common with civil engineering works. We test all main options in integrating a ground source heat pump (GSHP) system with the construction and retrofit of an archetypal, office building. A new simulation model is developed and parameterized using actual data in the UK. We incorporate unavoidable uncertainties and randomness in how the decisions are triggered, and test the effectiveness of proactive measures to embed future options. The model highlights how sensitive the range of cost-effective solutions is to the setting of renewable energy incentives, discount rates, technical performance and life-cycle asset management of interdependent infrastructure. This points to a clear need for establishing appropriate regulatory standards. We expect this model to find increasing applications in the planning and designing of integrated complexes of buildings, transport facilities, renewable energy supply, water supply and waste management in dense urban areas, which are an increasingly key part of sustainable urban development.

**Keywords:** Flexible Design, Options Imbedded Design, Infrastructure Integration, Resilience, GSHP, LCC, Monte Carlo Simulations

## INTRODUCTION

In this paper we develop and test a new, generic modeling approach for a realistic assessment of the costs and benefits of integrating the construction/retrofit of two or more different types of infrastructure. Infrastructure integration have attracted increasing attention across different sectors ranging from building works, energy, transport, water, waste to ICT, for potentially large benefits in cutting costs, reducing key resource consumption, improving service quality and achieving wider societal benefits. However, integrative planning and design also face serious challenges that arise from hitherto unfamiliar conflicts in scheduling investment and coordinating construction and operations. Furthermore, infrastructure investors and designers (either public or private) often have reasons to doubt whether infrastructure integration would bring real, net benefits, particularly in sectors where construction process is already highly complex, expected service life long, costs uncertain and the decision-making process often slow and unwieldy, such as is common with civil engineering works.

We develop the new model with the above challenges in mind. In particular we aim to make a new extension to

the future options approach such as put forward by Ellingham and Fawcett (2006)<sup>1</sup> and de Neufville and Scholtes (2011)<sup>2</sup>. The model aims to assess in a realistic and robust way the costs and benefits of embedding construction and retrofit options to enable the integration of different types of infrastructure. The model is designed in particular to address the challenges arising from construction process conflicts, long expected life cycles and significant uncertainties in costs and decision-making processes. We expect this model to find increasing use in the planning and designing of integrated complexes of buildings, transport facilities, renewable energy supply, water supply and waste management, such as necessary in dense urban areas and large building complexes.

## INTRODUCTION TO MODEL APPLICATION

A new simulation model is developed and parameterized using actual data in the UK to test realistic combinations of energy prices, engineering and building system performance and decision-making processes. We incorporate unavoidable uncertainties and randomness in how the decisions are triggered, and test the effectiveness of proactive measures to embed future options in engineering and building design. The model provides a systematic assessment of the key dimensions to decision making. It highlights how sensitive the range of cost-effective solutions is to the setting of renewable energy incentives, cash flow discount rates, the technical performance of GSHP systems and a proper life-cycle asset management of interdependent infrastructure. The conclusions point to a clear need for establishing smart standards in engineering, planning and governance for exploiting the technical potential of the GSHP systems and achieving robust financial and energy savings.

GSHP is among the most important options under consideration in decarbonising building energy use, especially in urban areas (DECC 2012)<sup>3</sup>. In dense urban areas of the UK where recent population and employment growth has been significant, incorporating GSHP has proved to be a major challenge. After some unsuccessful pilot projects to install and operate GSHP systems in high profile office buildings, there is a widely held belief that GSHP systems are not cost effective, particularly given the uncertainties in future energy prices. Few businesses have the intention currently to implement GSHP, except in a very small number of flagship green building projects. Nevertheless, a large number of businesses and developers are concerned with the likely rise in future energy prices as well as CO<sub>2</sub> emissions, and wish to incorporate more sustainable energy solutions so long as there is a robust financial justification of their investments.

Given the high levels of uncertainties over energy prices, GSHP system performance and financial constraints, decision making for long-lasting investments such as the GSHP systems is challenging. Indeed, the decision to install and operate GSHP systems is subject to uncertainties across many factors. Furthermore, the long-term nature of the investment makes it necessary to consider how the designs and installations can adapt to different future circumstances.

The model application aims therefore to establish a generic approach for assessing the integration, taking appropriate account of the exogenous trends and the partial and fragmented nature of their projections. In other words, it aims to define how much flexibility there should be to bring justifiable financial returns on investment in light of the uncertainty of the future circumstances and the cost of creating and exercising the options.

## CORE PROBLEM AND TEST SCENARIOS

The core problem of integrating a GSHP system with an office building can be translated into a modeling process where the decision-maker faces uncertainties of a number of exogenous conditions. Scenarios that represent different future option designs and levels of flexibility (Figure 1) are then tested to evaluate the profile of financial costs and benefits. The three principal test scenarios are:

Scenario 1 – ‘All Initial’: All the GSHP system is included when constructing the office building. This consists of a total investment of the GSHP system at £1,760,000 (£1,200,000 for 203 boreholes and bars, and £560,000 for the heat pump equipment). 127 bars costing £750,000 are placed in the gardens and 76 bars costing £450,000 are placed under the foundation of the building. Because the underground works take place prior to the foundation of the

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3 DECC (2012), Fossil fuel Price projection, Department of Energy and Climate Change London


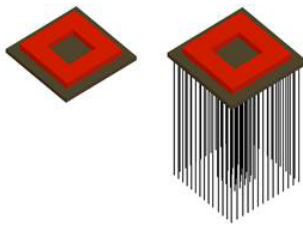
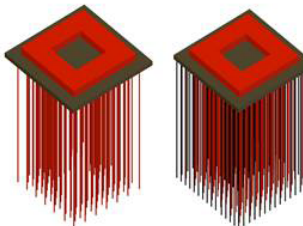
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office building, it incurs the lowest unit cost to make the boreholes and install the bars. It is also possible to put in a maximum number of boreholes on the site at a low cost. The GSHP will supply cooling, heating and hot water loads in the building.

Scenario 2 – ‘No Initial’: No GSHP is included when constructing the office building. The grounds that are not covered by the building’s foundation can potentially allow 77 bars to be put in at a later date, at a cost of £454,800 (in today’s prices, ditto below); if this option is taken up at a later date, a smaller heat pump (£215,000) will be required. This gives a total cost of £669,800 and will supply 38% of the total building energy load. Any loads that are not covered by the GSHP system are supplied by the conventional systems, i.e. the most efficient boiler and the most efficient electrical air conditioning system as currently available.

Scenario 3 – ‘Flex Initial’: A smaller initial investment is made to put in 122 bars at £721,200 under the building’s foundation. If at a future date the GSHP option is taken up, a further 81 bars may be put in (at £478,800) in the exposed grounds; the equipment will cost £560,000. Before GSHP, building energy will be supplied by conventional systems, same as with ‘No Initial’.

1 All Initial	2. No Initial	3. Flex Initial
Initial (and fixed)	Initial ➡ After trigger	Initial ➡ After trigger
		
Initial: 203 bars + HPs £1,760,000	Initial: 0 bars ➡ After trigger: £0,00 +77 bars + HPs £ 669,800	Initial: 122 bars ➡ After trigger: £721,200 +81 bars + HPs £ 1,038,800

**Figure 1 – Principal test scenarios**

The model incorporates the uncertain exogenous conditions through Monte Carlo simulations, each over an expected building structure life-time of 50 years.

A dynamic system is used to evaluate annually the conditions for triggering the embedded options (scenarios 2 and 3) through the following four steps:

1 - Define probability distribution (PD) for each exogenous variable, i.e. gas and electricity prices, heating and cooling loads and the GSHP system’s coefficient of performance (COP). The probability distribution of gas and electricity prices comes from the National Grid (2011)<sup>4</sup> projections; the PD on heating and cooling loads are derived from estimates from GIEnergy<sup>5</sup> and ASHRAE<sup>6</sup>; the COP was given according to London’s soil characteristics in London (mean value: 2.95), based on current research at Department of Engineering, Cambridge University.

2 – Define the trigger conditions for investors under Scenarios 2 and 3. The basic trigger is the overall financial saving which is defined as the difference between the savings on energy expenditure through using the GSHP (relative to using conventional systems) and the capital cost of the GSHP infrastructure and equipment. Any renewable energy subsidies may be included or excluded. If the saving is positive, the decision is triggered. The savings can be defined in terms of myopic evaluation (ME) - i.e. current year savings greater than annualised capital cost -, or in net present value evaluation (PVE) - i.e. comparing the savings and capital cost over 30 years in net present value (NPV); our main tests are based on the latter, NPV approach. In addition, we have tested alternative decision/implementation time-lag profiles in exercising flexible options (see Step 4 below).

3 - Monte Carlo simulation, which is to incorporate the probability distributions of exogenous variables and test the

4 National Grid (2011). UK Future Energy Scenarios: UK gas and electricity transmission, November 2011

5 GI Energy. Source: <http://www.gienery.net/> . Last access: March, 2014

6 ASHRAE (American Society Heating, Refrigerating and Air-conditioning Engineering). Source: <https://www.ashrae.org/> . Last access: March, 2014

triggers dynamically over a period of 50 years which is our assumption of the working life of the office complex. Each test is performed 1,000 times, which according to our tests (from 500-10,000 runs) can adequately reveal the uncertainty profiles. The tests output a range of indicators that help decision-makers map cost-effective solutions.

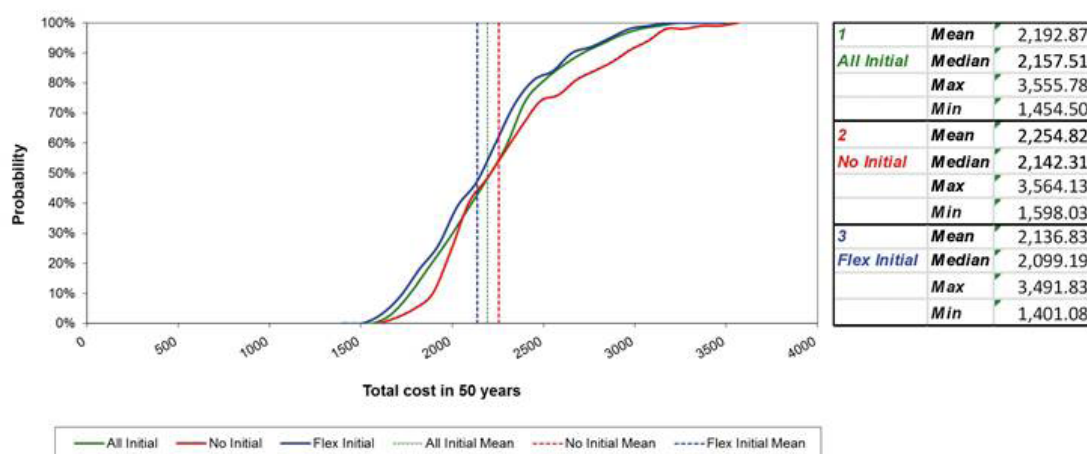
4 - Sensitivity analyses. By changing the above mentioned test variables one at the time, a number of sub-scenarios have been tested. This includes excluding the Renewable Heating Incentives (RHI), varying the discount rate from 6% down to 3% and up to 12%, varying the energy prices, lowering the COP to account for inappropriate uses over time, and alternative decision/implementation time-lag profiles in exercising flexible options that is typical in business decision making processes. The tests represent a comprehensive range for identifying the roles played by each of the exogenous variables, the current cost-effective envelope for GSHP solutions, and possible measures to expand this envelope.

## TEST RESULTS SO FAR

The model tests are still on-going, but they have proven that the GSHP-office building example is an effective case in testing our new approach. Results so far indicate that the cost ranking of the three principal scenarios is very sensitive indeed to the level of discount rates, the fluctuation of technical performance of the GSHP within the realistic range for London, the level of the Renewable Heat Incentive, and the timeliness of the decision-making process for GSHP installation/operation. Flex Initial (Scenario 3) has the promise of becoming the most cost-effective design under a remarkably wide range of circumstances relative to what has hitherto been considered. The cost-effective envelope of the flexible approach can be significantly expanded if the decision making processes and construction technology further improves. However, there are circumstances where either All Initial (Scenario 1) or No Initial (Scenario 2) ranks the most cost effective.

Under the 'central' projection of the exogenous variables, the mean total cost for building energy supply under Flex Initial is £2,136,830 in NPV, against £2,192,870 under All Initial and 2,254,820 under No Initial (Figure 2). The significant saving under Flex Initial is achieved through allowing investment in renewable energy to proceed when it is needed and not before. A substantial savings can be made whilst enabling construction to proceed as per demand for the office building.

The value of the flexible solution emerging from the results is due to the fact that, according to the probability distributions for uncertain elements, investing in the GSHP system is often expected to be more cost effective with embedded options than an option-free solution, if (1) gas and electricity prices continue to rise , (2) the Renewable Heat Incentive (RHI) is in place, and (3) the technical performance of the GSHP is good (its COP=2.95 on average). Under the same circumstances doing nothing (i.e. under No Initial) is likely to cost more money, as well as consuming more gas and electricity.



**Figure 2 – Probability distribution of GSHP costs over a 50-year office building lifespan (1,000 Monte Carlo simulations) (NPV in £1,000 & 2018 prices)**

Simulations under all two trigger strategies show that results do not change substantially in using either myopic evaluation (ME) or present value evaluation (PVE) (Table 1).

**Table 1 - Total net costs for building energy under myopic evaluation (ME) and present value evaluation (PVE) triggers (Results**

from 1,000 simulations, all values in Nin £1,000 & 2018 prices)

			Design Scenarios		
			All Initial	No Initial	Flex Initial
Trigger strategy	ME	Mean	2,200.39	2,379.67	2,143.39
		Median	2,157.24	2,258.00	2,094.96
		Max	3,634.15	3,725.11	3,577.68
		Min	1,509.22	1,662.21	1,455.75
	PVE	Mean	2,192.87	2,254.82	2,136.83
		Median	2,157.51	2,142.31	2,099.19
		Max	3,555.78	3,564.13	3,491.83
		Min	1,454.50	1,598.03	1,401.08

Five sets of sensitivity analyses (as listed in Step 4) have been conducted. We summarise here the results under the PVE trigger, although in most cases the ME trigger gives very similar results. First, if the discount rate for net present value is lowered from 6% to 3%, the cost ranking of the scenarios does not change but the difference between All Initial and Flex Initial will narrow. However, if the discount rate is raised to 12%, No Initial becomes the lowest cost solution. Secondly, if the mean coefficient of performance (COP) of the GSHP system is lowered from 2.95 to 2.22, which is at the low end for systems in the London region, the GSHP system will no longer be cost effective- in such cases No Initial ranks the cheapest. Thirdly, the current level of RHIs appears to have been set at the right level to make the use of GSHPs financially competitive – removing the RHIs will largely undermine the financial case for the use of GSHPs. Finally, even under favourable conditions to the GSHP, if the senior business managers delay exercising of the GSHP option when the financial triggers have been reached, the Flex Initial scenario can also become a less competitive scenario. In such conditions All Initial will emerge as a relatively cheap solution.

## CONCLUSIONS SO FAR

The study shows that it is feasible to establish a future-option based model for testing in a realistic and robust way integrative designs of different types of infrastructure in terms of medium to long term costs and benefits such as typical in building and infrastructure construction. In particular, in our main case study, we have examined the integration of a GSHP system with an archetypal office building in dense urban areas, which is currently perceived to be a risky and unappealing investment in financial terms. Whether a significant net benefit can be achieved depends critically on a number of future external conditions that are difficult to predict in the decision-making process without a proper analytical tool. Our model has started to provide such a tool in managing those risks by taking account of the significant uncertainties and assessing different designs including those incorporating embedded future options. This accounts for both the benefits and costs of flexibility.

The new method presented in this paper has shown to be an effective way to assess the integrated infrastructure design, out of a set of possibilities. This will help minimise the risk of inefficient investment through adoption of flexible strategies. Indeed the results indicate that the flexible approach can be the most cost effective – particularly if there is proper governance in the decision-making process - because it can take advantage both from the use of a well performing GSHP system and from the financial savings due to the option of triggering the investment at the right time and not before.

The model is designed in particular to address the challenges arising from construction process conflicts, long expected life cycles and significant uncertainties in costs and decision-making processes. In future work we will extend the model for applications in the planning and designing of integrated complexes of buildings, transport facilities, renewable energy supply, water supply and waste management, such as found in dense urban areas. Indeed, similar to incorporating a GSHP system into a new building, other kind of infrastructures integration - such as configurations of building and transport facilities – also largely depends on the future configuration of the pertinent exogenous conditions (i.e: population, availability of public transport investment, fuel prices, etc). Typically, at the outset of planning and designing infrastructure facilities, comparatively little is known on the future configuration of the exogenous conditions such as operating costs and levels of use over their long design. The modeling approach proposed here contributes to the foundation of a more appropriate approach to planning, designing and assessing investment strategies in such circumstances.



# Towards a Co-Evolutionary Model of Demographics and Infrastructure

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<http://discovery.ucl.ac.uk/1469388/>

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## ABSTRACT

National infrastructure systems provide a foundation for economic prosperity and well-being. In addition to factors such as technological change and obsolescence, infrastructure systems need to respond to changing levels of demand, which is strongly driven by population growth. However demographic change is not independent of economic conditions, or the nature and quality of infrastructure. This research is concerned with the interrelationships between demographics, economy and infrastructure.

The paper therefore develops a novel approach to modelling the evolution of a national economy in the context of changing demographics and infrastructure provision. This approach is based in a model with coupled sub-systems which are spatially disaggregate with explicit temporal dynamics. A version of the model is calibrated using a demographic component which incorporates both natural change and migration, and an economic model which recognises both labour and capital as factors of production. Infrastructure is present as an influence on accessibility, geographical attractiveness and economic productivity.

The performance of the model is explored through a variety of scenarios which are offered as an initial proof of concept of the feasibility of implementing a co-evolutionary model of demographic and economic growth over a medium to long time horizon. These scenarios indicate the influence of government policies for international migration and infrastructure investment on regional development and performance.

**Keywords:** Demographics, Economy, Infrastructure

## INTRODUCTION

This paper reports investigations into the feedback and linkages between demographic change and infrastructure provision which are being undertaken by the Infrastructure Transitions Research Consortium (ITRC). National infrastructure systems (NIS) provide a foundation for economic productivity and human wellbeing. They shape many of the interactions between human civilisation and the natural environment<sup>1</sup>. However, the NIS for Great Britain faces considerable challenges in the future to serve a globalised economy and to meet the government's commitment on reduction in greenhouse gas emission<sup>2</sup>. Infrastructure UK (IUK), with support from organisations such as the ITRC, are amongst many groups on the international stage who are tasked with addressing such problems.

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1 Hall, J.W., Henriques, J.J., Hickford, A.J. & Nicholls, R.J. (2012, eds). A Fast Track Analysis of strategies for infrastructure provision in Great Britain: Executive Summary. Environmental Change Institute, University of Oxford.

2 Tran, M. et al (2014). National infrastructure assessment: Analysis of options for infrastructure provision in Great Britain, Interim results. Environmental Change Institute, University of Oxford.

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The population of the UK is currently growing rapidly under the influence of both international migration and natural change. This growth has been spatially uneven, which has important implications for infrastructure provision. ITRC has therefore laid down a series of spatially explicit demographic scenarios as a driver of future infrastructure requirements<sup>3</sup>.

In the ITRC programme to date the reverse coupling of demographics to infrastructure has been articulated less explicitly. Interregional migration flows are typically viewed as business as usual, in common with core national projections. However the dependence of future demographic change on infrastructure is obvious – thus a new high speed link between London and Birmingham would change relative accessibilities, which are the key driver of migration and commuting flows between these regions. Infrastructure can also influence population change indirectly through economic growth – for example, the construction of a new desalination plant in East Anglia (say) would create new jobs, tending to encourage the inflow of migrant workers. In short, “population growth leads to increased demand for infrastructure services, but better infrastructure services also attract population to a region”<sup>4</sup>.

This paper therefore seeks to explore the dynamic co-evolution of demographics, the economy and infrastructure, as series of coupled subsystems. Models of this type have been suggested in the past for abstract multi-agent systems<sup>5</sup>, and co-evolutionary models have been explored to some extent in the context of both ecological systems<sup>6</sup> and economic markets<sup>7</sup>. None of these models includes either infrastructure or a spatially explicit representation of a real demographic system. Of course linkages between population (or at least ‘demand’) and economic sectors, including infrastructure, are a feature of well-established input-output models, but although substantial work has been invested in the regional disaggregation of such models<sup>8</sup> these approaches in turn lack an evolutionary perspective. The approach to be adopted here is therefore unique in exploring the co-dependence of demographics and infrastructure within a spatially explicit modelling framework.

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3 Zuo, C., Birkin, M., Malleson, N. (2014) Dynamic Microsimulation Modelling for National Infrastructure Demand in an Uncertain Future, *GeoSpatial Information Science*, forthcoming.

4 Beaven, R., Birkin, M., Crawford Brown, D., Kelly, S., Thoung, C., Tyler, P., Zuo, C. (2014) Future Demand for Infrastructure Services, in Tran, M. et al (eds) *Planning Infrastructure for the 21st Century*, Cambridge University Press (forthcoming).

5 Epstein, J., Axtell, R. (1996) *Growing Artificial Societies*, Brookings Institution.

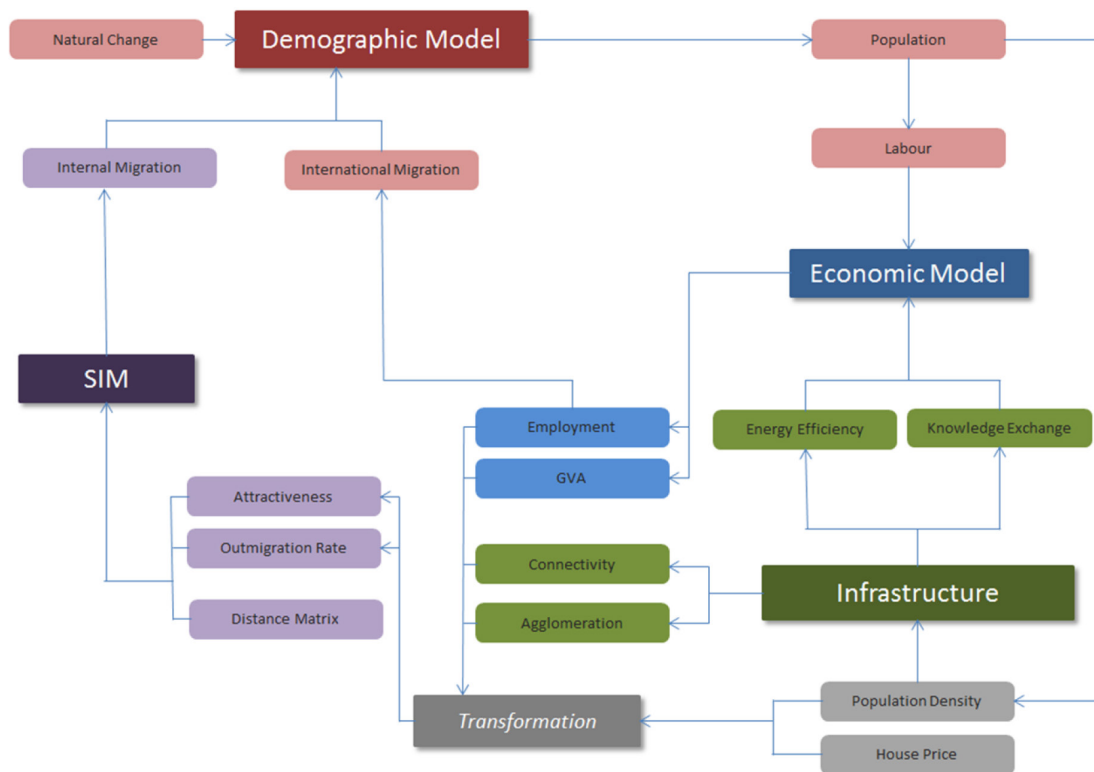
6 Dove, M. (1993) The coevolution of population and environment: The ecology and ideology of feedback relations in Pakistan, *Population and Environment*, 15, 89-111.

7 Boucekkin, R., de la Croix, D., Licandro, O. (2002) Vintage Human Capital, Demographic Trends, and Endogenous Growth, *Journal of Economic Theory*, 104, 340-375.

8 Miller, R., Blair, P. (2009) *Input-output analysis: foundations and extensions*, Cambridge University Press.

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The structure of the model in its current form is illustrated in Figure 1. The link from population to the economy is indicated through the flow of labour as a factor of production, while the reverse link is effected through a combination of spatial processes which underpin population movements. The role of infrastructure is articulated as of particular importance in view of the substantive focus of this work.



**Figure 1 Structure of the modelling framework**

$$Pop_{LAD}^Y = Pop_{LAD}^{Y-1} + NC_{LAD}^Y + {}^0IM_{LAD}^Y + {}^1IM_{LAD}^Y - {}^0OM_{LAD}^Y - {}^1OM_{LAD}^Y \quad (1)$$

For a given level of outmigration, a production-constrained spatial interaction model can be introduced to generate inter-regional migration flows:

$$T_{ij} = A_i * OM_i * Att_j * f(d_{ij}), \quad A_i = \frac{1}{\sum_j Att_j * f(d_{ij})} \quad (2)$$

where  $T_{ij}$  represents the migration flow from region (i) to region (j),  $Att_j$  is attractiveness of region (j) and  $d_{ij}$  is a measure of the distance or trip cost between region pairs.  $A_i$  is a balancing factor which ensures that the flows from each region are constrained to the overall level of outmigration.

There are two sets of parameters which need to be calibrated. Typically the distance function is articulated as a negative exponential  $f(d_{ij}) = \exp(-d_{ij})$  when  $\beta$  is a parameter related to the efficiency of the transport system; and attractiveness ( $Att_j$ ) is a synthetic variable which indicates the potential to attract migration into a region (j). These parameters can be calibrated based on historical migration data, which is generated from patient registration data in the National Health Service<sup>9</sup>.

In order to integrate the migration model (SIM) into the demographic model, it is important to understand the variation of attractiveness and out-migration rates, as these two variables are the key inputs of the SIM. Two simple linear models were built to predict these two variables based on a series of socio-economic variables<sup>10</sup>, including Population Density (PD), Total Employment (Emp), Average House Price (HP), Gross Value Added (GVA), Unemployment (Unemp), Average Road Speed (AS) and Total Population (Pop). A stepwise multivariate regression technique was applied to identify the most appropriate predictive variables.

According to the modelling results, the attractiveness of each Local Authority District (LAD) for a given year (Y) can be represented by Population Density, GVA, Average House Price, Total Employment and Average Road Speed of previous year (Y-1), denoted as:

$$Att_{LAD}^Y = K_1 PD_{LAD}^{Y-1} + K_2 GVA_{LAD}^{Y-1} + K_3 HP_{LAD}^{Y-1} + K_4 Emp_{LAD}^{Y-1} + K_5 AS_{LAD}^{Y-1} + e_{LAD} \quad (3)$$

The out-migration rate (OMR) can be written as a function of Average House Price, Population Density, Total Population, Total Employment, and GVA so the model can be written as:

$$OMR_{LAD}^Y = M_1 HP_{LAD}^{Y-1} + M_2 PD_{LAD}^{Y-1} + M_3 Pop_{LAD}^{Y-1} + M_4 Emp_{LAD}^{Y-1} + M_5 GVA_{LAD}^{Y-1} + e'_{LAD} \quad (4)$$

In equations (3) and (4)  $k_1 - k_5$  represent linear weights for the regression model for attractiveness;  $m_1 - m_5$  represent equivalent weights for the migration model;  $\{e_{LAD}\}$  and  $\{e'_{LAD}\}$  are vectors of errors for each Local Authority District. According to these equations, GVA and Employment are needed to estimate the local out migration rate and attractiveness. These two figures can be obtained from the economic model. In this study, Cobb-Douglas production function is chosen as the heart of the economic model. This can be written as:

$$Y = A * L^k * C^{1-k} \quad (5)$$

where Y is total production (the real value of all goods produced in a year); L is labour input (the total number of person-hours worked in a year); C is capital input (the real value of all machinery, equipment, and buildings), A is total factor productivity (TFP) which accounts for effects in total output caused by many other factors other than labour and capital, including technical innovation, organizational and institutional changes, education level etc.<sup>11</sup>; and k is the output elasticity of labour. The k value is approximately equal to the labour's share  $(W*L / (W*L+C))$ <sup>12</sup>, which gives an approximation  $k = 0.64$ .

9 Lomax, N., Stillwell, J., Norman, P. and Rees, P. (2014) Internal migration in the United Kingdom: analysis of an estimated inter-district time series, 2001-2011. *Applied Spatial Analysis and Policy*. Vol.7, pp25-45

10 Rees, P., Fotheringham, S., Champion, T. (2004) *Modelling Migration for Policy Analysis*, in Stillwell, J., and Clarke, G. (eds.) *Applied GIS and Spatial Analysis*, Wiley, Chichester

11 Hulten, C., Dean, E., Harper, M. (2001). *New Developments in Productivity Analysis*, University of Chicago Press. pp. 1-54.

12 Douglas, P., (1976), The Cobb-Douglas Production Function Once Again: Its History, Its Testing, and Some New Empirical Values, *Journal of Political Economy*, 84(5), pp.903-916



Assuming the investment on capital and labour are all from the earning (e.g. total production) of the previous year, we have:

$$Y_{Nation}^{year-1} = \sum C_{NUTS2}^{year} + \sum L_{NUTS2}^{year} * W_{NUTS2}^{year} \quad (6)$$

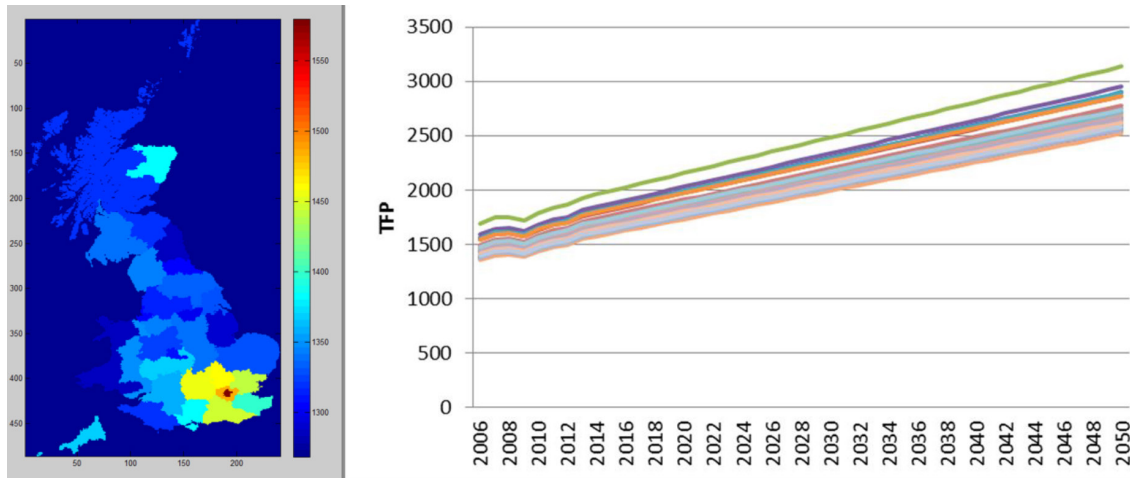
where represents the average annual wage for a labour during a given year in a NUTS2 region. Therefore, when wages and capital are fixed, the optimised employment can be estimated.

Total factor productivity for the whole country, and for individual regions, is calculated based on the GVA, employment and average wage obtained from the ONS official labour market statistics. Table 1 shows the relevant input data and TFP for the first 10 years (2001-2010).

Year	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Wage (£K)	20.3	21.4	21.6	21.9	22.8	24.3	25.5	26.8	28.4	27.4
Employment (million)	27.7	27.9	28.2	28.5	28.8	29.0	29.2	29.4	29.0	29.0
GDP (trillion £)	0.92	0.96	1.02	1.08	1.14	1.20	1.27	1.31	1.28	1.33
Capital (trillion £)	N/A	0.32	0.35	0.40	0.42	0.43	0.45	0.48	0.49	0.48
Labour's Share	N/A	0.65	0.63	0.61	0.61	0.62	0.62	0.62	0.637	0.62
TFP	N/A	1308.	1335.	1339.	1376.	1429.	1481.	1491.	1466.	1524.

**Table 1. The economic data and estimated TFPs for the whole country**

Then, the projected local TFP for each NUTS2 region is calculated on the basis of a series of assumptions: (1) TFP grows linearly; (2) the relationship between TFP and average wage stays constant; (3) the proportion of investment of each region remains at the 2006 level; (4) the saving rates for each region remains at the 2006 level; and (5) the growth rate of TFP remains as the first 7 years (2001-2007).



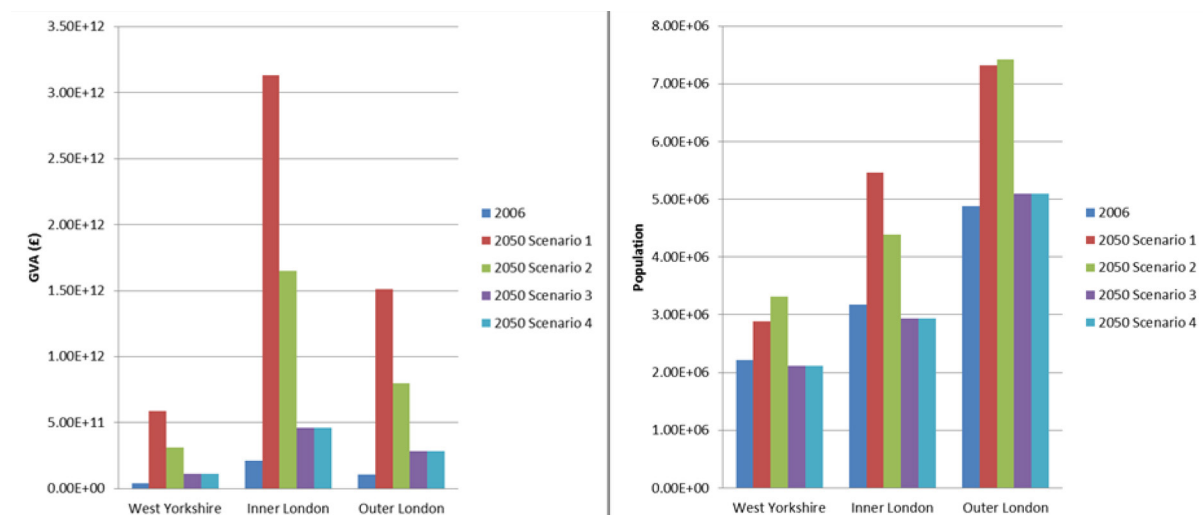
**Figure 2 Calibrated TFP by NUTS2 regions (2004) and b) Projected TFP for 2003-2100 by NUTS2 region**

The operation of the model can now be summarised as follows. The primary objective is to project changes in population and Gross Value Added for each region under a variety of policy scenarios. Let us suppose for the sake of illustration that laissez faire policies are adopted without restraint on migration, (and furthermore that infrastructure is able to adapt swiftly and smoothly to increased demand. For a given base year, the population, wage rate, TFP and capital employed are all known. Now assuming demographic growth then productivity in the following year will increase with greater availability of labour (from equation (5)). However population growth also affects regional attractiveness and migration rates in (1)-(4), which are also influenced by productivity and employment rates. Hence the dynamics of economic performance and demographic change are interdependent and co-evolutionary.

## RESULTS AND DISCUSSION

The relationships between economic growth, demographic change and infrastructure have so far been tested by applying four different policy scenarios. In the first scenario, it is assumed that infrastructure and migration policy can meet the requirements of any growth in population or economy. The second scenario assumes that the investment on infrastructure is just enough to maintain its existing function and standard, but that each region has a ‘carrying capacity’ up to 50% higher than today’s level. In the third scenario the infrastructure can support any population size, but international immigration remains at its existing level. The fourth scenario introduces an explicit link between infrastructure and demographics, as any increase in population gives rise to increased congestion and slower travel speeds on a fixed transport infrastructure. This creates a negative feedback loop because average travel speed correlates to region attractiveness in equation (3).

Indicative results for the four policy scenarios are shown in Figure 3. For convenience, results are presented for three example regions, Inner London, Outer London and West Yorkshire. Growth in both the population and the economy (as measured by GVA) is naturally highest in scenario 1 where labour flows freely as a factor of production. The city of London appears to be the most significant beneficiary of a free flow of (skilled) labour. Scenario 3 indicates that current immigration policies have a significant damping effect on economic growth according to this model. Infrastructure scarcity is a further limiting factor in scenario 2, and this effect is especially pronounced in the London regions as one might expect. Scenario 4 looks rather like scenario 3 in the results presented here, because it rests on the same assumptions about international migration. However in this instance sub-regional variations in the distribution of population are considerable.



**Figure 3 GVA and Population for selected NUTS2 region on 2006 and 2050 under different scenarios**

The four scenarios presented here are offered as an initial proof of concept of the feasibility of implementing a co-evolutionary model of demographic and economic growth over a medium to long time horizon. All of the scenarios are based on a rather abstract view of the role of infrastructure. Future work will explore this dimension in greater detail, for example by investigation of the relationship between total factor productivity and agglomeration, energy efficiency and knowledge exchange<sup>13</sup>, as well as connectivity for which scenario 4 constitutes a preliminary test. In this way, a more sophisticated representation of the economy (than equations 5, 6) will be offered, while still recognising the positive relationship between labour, capital and economic performance. Alongside transportation, other key infrastructure sectors such as water, waste, ICT and energy will be represented. This programme promises a distinct and exciting perspective on the dynamic interplay of social and economic policies, regional development, infrastructure provision and prosperity.

<sup>13</sup> Carlsson, R., Otto, A., Hall, J. W. (2013). The role of infrastructure in macroeconomic growth theories, Civil Engineering and Environmental Systems, 30th Anniversary Special Issue, 30(3–4).

# Infrastructure Provision and Social Needs



# It's the Little Things that Count...

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<http://discovery.ucl.ac.uk/1469389/>

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## ABSTRACT

This paper will discuss the importance of detailed design decisions in the long term sustainability of any infrastructure system. It presents the concept of Universal Composition, first introduced by UCL's new Universal Composition Laboratory ('UCL-squared') and emerging from the need to design in space and time for multiple senses towards the creation of more accessible, understandable and meaningful environments. It thus presents infrastructure design from the point of view of human perception, and argues the need to design for the senses in order to encourage sustainable behaviours concerning human mobility, transport and locational choice.

After first explaining people-environment interactions, it discusses how the design of our urban infrastructure systems and environments can help stimulate our senses and thus behavioural change. Through two examples concerning bus stops implemented in London, it will explain how the role of both low and high tech technologies can help enhance interaction, improve accessibility and encourage usage. Thus, this paper aims to show that seemingly small details have a big role to play in the creation of infrastructure systems which enable, rather than inhibit, long term sustainable development.

**Keywords:** Urban Infrastructure Systems, Universal Composition, People-Environment Interactions, Multisensorial Design, Space-Time

## INTRODUCTION

All too often, when thinking about infrastructure, people think about large systems – railways, bridges, communications networks, health systems and so on. However, it is useful to pause for a moment to think about the purpose of infrastructure. The word means “that which lies underneath and supports a structure”<sup>1</sup> and in the context of interactions between infrastructure and people, this includes the support for the structure of society as well as support for structures such as buildings, transport or communications systems. According to Tyler, infrastructure has an important role to play in the improvement of quality of life and thus the achievement of societal wellbeing. In the search for societal wellbeing, Tyler (2013<sup>2</sup>, 2014<sup>3</sup>) suggests that we should think of and design city systems according to the 5-city model, based on five basic principles: 1. a city should be courteous; 2. active and inclusive; 3. felt as being owned by the public; 4. healthy; and 5. able to adapt to changing needs over time. Each of these ‘cities’ is described in terms of a person-

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1 Oxford University Press (1989), *Oxford English Dictionary*

2 Tyler N. (2013) Future Cities: Meeting the Brundtland challenge. ISNGI Wollongong

3 Tyler N. (2014) *A vision for cities: the 5-city model* ARGnote 1(5) [www.cege.ucl.ac.uk/arg/ARGnote.aspx](http://www.cege.ucl.ac.uk/arg/ARGnote.aspx)

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environment context. That is, the city should be designed to: 1. encourage people to show mutual respect for each other; 2. make activities accessible to everyone; 3. help make people feel safe; 4. contribute to positive health gain; and 5. help meet people's needs in the future. Thus in order to obtain societal wellbeing, infrastructure design must first address how individuals encounter infrastructure and the implications these encounters have for both the people and the infrastructure system itself. It is therefore incumbent upon designers to design these interactions between people and infrastructure. Thus this paper will discuss infrastructure in terms of people-environment interactions.

## PEOPLE-ENVIRONMENT INTERACTIONS

With societal wellbeing being dependent on our people-environment interactions, in this section we explore what these interactions are. Three issues that need to be considered when considering the interface between people and the environment are: the way in which a person perceives the environment; the way the environment changes over time; and the extent of the environment that needs to be considered.

### Perception of 'Environment'

It is important to realise that what is loosely called 'the environment' is something which is experienced by individuals in a way that is highly idiosyncratic. This is because of the way in which the human being responds to their immediate environment. Their responses are governed by the brain, but in particular by the preconscious mechanisms within the brain that determine the responses to environmental stimuli, and whether they are subconscious or conscious. To appreciate this, it is helpful to think about one sense, such as vision, as an example. Instead of thinking about vision as being active – "I look at the street" – we really should think of it as a data collector – "the street is showing me these features". Of the billions of stimuli being received by the brain in the form of bits of data, only a few reach the person's conscious state.<sup>4</sup> The same is happening, in parallel, with our other senses such as hearing, touch, smell and taste. It is also important to note that there are many more senses than just these, including pain, balance, spatial perception, rhythm, colour, fear, fairness and so on are all crucial to a person's survival – making it too massive an operation for the brain to process consciously.<sup>5,6</sup> We understand our environments through sensorial interactions and thus the multisensorial design of our infrastructure systems can make them easier to perceive on a preconscious level, rendering them more intuitive, understandable, navigable and accessible.

### Temporal Environments

The environment is in a state of constant and continuing change. Every time a person walks through a certain street or place, it will be different – there will be different colours, movements, sounds, images, lighting and so on. One of the main causes of this change is people. In an instant, 'other' people actually become part of the infrastructure with which one person interacts – they cluster around a sign or a shop window, move into and out of shops, move in and change between different directions and they stop. Yet there is a tendency to design the environment as though it were somehow permanent and unchanging. If we want to improve people-environment interactions, we need to explicitly incorporate these environmental changes in our design. In essence, we need to design in time as well as space.

### Personal versus Universal

As the person is the unit of interaction, we have to start by ensuring that everyone is taken into consideration when designing the urban environment. Sensorial capabilities vary between people, and many people lack a sense, such as vision, or their senses can deteriorate over time. In order to be inclusive we need to consider combinations of senses in relation to our design. As these interactions occur between people and the environments they use, we also need to consider all elements of the environment so that it can offer as many possibilities for interaction with people as possible. While these interactions are generic and apply everywhere, how we design them in different places will need to consider a number of local factors, including spatial, cultural and climatic features so that the design will be appropriate in its intended location. Thus the 'personal' and the 'universal' are both essential in our concept of how to think about the urban realm.

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4 Trans4mind, <http://www.trans4mind.com/transformation/transform4.1.htm> Accessed 28 May 2014

5 *Ibid.* Accessed 28 May 2014

6 Johnson K. (2009) *The Element*. Penguin, London, UK

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## Introducing 'Universal Composition'

In order to develop a design approach which embraces all three of these characteristics, we have developed the concept of Universal Composition - the multisensorial design of the environment in space and time. It refers to the compositional processes by which more 'temporal' art forms such as music, poetry, or dance achieve their objective through the blend of different sensorial stimuli in space and time. This can be applied to 'static' art forms such as built form and hard transport infrastructure, which in effect are temporal in its composition of movement. It considers elements of the environment as a product-process pair, rather than either a product or a process. It is universal because it relates to everyone, everything, everywhere at every time. The Universal Composition Laboratory at University College London (UCL<sup>2</sup>) is a new multidisciplinary design-research laboratory which studies and implements the principles of Universal Composition in all its projects, with the aim to improve societal wellbeing.<sup>7</sup>

One of the outcomes from the universal composition approach is that it needs to concentrate on the actual interaction between a person and their immediate environment – how they hear it, see it, feel it and so on – in space and time. This means that it is crucial to consider the small details of the environment, not only in the sense of the small elements of the system (e.g. a lamp pole or bus stop) but also the sensorial details of those elements (e.g. their colour, sound and feel). We argue that by paying greater attention to these small but numerous elements of the environmental infrastructure, great change in people-environment interactions can be achieved through their sheer number and far-reaching distribution. London, for example, has almost 20,000 bus stops and small changes to improve our interaction with them can thus yield a great difference in pedestrian/ passenger behaviour across the network, as well as affect other urban systems such as social and environmental. UCL<sup>2</sup> argues that it is indeed the little things that count.

## COMPOSING FOR OUR SENSES

Considering only the basic senses described above, the difference we can make to people's lives through the composition – i.e. multisensorial spatio-temporal design - of their microscale environments is clear. In the following sections we will investigate how we can redesign two simple activities which are key to any transport infrastructure system - walking and waiting – by applying the principles of universal composition.

### Composing for walking

First we would like to highlight the role of infrastructure in designing 'speed', or what Adhitya refers to as the composition of urban rhythm.<sup>8</sup> This relates strongly to Lefebvre's theory of Rhythmanalysis<sup>9</sup> and the embodiment of environmental rhythms surrounding us which we measure against the metronome of our own internal bodies. According to Adhitya<sup>10</sup>, we should be composing these urban rhythms at the appropriate spatial scale for the speed at which they are travelled through. In order to compose this temporal movement, we must first design them at the appropriate spatial scale. By designing for the stimulus at a typical walking speed, we would make the environment more interesting, stimulating and enjoyable for people, whereas designing for a typical vehicular speed would yield environments that are rather boring for pedestrians. For example, the rhythm of activity provided in Cat Street (Figure 1) provides a level of stimulus that is inviting enough for people to be there. Grafton Way (Figure 2) and Paddington Basin (Figure 3) however, provide little stimulation and thus remain relatively empty passages through which people pass as quickly as possible. Thus, in order to improve people-environment engagement, we must design, or rather compose, places with the appropriate rhythm.

### Composing for waiting

The act of waiting is another activity in which we often find ourselves obliged to partake. However, the design of our infrastructure means that this becomes, more often than not, a chore rather than a pleasurable activity. A simple design solution is to provide seating for people to rest themselves and their belongings. The physical design is easy enough – its form as well as the location of the seats. However, universal composition calls for the design of the

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7 UCL, *Universal Composition Laboratory*, <http://www.cege.ucl.ac.uk/arg/ucl-squared> Accessed 28 May 2014

8 Adhitya S (2013) *Sonifying Urban Rhythms – towards the spatio-temporal composition of the urban environment*, Paris, Venice

9 Lefebvre (2004) *Rhythmanalysis: Space, Time and Everyday Life*, Continuum, London

10 Adhitya (2013)

seating in a multisensorial, temporal way. The view from the seat should be considered, as well as its surrounding soundscape, lighting, and the available activities there – e.g. a book loan, coffee bar, etc. – that make sitting and waiting a pleasure rather than a chore. Figure 4 shows an example where the added height available from standing on the seat enabled people to enjoy watching a concert being given behind the bus stop even though the concert itself was hidden behind screens. Universal composition should encourage multiple uses over time.

## UNIVERSAL COMPOSITION IN LONDON

UCL<sup>2</sup> is currently involved in a number of experiments in the public domain where multisensorial design in space and time can be explored. The two examples discussed in this paper both concern bus stops – a result of responding to an opportunity rather than being the only possibility. However, bus stops are an important ‘phase change’ element of our infrastructure system, being the point at which we transform from pedestrian (walking) to passenger (waiting), and should be composed with care.

### Interactive bus stops

The first example consists of two interactive bus stop installations in Regent Street in London on 22 June 2014. On this day, the street was closed to traffic for the ‘Day of the Bus’<sup>11</sup>, and Transport for London granted permission to UCL<sup>2</sup>, in collaboration with Goldsmiths University, to transform 2 bus stops. Through a series of multisensorial, low and high tech interventions, we sought to change people’s perception of the bus stop from something where they are discouraged to linger, to a place where it is great to be.

The first bus stop was transformed into a digital musical instrument which could be played by the public<sup>12</sup>. The seating was fitted with pressure sensors which were linked to digital synthesizers, creating a series of ‘musical chairs’. New signage advertising the bus routes was created, which could be played like percussion instruments.

The second bus stop was used as a physical foil, in which the public, through a series of practical visual activities, could change the ‘image’ of a bus stop and thus the perception of its function(s)<sup>13</sup>. The public was invited to decorate it as well as arrange different types of furniture and other objects to create the sense of, for example, a ‘living room’ or an ‘office space’. The objective was to position the passer-by to view this everyday infrastructure object as an important compositional element of their urban environment which can change over time.

Through these interventions, we hoped to use universal composition to change the perception of a bus stop from being an everyday urban object to being a pleasurable experience in the urban realm, and thus open up the possibilities of what it could be. This event was a starting point for further multisensorial design interventions to other bus stops in London, which we are currently developing.

### ‘Edible’ bus stops

The concept of ‘Edible bus stops’ started life as a guerrilla gardening initiative in South London (Figure 5<sup>14</sup>) when a group of local residents decided to take over a piece of derelict ground near a bus stop to create a garden and thus improve the environment of the bus stop. UCL<sup>2</sup> intends to apply this idea to central London by constructing an ‘edible bus stop’ at a central London bus stop located in a busy corridor with limited pedestrian space and surrounded by buildings on either side of the street<sup>15</sup> (its current appearance can be seen in Figure 6). The plan is to construct a 50m-long garden using plants which are suitable for the area and have the best impact on local wildlife. We are investigating plants that generate better health benefits, through the improvement of the air quality, as well as being aromatic and colourful, and possibly even edible. In addition, we are working with Transport for London to determine what can be done with the current shelter, which is more of an obstacle to pedestrians along the narrow pathway. We hope to recompose the shelter into a new organic design, such that the seating is integrated alongside the garden and the shelter provided by the plants from the garden. Based on the previous experience of interactive

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11 Transport for London. <http://www.tfl.gov.uk/campaign/our-events> Accessed 28 May 2014

12 designed by Sara Adhitya, UCL<sup>2</sup>, Music technology: Matthias Moos, Alexander Bigden, Goldsmiths, University of London

13 designed by Liliana Ortega, UCL<sup>2</sup>

14 <http://www.theediblebusstop.org/> Accessed 28 May 2014

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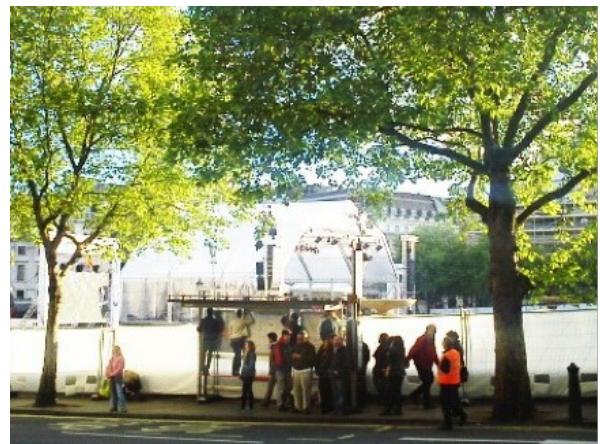
**Figure 1** Cat Street, Tokyo, Japan



**Figure 2** Grafton Way, London, UK



**Figure 3** Paddington Basin, London



**Figure 4** Bus stop assisting a concert in Trafalgar Square, London



**Figure 5** The Edible Bus Stop in Lewisham, London



**Figure 6** Site of a future 'edible bus stop', Gower Street, London

bus stops described above, we also hope to integrate audio and visual technology to aid interaction with and communication of the system. The bus stop will thus become a dynamic element in space and time – it will look and smell different according to the seasons, as well as itself contribute to different microclimatic conditions. Furthermore, it will compose new people-environment interactions through encouraged interactions with it, and it is anticipated lead to different behavioural outcomes. This project is currently in the stages of planning approval.

## CONCLUSIONS

In order for infrastructure to support the improvement in societal wellbeing, it is necessary to consider our interactions with it from the perspective of the sensing individual. In order to be used, infrastructure should be considered as a provider of pleasurable experience, rather than something that is imposed. At UCL<sup>2</sup>, we believe that positive change starts from positive experiences, and that the dynamic, multisensorial design of our people-environment interactions is the key. Our interactive bus stops are an example of how rethinking the design of one element in a big network can in fact help change the perception of a whole infrastructure system and assist in large-scale behavioural change. By applying the principles of universal composition to these seemingly small but numerous infrastructure elements, UCL<sup>2</sup> aims to improve the perception of our next generation infrastructure systems and promote sustainable and positive change.

# The Coherence Problem: Mapping the Theory and Delivery of Infrastructure Resilience Across Concept, Form, Function, and Experienced Value

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## ABSTRACT

In this contribution we explore the interface between the functional characteristics of infrastructures as artefacts and social need supplier. Specifically we are concerned with the ways in which infrastructure performance measures are articulated and assessed and whether there are incongruities between the technical and broader, social goals which infrastructure systems are intended to aspire to. Our analysis involves comparing and contrasting system design and performance metrics across the technical — social boundary, generating new insights for those tasked with the design and operation of networked infrastructures. The assessment delivered in the following sections is inherently interdisciplinary and cross-sectoral in nature, bringing thinking from the social and environmental sciences together with contributions from mathematics and engineering to offer a commentary which is relevant to all types of physical infrastructure.

**Keywords:** Infrastructure, Resilience, Multi-Disciplinary, Concept Coherence

## SUBTITLE REQUIRED

Networked infrastructures are “material mediators between nature and the city”<sup>1</sup> and facilitate modern urban life. They channel and modulate flows of information, goods, wastes and people and yet their configurations and the relationships of those configurations to the viability of the services they provide over short and long time scales remain under-studied. Marked spatial differences exist both within and between cities in networked infrastructure characteristics such as network topology, connection intensity, processing capacities, user accessibility and redundancies. These characteristics will underpin the ability of infrastructural services to resist and persist in the face of short term, perhaps sudden shocks. They will also underpin the ease with which infrastructures can be altered to accommodate longer term changes in operating conditions, making some transition pathways more or less feasible, more or less costly, and more or less environmentally damaging.

However, many of the system level relationships between the physical characteristics of networked infrastructures and the socio-economic services which such networks provide are not well understood. This deficiency is particularly acute in the context of being able to ensure commensurability between the metrics we use to portray desirable features of networked infrastructure and those we use to express required service provision performance. The next generation of infrastructures will need to exhibit strong correlation between these two metrics.

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<sup>1</sup> Kaika, M. & Swyngedouw, E. (2000) Fetishizing the modern city: the phantasmagoria of urban technological networks. *International Journal of Urban and Regional Research* 24 (1), 120-138 p20.

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In this contribution we explore the interface between the functional characteristics of infrastructures as artefacts and social need supplier. Specifically we are concerned with the ways in which infrastructure performance measures are articulated and assessed and whether there are incongruities between the technical and broader, social goals which infrastructure systems are intended to aspire to. Our analysis involves comparing and contrasting system design and performance metrics across the technical – social boundary, generating new insights for those tasked with the design and operation of networked infrastructures. The assessment delivered in the following sections is inherently interdisciplinary and cross-sectoral in nature, bringing thinking from the social and environmental sciences together with contributions from mathematics and engineering to offer a commentary which is relevant to all types of physical infrastructure.

We first turn to a wide (and still growing) body of literature which seeks to describe desirable systemic features of networked utility supply. Although the reader will doubtless be aware of much of the terminology used in these contributions, the detail is worth revisiting in light of the agenda set out above. The meanings we ascribe (see Table 1) are abstracted from a range of literature sources and are intended to communicate a consensual view of each descriptive term rather than offer an orthodox definition. It is worth noting that many of these concepts are synonymous with each other and their definitions are, or have been, contentious.

**Table 1 : Standardized definitions of concepts**

CONCEPT	GENERALISED DEFINITION
<b>Resilience</b>	The ability of the system to reduce the chances of a shock, to absorb a shock if it occurs (abrupt reduction of performance) and to recover quickly after a shock (re-establish normal performance).
<b>Robustness</b>	Strength or the ability of elements, systems, and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function.
<b>Flexibility</b>	The ability of a system to respond to potential internal or external changes affecting its value delivery, in a timely and cost-effective manner.
<b>Vulnerability</b>	Vulnerability is the antonym to system robustness and resilience taken together, in the same way that risk and safety are opposite.
<b>Reliability</b>	The probability that a component or system will perform a required function for a given period of time under stated operating conditions.
<b>Redundancy</b>	The extent to which substitutable components or other units of analysis exist (active or as standby) and are capable of satisfying functional requirements in the event of disruption, degradation, or loss of functionality.

The terms presented in Table 1 pepper debate and dialogue on infrastructure policy and planning, offering a convenient language set with which to illustrate the relationships between form and function. They also proclaim a normative ambition; inferring that each feature needs to be either stimulated (e.g. resilience) or depressed (e.g. vulnerability). Leaving aside for one moment the alarming lack of scrutiny regarding whether these system features can be designed and managed to a level of finesse which secures long term societal benefit, the language of resilience has spawned a new perspective on the relationships between the social and economic security of our communities and the engineered systems which currently underpin their functioning. But a language with which to discuss new concepts is rarely sufficient (of itself) to catalyse change – particularly change in engineered systems. So how are we to analyse the current state of our infrastructure systems and design interventions which might improve their systemic behaviour to make them more robust or less vulnerable ? Turning the rather abstract and ambiguous promise of rhetoric into (confidently) actionable strategies requires the operationalization of the concepts listed in Table 1.

We next turn to a set of analytical approaches which uses the same language as that presented in Table 1 and which attempts to characterise, and oftentimes quantify, the extent or degree of robustness etc. in a networked system. Other methodologies are also adopted (for example simulation modelling) but we focus here on the use of graph theory as a convenient and, we would argue, representative example of attempts to measure desirable systemic infrastructure properties.

Graph theoretic approaches are based on a representation of a network as a series of nodes and vertices. Relatively simple rules can be used to describe the topology of relatively complex networks. The aim here has been



to determine universal laws that govern the development and functionality of complex natural and technological networks. In the context of the physical infrastructure networks that underpin energy, transport, water etc. conveyance, it is the relationship between network configuration and service delivery in the face of planned or unplanned change which forms the focus of this work. For such large scale networks both simple and more advanced measures of node and vertex patterning can provide valuable indications of whole system fragility. For example, the identification and characterisation of scale free networks has been influential in understanding the relationships between connectivity and robustness (first reported in *Nature* by Albert *et. al.*, 2000<sup>2</sup>). Subsequent work<sup>3</sup> has explored the robustness of complex networks in terms of the relative impact of node failure for different network configurations.

Graph theory applications to physical infrastructures propose that an understanding of organized complexity is fundamental to our ability to understand, design, and operate next-generation infrastructure networks and identify potential incongruities in the measures used to characterise network parameters such as vulnerability and robustness. However, graph theoretic (like many complex system) approaches struggle to generate learning outcomes which can be turned in to reliable interventions. They help us understand phase transitions and critical phenomena rather than better predict the future behaviour of all system components (i.e. it supplies general lessons and heuristics rather than laws). The assumption of equivalence between graph and physical infrastructure network becomes eroded the closer the analysis gets to supporting intervention. For example, several of the assumptions needed to ensure the mathematical integrity of graphical analysis (e.g. that the network is located in a single plane) make little sense in terms of real networks. The other major challenge for this family of analytical approaches is that, unlike the rather generic and anonymous nature of nodes and vertices on a graph, engineered infrastructures are (i) often not homogenous in terms of the properties and behaviour of nodes and vertices, and (ii) deliver services and value to communities.

Indeed, there is an assumption in much of the technical literature that structure affects function and that network architecture can be used to analyze network stability, robustness, component failures, demand growth etc.. However, the type of functionality being referred to here is one level away from what we should be interested in. Stability and robustness are merely means to an end in terms of ensuring that our communities have sufficient and equitable access to energy, water etc..

Both abstract discussion of desirable system properties and the application of formal methods to scrutinise system properties have an improvement imperative at their heart. They both seek enhancement of service provision quality which, in the case of infrastructures, infers 'better' (more resilient / less vulnerable) energy, telecoms, water, energy etc. services. But what does this mean in terms of a tangible personal or collective experience of an infrastructure ? Do the concepts and metrics discussed above have meaning or significance for the customers of networked services ..., and does it matter ?

We primarily experience engineered infrastructure as a service delivery mechanism – a form of conduit through, or by which, we obtain value and amenity in both sensory and economic forms. Consequently, service failures are both qualitative and quantitative and will have impacts beyond an immediate lack of X. It is the social, economic, and in some cases, life support functions which infrastructure provides that shape citizen attitudes towards service quality. These features of the experience of infrastructure create challenges for those charged with its planning and management;

- Secondary and tertiary forms of value are often difficult to identify and therefore difficult to incorporate into plans.
- Any degradation in levels of service (irrespective of cause or time to recovery) is considered as failure by those affected (and also by regulators).
- Those at the end of the pipe or wire are unlikely to value system flexibility, resilience etc. unless they are aware of what might have happened in the absence of such system characteristics.
- The financial, opportunity, and transition costs of instilling system resilience etc. (ultimately borne by citizens) will be critically compared with BAU scenarios, raising questions of (e.g.) how much redundancy or flexibility is needed / desired.

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2 Albert, A., Jeong, H., and Barabási, A-L. (2000) Error and attack tolerance of complex networks. *Nature* 406, 378–482

3 Paul, G., Tanizawa, T., Havlin, S., and Stanley, H.E. (2004) Optimization of robustness of complex networks. *The European Physical Journal B*, 38(2):187:191, 2004.

We note that there is little published work which reports on public conceptions of resilience etc. and provides infrastructure system designers and managers with informed guidance on either suitable system features or acceptable costs. Significant research in this space is sparse although there are signs of recent and well presented engagement <sup>4</sup>. We are also a long way from understanding the extent to which attributes such as flexibility and redundancy might be sourced from the psychological and the social rather than from the engineered and the material. Such an agenda would need to engage with a wider appreciation of what an infrastructure is; one which encompasses both the utility supply medium, the organisations manage and regulate the medium, and the utility beneficiaries. Such agendas are gaining ground in other contexts but are not yet prominent in infrastructure studies.

To summarise, there are three levels of analysis which we argue drive debates around infrastructure provision; (i) abstract frameworks for thinking about the relationships between socio-technical system behaviour and long term societal prosperity, (ii) methodologies which attempt to capture these abstract features in formal descriptive or quantitative measures of the performance of the physical system and (iii) considerations of the relationship between infrastructures and the communities they serve. Although all three perspectives reflect laudable intent and are informed by similar ambitions, it is mistaken to assume that they are necessarily complementary. The disparity being alluded to here concerns a fundamental tension between form and function. To pose this concern as a query - does improving the design and operation of networked infrastructure using the metrics presented in Table 1 reliably deliver the benefits claimed for the related concepts in the abstract sense? Does 'robustness' in a network configuration or materials properties sense correlate with 'robustness' in the sense of a system which is 'relatively insensitive to change from external pressure and which returns rapidly to some equilibrium state of functioning'? In order to answer this question we need to be able to relate form (structure, configuration, physical properties) to function (e.g. service delivery).

Infrastructures as artifacts sit at the juncture of ambition and experience – they are a means for fulfilling the promise of universal access and a tool for rendering social value from spatial fragmentation. We argue that the interfaces between the three levels of analysis that we have described above need to be better understood if ambition is to be reliably turned into change on the ground. Specifically, the intellectual and methodological landscapes which shape how resilience, flexibility etc. are mapped between concept, form, function, and experienced value, deserve greater attention. This is not to demand consistency of semantic meaning or interpretation across all four components but rather to ensure that the interventions we adopt to promote resilience are true to the intended benefits of resilience as articulated when we speak of the attribute in more abstract terms. One suspects that simply asking the question (e.g. '*will this intervention bring about the ...* ') at appropriate junctures would go some way towards delivering such assurance.

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4 Moser, C., Stauffacher, M., Blumer, Y.B., and Scholz, R.W. (2014) From risk to vulnerability: the role of perceived adaptive capacity for the acceptance of contested infrastructure. *Journal of Risk Research* (in press)

# Consumer and Community in the Future Electricity Network: an Insight from Smart Grid Projects in Europe

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## ABSTRACT

Integration of growing shares of renewable energy sources into the electricity networks have resulted in the need for electricity network upgrade through pervasive deployment of information and communication technologies. Having power sources close to the consumer premises and exploiting the potential of smart metering infrastructure may lead to consumers' empowerment and energy savings. Therefore, the consumer should be approached with clear engagement strategies in the early stages of the technological system development. The analysis of European smart grid projects points to an increasing interest in consumers and communities as focal players for the success of the future electricity system. This necessitates characterization of the consumer as well as the community from what concerns values, beliefs and goals that are culturally and geographically located. In this context, this contribution presents and discusses some EU smart grid projects with a focus on consumers and on their interactions within the community. The abstract also demonstrates successful consumers' engagement strategies in large-scale deployment of smart metering systems at national level, highlighting the need to address social needs and concerns at an early stage of the technological system development.

**Keywords:** Smart Grids, Consumer, Community, Social Aspects

## INTRODUCTION

Growing concerns over climate change, security of power supply and market competitiveness have resulted in a need to integrate increasing shares of renewable energy resources close to the consumers' premises, thus allowing the electricity end-users to also operate and behave as energy producers. This may introduce additional flexibility into the system on one hand side and on the other impose increasing challenges for electricity system operators and energy providers in managing the power system operation and delivering secure and reliable power supply. As a result, the introduced system complexity would require an upgraded electricity network with two-way information and power exchange between the suppliers, distribution system operators (DSO) or any third-parties and the consumers through pervasive deployment of information and communication technologies. The adoption of such network infrastructure may theoretically lead to changes in the energy consumption, however, when customer behaviour is not aligned, potential energy gains may not be realized. To this end, despite the technical and technological challenges, the focus should be on new market structures, new services and primarily new social processes that demand the adoption of more intelligent electricity infrastructure. In this new perspective, it is important to understand and involve consumers and the communities within which they are acting in order for them to fully understand the smart grid potential and consciously assume their role as active participants in the future electricity system.

In light of the above and of the growing interest of researchers and policy makers on the role that consumers will play

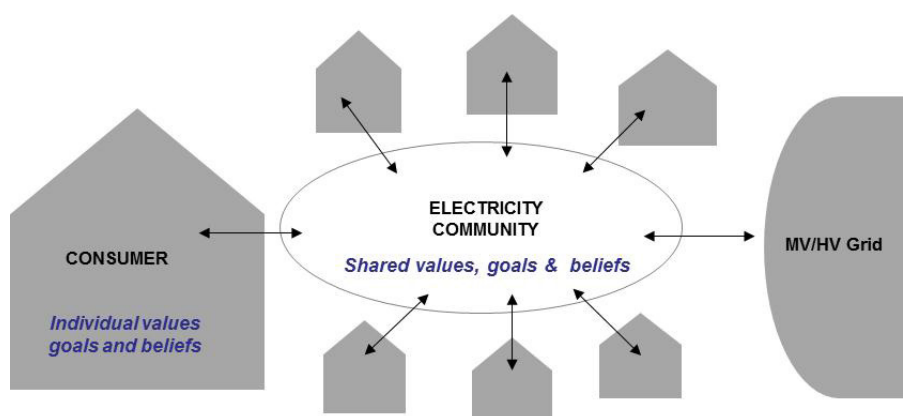
in the future electricity system, this contribution will present findings of the analysis of the JRC European smart grid projects inventory, specifically focusing on projects that emphasize electricity consumer and community aspects. The discussion will further focus on smart metering infrastructure and consumers' social needs, highlighting the experience of few Member States' plans for national roll-out of smart metering systems and focusing on the values that such systems may bring to the consumers.

## THE CONSUMER

The electricity consumers, their daily routines and the social context in which they operate are gaining increasing interest in policy and research. Many studies have been recently<sup>1</sup> published where consumers have been involved in interviews and studies to assess their perceptions, understanding and willingness to pay for the development of smart grids technologies. These studies acknowledge a consumer positive attitude towards smart grid technologies; however, they also recognize the need to further explore values, beliefs and goals in the context of these new technologies and to strive for trust, transparency and feedback to gain consumer involvement and acceptance<sup>2</sup>. Research on behavioural change in energy related behaviour has typically focused on motivating the consumers in their passive role. With smart grids the consumers will assume an active role as energy users and producers. Therefore, the challenge ahead is to understand the consumer active role and participation in smart grids, including the relation with the DSO and other service actors, and among and across the communities of consumers.

## THE COMMUNITY

The actors who decide to integrate their distributed generation units in a cooperative micro grid constitute a community. Indeed, one of the biggest achievements of future smart grids will be their distributed mode of operation where the coordination of energy consumption will become first priority. A vision of "electricity community grid" that relies mostly on local energy sources and storage is gaining acceptance. In Figure 1 we present a simplified representation of a community electricity grid.



**Figure 1: Smart grid framework at household and community level**

Whilst conventional energy production capacity used to be predominantly owned by a small number of large utilities, an increasing number of installed renewables is now owned by citizens, farmers and energy cooperatives. Such cooperatives present an interesting form of social innovation in which citizens together develop completely new ways

<sup>1</sup> Krishnamurti, T., Schwartz, D., Davis, A., Fischhoff, B., De Bruin, W.B., Lave, L., Wang, J., 2012. Preparing for smart grid technologies: A behavioral decision research approach to understanding consumer expectations about smart meters. *Energy Policy* 41

Diaz-Rainey, I., Ashton, J.K., 2008. Stuck between a ROC and a hard place? Barriers to the take up of green energy in the UK. *Energy Policy* 36

Ngar-yin Mah, D., Van der Vleuten, J.M., Hills, P., Tao, J., 2012b. Consumer perceptions of smart grid development: Results of a Hong Kong survey and policy implications. *Energy Policy*, 49

<sup>2</sup> Gangale, F., Mengolini, A., Onyeji, I., 2013. Consumer Engagement: An insight from smart grid projects in Europe. *Energy Policy* 60, 621-628.



to organize the energy system driven by a sense of community and local ownership. Some studies argue that for the smart grid to be successful, policies should be designed to enhance the autonomy of communities (local group of end-users) to support them in applying renewable sources and limit the power supplied by central power plants<sup>3</sup>. The challenge will be to enable consumers into forming communities according to their energy consumption behaviour. Studies reporting about community engagement in renewable energy and smart grid projects highlight the essential role of building trust between local people and groups in taking projects forward<sup>4</sup>. Local cooperatives with groups of houses sharing micro-generator production are also emerging. Being part of communities should strengthen consumer's energy awareness by allowing comparisons of energy consumption data with other community members. However, some recent studies on community energy argue that there is a limit to how much groups can achieve on their own. Instead, external sources of support are required to succeed and this indicates the strong need for consistent policy support, as well as intermediary networks, to ensure community energy projects have the resources they need to progress and achieve their objectives<sup>5</sup>.

Community based approaches to social changes are becoming an increasingly important part of the landscape of sustainable development. In particular, approaches that uses community based social marketing are gaining field. Social marketing is an approach that seeks to identify the barriers that people perceive when attempting to engage in a certain activity. Community based social market merge this approach with insight into the importance of social norms and community engagement in changing consumer behavior<sup>6</sup>. Successful examples of the application of this approach show that well designed community based social marketing strategies can have significant impact on routine behaviors and can offer effective paths towards pro-environmental and pro-social behavior<sup>7</sup>. It follows that communities may have an important role to play in mediating individual behavior.

Further research and analysis is needed to understand the attributes that define electricity community, identifying the strong elements that can make a community relevant in the development of future smart grids.

## CLOSER INSIGHT INTO SMART GRID PROJECTS IN EU

The JRC Smart Grid inventory 2014<sup>8</sup> shows that the number of smart grid projects focusing on smart customer has been increasing since 2005. Out of total 459 Smart grid projects (R&D and Demonstration & Deployment), the JRC smart grid inventory identifies 148 projects having smart customer as one of the main project application. In particular, most of these projects indicate a focus on the residential sector that shows an increasing interest of energy providers to target household consumers. The geographical distribution of smart grid projects with focus on smart customer shows that the majority of the projects are located in EU15 Member States (Figure 2). In the EU 15, most of the projects are concentrated in a few countries; Denmark, France, UK and the Netherlands. However, if weighted by budget, it emerges that Spain and Italy have projects with bigger budgets.

The analysis of the JRC Smart Grid inventory shows an increasing number of smart grid projects focusing on consumer as part of a community, this being a neighbourhood, a city or in some cases a region. In particular, the analysis of multinationals smart grid projects started in 2013 that have a focus on smart consumers reveal an approach to smart grids as complex socio-technical systems emphasising the need to embed energy infrastructure in a broader context that goes beyond technological change. In this view, social dynamics are considered crucial in achieving a more efficient and environmentally compliant energy system. The integration of energy, information and social networks is seen as central to the success of smart grid deployment at energy community level.

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3 Wolsink, M., 2012. The research agenda on social acceptance of distributed generation in smart grids: Renewable as common resources. *Renewable and Sustainable Energy Review*, 16

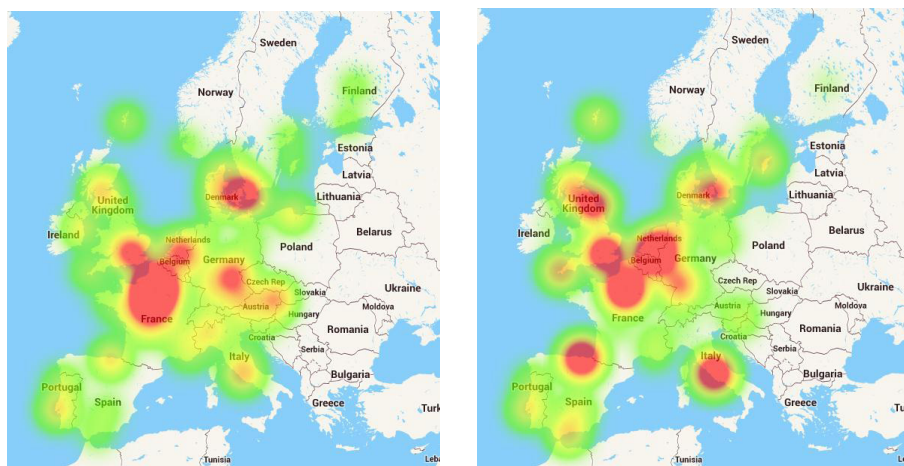
4 Alvia-Palavicino, C., Garrido-Echeverria, N., Jimenez-Estevéz, G., Reyes, L., Palma-Behnke, R., 2011. A methodology for community engagement in the introduction of renewables based smart microgrid. *Energy for Sustainable Development* 15

5 Seyfang, G., Park, J.J., Smith, A., 2013. A thousand flower blooming? An examination of community energy in the UK. *Energy Policy*, 61

6 Jackson, T., 2005. *Motivating Sustainable Consumption - a review of evidence on consumer behaviour and behavioural change*. Centre for Environmental Strategy, University of Surrey

7 Anda, M., Temmen, J., 2014. Smart metering for residential energy efficiency: The use of community based social marketing for behavioural change in smart grid introduction, *Renewable Energy*, 67

8 JRC Science and Policy Reports, Smart Grids Projects Outlook 2014; <http://ses.jrc.ec.europa.eu/reports-books-and-magazines>



**Figure 2: Geographical distribution of national smart grid projects with focus on smart customer.**  
**Left: number; right: weighted with the total budget**

Among the multinational smart grid projects started in 2013, three show an approach that aims at harnessing the benefits that electricity community diffusion may bring about at consumer level (improvement of electricity quality and reliability, energy savings) and systemic level (“electricity system” and “social system”)<sup>9</sup>. These projects are in their initial phase of development, therefore progress and results are not yet available. Nevertheless, from their conceptual framework some interesting concepts emerge. For example, the CIVIS project (*Cities as drivers of social change*) aims at enabling communities, interest groups, business and non-business players to decide how to allocate energy according to shared goals, intents and beliefs thus fostering the arising of new forms of social aggregations that can enact new forms of energy eco-systems. In a similar way, the CoSSMic project (*Collaborating Smart Solar-powered Micro-grids*) aims to develop the ICT tools needed to facilitate the sharing of renewable energy within a neighbourhood, investigating how to motivate people to participate in acquiring and sharing renewable energy in the neighbourhood. Finally, BESOS project (*Building Energy Decision Support Systems for Smart Cities – holistic approach to a community level dimension – research and demonstration project*) aims at enhancing existing neighbourhoods with a decision support system to provide coordinated management of public infrastructures in Smart Cities and at the same time to provide citizens with information to promote sustainability and energy efficiency.

These three projects are characterized by a common systemic approach where the interest is also on the social systems dynamics developed within the community. Values, goals and beliefs will need to be mediated and negotiated between the individual and the community. They also point to the need to characterize geographically and culturally a community and thus to the difficulties of scalability and applicability of a common approach throughout Europe.

On a national level, another interesting project addressing the community involvement is the MIETeC project<sup>10</sup> (Montdidier: Intelligence Energetique Territoriale pour la Collectivite) whose aim is to reach 100 % RES community for the region of Montdidier. The main tools to be developed within the project are a centralized data management system to balance the energy consumption across the town, coupled with storage solutions and demand side management along with an animation tool for consumers, based on different modes of communication (SMS, mails, community newsletters, etc.), to help them in managing their energy demand.

## SMART GRID INFRASTRUCTURE – POLICY IMPLICATIONS AND SOCIAL NEEDS

Advances in EU Policy clearly play a significant role in the adoption of smart grids and smart grid technologies at a national scale. The Recommendation 2012/148/EU<sup>11</sup> on smart metering deployment further clarifies that the smart metering system should be defined through the functionalities it provides. In particular, in the case of electricity, the

<sup>9</sup> Le prospettive di sviluppo delle Energy Community in Italia, Politecnico di Milano, 2014

<sup>10</sup> <http://www.smartgrids-cre.fr/index.php?p=mietec>

<sup>11</sup> Commission Recommendation 2012/148/EU, OJ L 73 p.9, <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32012H0148:EN:NOT>

Recommendation identifies ten minimum functional requirements that the smart metering system should provide in order to deliver full benefits to consumers and the energy grid while supporting technical and commercial interoperability and guarantee data privacy and security.

Member States such as the UK, Ireland and the Netherlands have placed the electricity consumer as focal point in their analysis of nation-wide smart metering deployment (above 80% of electricity consumers), addressing social acceptance and consumer engagement in the early stage of smart metering technological development. All three countries are proceeding with nation-wide roll-out of smart metering systems, to be completed by 2020<sup>12</sup>.

The Department for Energy and Climate Change in UK has agreed on establishing a Central Delivery Body (CDB), a new independent organisation responsible for raising awareness and educating customers on smart metering alongside suppliers own campaigns. As a legally independent company with a Board of Directors made up of both, consumer and supplier representatives, one of the main activities of the CDB will be on building consumer confidence in the installation of smart metering systems by the electricity suppliers.

The Irish energy regulator CER established the Smart Metering Customer Behaviour Trials<sup>13</sup> as part of the much larger smart metering technology trial which remains to date one of the largest and most comprehensive in Europe. It attempted among other things to measure the potential of energy consumption reports to change the behaviour of electricity and gas consumers being assigned to different Time Of Use tariffs and having access to different communication feedback channels.

In the Netherlands, social acceptance of smart metering systems, mainly related to data privacy concerns, resulted in an amendment to the legislative proposal by means of an introduction of a voluntary approach for consumers' acceptance of smart metering systems. In this perspective, the evaluation of long-term costs and benefits<sup>14</sup> associated with national smart metering roll-out sheds particular light on three aspects as policy attention points in the early stage of system development: social acceptance, effective use and efficient large-scale roll-out of smart metering systems.

To this end, the success of the smart grid deployment will critically depend on the overall functioning of the power system as a socio-economic organisation, and not just on individual technologies. As a result, the most important challenge for policy makers over the next decade will likely be the shift away from a supply-driven perspective, to one that recognizes the need for integration of different dimensions and actors of the smart grid.

## CONCLUSION

Integration of growing shares of renewable energy sources into the electricity networks results in the need for network upgrade through pervasive deployment of information and communication technologies. Having power sources close to the consumer premises and exploiting the potential of smart metering infrastructure may lead to consumers' empowerment and ultimately energy savings. Therefore, the consumer should be approached with clear engagement strategies and actively engaged in the early stages of the technological system development.

The analysis of the smart grid inventory points to an increasing interest in consumers and communities as focal players for the success of the future electricity system. This necessitates characterization of the consumer as well as the community from what concerns values, beliefs and goals that are culturally and geographically located. With an increasing trend of EU projects focusing on electricity consumers and communities, this contribution presented and discussed some EU smart grid projects that have a socio-technical system approach to smart grids with focus not only on consumers, but on their interactions within the community. Smart grid, integrating multiple layers, such as the energy, information and social networks is seen as focal to the success of renewable energy sources integration at community level. The abstract also demonstrates successful consumers' engagement strategies in large-scale deployment of smart metering systems at national level in few Member States, highlighting the need to address social needs and concerns at an early stage of the technological system development.

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12 JRC Science and Policy Reports, Smart Grids Projects Outlook 2014; <http://ses.jrc.ec.europa.eu/reports-books-and-magazines>

13 The Commission for Energy Regulation, Electricity Smart Metering Customer Behaviour Trials Findings Report, May 2011.

14 Smart meters in the Netherlands – Revised financial analysis and policy advice, KEMA July 2010



# Stepping Away from Trend Analyses for Regional Integrated Planning and Modelling

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<http://discovery.ucl.ac.uk/1469395/>

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## ABSTRACT

Strategic regional plans formulated by authorities aim to achieve aspirational objectives such as vibrant and connected communities, accessible and affordable transport, innovative and productive economy, and protected natural environments. But planners often lack decision support tools capable of tracking complex dynamic interactions between these various components.

Many current regional planning models rely on feed-forward trend analyses. These trends are based on demographic or economic assumptions that lock-in regional growth into a unique pathway. The weaker the initial assumption is, the less plausible the evolution of other components of the regional development. In fact, useful regional planning models need to reproduce the co-evolution of land use, transport, economic and demographic dynamics.

We have developed a dynamic model that includes five interconnected modules: (1) a cellular automata-based land use module, (2) a 4-step transport model with dynamic allocation of traffic, (3) a dynamic input/output economic model, (4) a synthetic population-driven demographic model, and (5) a utility module to capture the evolution of demand for energy and water as well as production of sewage and solid waste. We use a sophisticated simulation platform called GEONAMICA to build and integrate foregoing modules for the Illawarra region in New South Wales, Australia. This paper presents the ongoing development of the model, as well as preliminary results from scenario analysis. We conclude the paper by discussing intended future work.

**Keywords:** Regional Planning, Integrated Modelling, Land Use, Transportation

## INTRODUCTION

Strategic regional planning concerns long term projects that aim to bring about sustainable development through shrewd investment in and management of public and private resources<sup>1</sup>. This is often a challenging process as it requires careful balancing of competing priorities such as vibrant and connected communities, accessible and affordable transport, innovative and productive economy, and protected natural environments<sup>2</sup>.

Although modelling offers an attractive solution to this problem, many current regional planning models rely on feed-forward trend analysis. These trends are based on demographic or economic assumptions that lock-in regional growth into a unique pathway. A weaker initial assumption can result in a less plausible evolution in other aspects of

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1 United Cities and Local Governments. Policy Paper on Strategic Urban Development. (2010).

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the regional development. Regional planning models need to follow observed patterns to become useful. To this end, such models should incorporate land use, transport, economic and demographic factors that interact with each other and co-evolve in a simulation environment<sup>3</sup>.

We have embarked on a project that aims to develop an integrated model encapsulating five interconnected modules: land use, transportation, econometric input/output model, synthetic population-driven demographic model and a utility module. This paper entails the first phase of the model development that features integrated land use and transportation models.

## METHODOLOGY

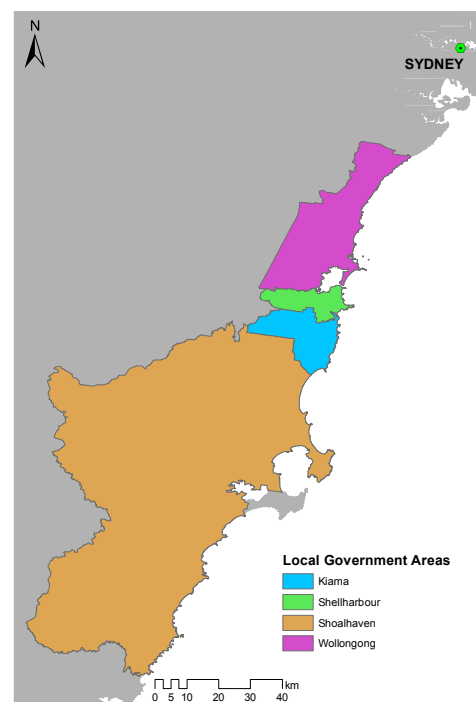
### Study area

The Illawarra, a coastal region located south of Sydney in Australia, is our study area that consists of four Local Government Areas (LGAs): Wollongong, Shellharbour, Kiama and Shoalhaven (Figure 1). These four LGAs occupy the coastal plain limited on the east by a forested escarpment, hence geographically well-demarcated as a region. According to the 2011 census<sup>4</sup>, the population of the Illawarra region stood at 368,814 persons, 52% of which lived in Wollongong LGA only.

### Software framework and models

We use a sophisticated simulation platform called GEONAMICA<sup>5</sup> to build and integrate identified modules. The constrained Cellular Automata (CA) based land use model in Geonamica has been used in many applications around the world, both in the original form and its variants<sup>6,7,8</sup>. The main variable of the land use model is a land use map in raster format which is iteratively updated in yearly time steps over the course of the simulation. In the fully-integrated model, the demands for land uses are passed on by the economic and demographic models. However, in the absence of those two models in this phase of the model development, those demands are provided exogenously. The land use transitions are driven by endogenously calculated transition potential for which neighbourhood effect, physical suitability, accessibility (mainly to transport) and zoning contribute as key factors. A complete description of the land use model is available elsewhere<sup>6,9</sup>.

Transport model is based on a classical four step approach<sup>10</sup>, but has been made dynamic<sup>9</sup>. The land use model provides input to determine origins and destinations of trips, while



**Figure 1. The Illawarra Region, New South Wales, Australia**

3 van Delden, H., Seppelt, R., White, R. & Jakeman, A.J. A methodology for the design and development of integrated models for policy support. *Environmental Modelling & Software* 26, 266-279 (2011).

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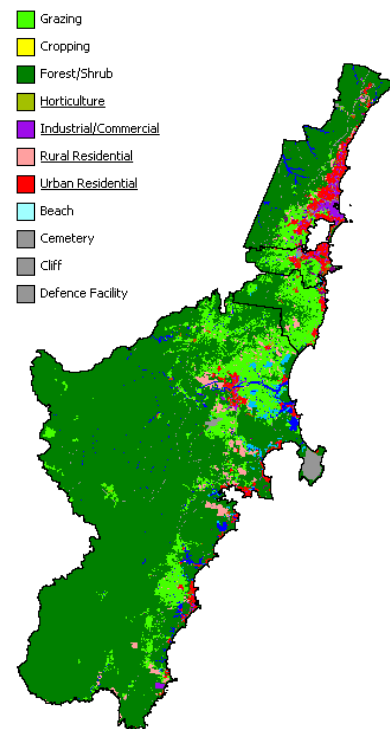
10 McNally, M.G. The Four Step Model. In: *Handbook of Transport Modelling* 35-52, (2000).

transport model influences land use change by means of accessibility. This two-way communication provides the dynamic basis to the transport model.

## SETTING UP THE INTEGRATED MODEL

Land use model requires a number of geospatial datasets. The main input, which is the land use dataset, is derived from the catchment-scale land use maps collated by the Australian Collaborative Land Use and Management Program (ACLUMP). The land use classification used in this study includes 23 classes out of which 6 are dynamic (Figure 2). The dynamic classes include urban residential, rural residential, industrial/commercial, horticulture, grazing land and forests. A slope layer is used as the only input for the physical suitability component, while three datasets (Local Environmental Plan, conservation areas and Strategic Regional Land Use Policy-SRLUP of NSW) are used as inputs for the zoning component. Road network and railway stations are used to determine accessibility. Spatial resolution used in the land use model is 100m.

The same road network serves as a major input to the transport model. Travel zones as identified by the Bureau of Transport Statistics (BTS) NSW are used as transport zones, which is the other major input to this model. We model 5 time periods of a typical weekday (midnight, morning, noon, afternoon, evening), two modes (car and public transport) and 4 purposes (work, shopping, social and home). A multi-dimensional Origin Destination (OD) matrix for 175 travel zones in the region is prepared using the Household Travel Survey data gathered by BTS.



**Figure 2. Land use classification**

## Calibration, validation and scenario exploration

The calibration period used is from 2006 to 2012. As such, land use and transport models start with initial data (2006), and dynamically update these in yearly time steps until 2012. The simulated land use map, OD matrix and road network assignment layer for 2012 are saved for comparing against the observed data for 2012. Observed land use data for 2012 is prepared using a feature extraction procedure applied on very high resolution satellite imagery. Only two land use classes (urban residential and industrial/commercial) are extracted by this method. Hence, the detailed calibration of the land use model is limited to only these two classes in this initial phase.

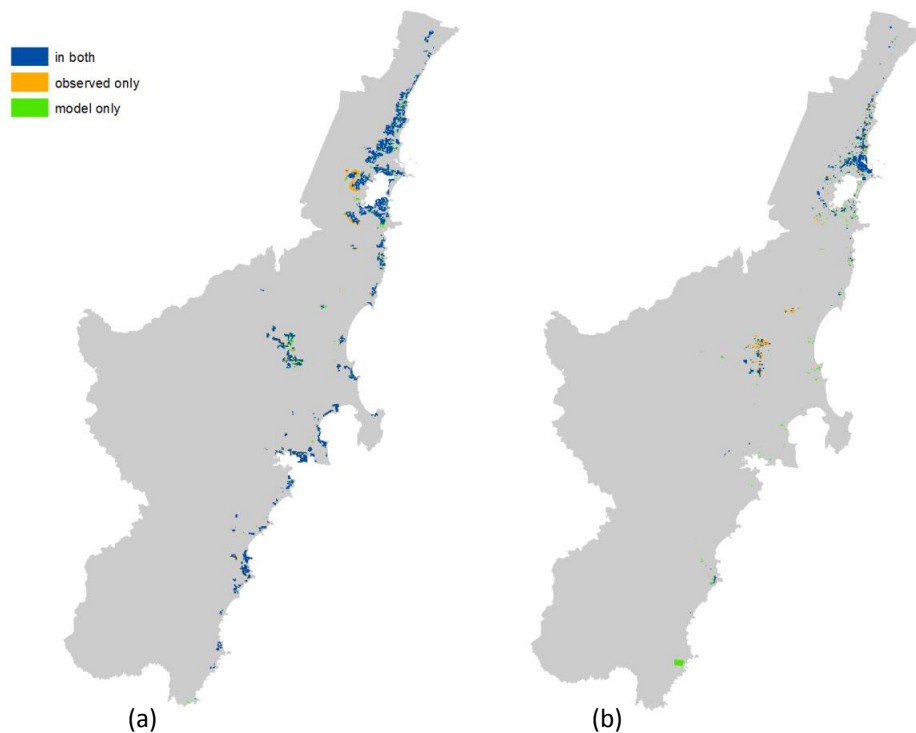
When the agreement between simulated outputs and observed data is not sufficient, a number of model parameters are systematically changed and the model is re-run for the same period until a reasonable match is achieved. Calibrated model parameters include neighbourhood rules (attraction and repulsion between land use classes), accessibility parameters, trip distribution during the day, cost sensitivity of trips for different purposes and transport mode aversion costs, among many others.

Once the model is sufficiently calibrated, the model is then run to the future (2012 – 2022) using the calibrated parameters. Only the baseline scenario is explored in this study to identify potential outcomes if observed patterns continue into the future.

## RESULTS AND DISCUSSION

Calibration of the land use model is limited to only two land use classes namely, urban residential and industrial/commercial. Figure 3 depicts comparisons between observed and simulated land use for these two classes in 2012. The agreement between observed and simulated outputs is acceptable both visually (Figure 3) and statistically as evident by Kappa coefficients of 0.9 and 0.73 for urban residential and industrial/commercial land uses, respectively.





**Figure 3. Comparison of observed land use and simulated land use for 2012, (a) urban residential, (b) industrial/commercial**

However, a higher Kappa coefficient could also suggest that land uses are inert, as is the case usually for urban residential, industrial and commercial land uses. In such cases, a contingency table (Table 1) could be used to gain deep insights into model's performance. Values along the diagonal in Table 1 indicate areas where the model performs well. For example, our land use model is able to correctly identify 13579 urban residential cells. However, 213 industrial/commercial land use cells are incorrectly labelled by the model as urban residential.

**Table 1. Contingency table for observed and simulated land use classes in 2012**

Model	Urban Residential	Industrial/Commercial	Other
Observed			
Urban Residential	13579	673	801
Industrial/Commercial	213	3751	1357
Other	1438	516	178160

Performance of the transport model is established mainly by comparing observed and simulated OD matrices at an LGA level (Table 2 and 3). While the transport model has predicted correct magnitude in terms of the number of trips between all LGA pairs, the absolute difference between observed and simulated values call for further calibration.

**Table 2. Observed trip origin-destination matrix for transport mode 'car'**

Trips	D			
O	Kiama	Shellharbour	Shoalhaven	Wollongong
Kiama	36369	11833	4059	4919
Shellharbour	10322	132140	1625	51671
Shoalhaven	3335	827	303351	5018
Wollongong	7261	52781	5108	565712

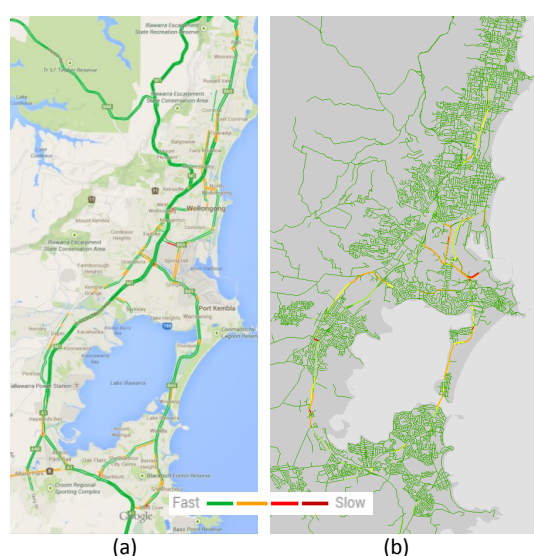


**Table 3. Simulated trip origin-destination matrix for transport mode 'car'**

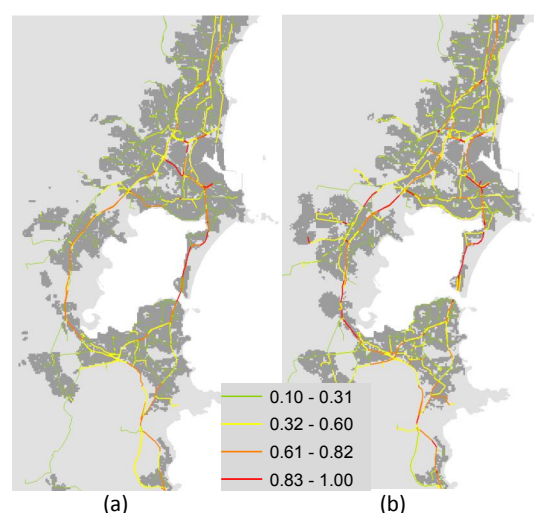
Trips	D			
O	Kiama	Shellharbour	Shoalhaven	Wollongong
Kiama	24866	17786	7876	10307
Shellharbour	16637	94960	6701	60894
Shoalhaven	12015	4909	247010	3091
Wollongong	10679	64449	6121	435528

Our transport model records the speed at which vehicles move in the network during chosen time periods of the day for all simulated years. Figure 4 illustrates network speeds during morning peak on a typical weekday. Observed network speeds in Figure 4 are extracted from Google traffic maps. This comparison shows that the transport model is able to identify key network links that are subjected to significant congestions, thus adding to the confidence in using this model.

Baseline scenario (Figure 5) suggests a potentially significant urban growth to the left of the 'Lake Illawarra' which is an area identified and promoted for residential development in the SRLUP prepared by the NSW Government. It is important to note that this growth can lead to higher network congestion, thus reminding us the importance of combining the growth plan with an appropriate transport plan for the region.



**Figure 4.**



**Figure 5.**

## CONCLUSION

This study marks the first phase of a larger project that aims to develop an integrated dynamic model in support of regional planning. In this phase, we have set up, calibrated and validate integrated land use and transport model. Calibration and validation results give confidence in using the model for scenario exploration, although there is room for improvement. In particular, residential land use could be further disaggregated into density-based classes. Same goes for industrial/commercial class which should be split into two classes. Land use model should also be calibrated for other land use classes. Number of trips produced by the transport model between origins and destinations needs further calibration.

In addition to improving calibrated model parameters, we are currently in the process of integrating an econometric input/output model and a synthetic population-driven demographic model into our framework. A conceptual model for utility consumption and network performance is also being developed.

## ACKNOWLEDGEMENT

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# Alternative Energy Sources and Energy Infrastructure for Dutch Greenhouses – Investigating Growers' Preferences

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<http://discovery.ucl.ac.uk/1469396/>

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## INTRODUCTION

Growing plants, vegetables and flowers in greenhouses constitutes the core business and capability of the Dutch horticulture industry. Greenhouse owners in the Netherlands use advanced technology to maintain the quality of products and to remain competitive in international markets despite high cost of labour and energy.

Today, Dutch greenhouse growers mainly depend on natural gas for heating their greenhouses. Next to boilers, many units of combined heat and power (CHP) have been installed over the last decade which deliver heat, produce electricity and even CO<sub>2</sub> for more efficient crop harvesting. However, the sector has come to realize that, in foreseeable future, they need to switch to other energy sources to secure their energy supply and increase the sustainability of their business for reasons of depleting natural gas, and fierce market competition.

The sunk investments in energy technology are enormous and largely depend on regional energy infrastructure for gas, electricity, heat and CO<sub>2</sub>. Furthermore, growers are exposed to gas, electricity and CO<sub>2</sub> markets and must face their rising prices. Adopting alternative sources and technologies requires substantial investment and carries substantial risk. All these considerations make the decision process to adopt new energy source a complicated and fuzzy one.

In this study, we investigate growers' preferences and opinions regarding three potential alternative energy sources and associated technologies: solar thermal energy, geothermal energy and biogas.

We use established methods from consumer behaviour theory and choice-modelling to elucidate how growers form an opinion and decide on the next technology to employ and grow their business.

**Keywords:** Greenhouse, Alternative Energy, Choice modelling, Stated Preferences, Attitudes

## BACKGROUND

In a greenhouse, a protected micro-climate is created and maintained. In the early 20th century, heating already was used to warm greenhouses in early spring and to secure crops from late frost. Following the availability of natural gas, from the seventies central-heating systems have been installed on a large scale, which allowed many growers to adopt a cultivation season that runs from February till November, depending on the crop grown.

A greenhouse is also a giant collector of solar heat, which over a year accumulates far more energy than required to maintain temperature. In current greenhouse designs, however, on hot days the surplus heat is released by ventilation, while on moderate and cold days, the central heating is switched on. As a consequence, currently, in the Netherlands,

greenhouses consume large amount of energy, which is equivalent to 7% of total national consumption<sup>1</sup> from conventional sources, mainly from natural gas. Thus the horticultural industry has become highly dependent on secure, affordable energy to remain competitive. This emphasises the sensitive role of energy infrastructure – the natural gas network, the electricity grid, and increasingly local or regional CO<sub>2</sub>, heat or biogas grids play in the horticulture industry.

Individual growers and sector organizations have recognized this situation, and developed strategies to deal with the problem of high energy dependence of greenhouses by new greenhouse designs such as the “closed greenhouse” concepts or the “energy-producing greenhouse” (Kas als Energiebron) systems. Some greenhouse companies, based on scientific studies and support from research centres, have invested in geothermal heat sources and infrastructure for seasonal heat storage and heat distribution.

Meanwhile, the Dutch government has supported improving sustainability and efficiency in the greenhouse sector notably through the agreement called the GLAMI covenant<sup>2</sup>. This agreement sets out number of targets, and stipulates that among others, energy efficiency and sustainable energy sources are discussed. In terms of efficiency, the greenhouse sector has been quite successful, thanks to the rapid adoption of CHP technology, where natural gas is consumed to produce heat, electricity and CO<sub>2</sub> for cultivation<sup>3</sup>. With the CHP technology and energy conservation innovations and new isolation methods implemented in the greenhouses, the sector has been able to reduce energy consumption by 53% in 2010 compared to the amount used in 1990. Consequently, the CO<sub>2</sub> emissions were reduced by more than the amount expected in the GLAMI. However, with respect to sustainability the sector has not been so successful. From 4% target for using sustainable energy sources (as mentioned in the Agro covenant) only 1.6% was reached by the sector in 2010. Currently more than 18 percentage points are required to reach the 20% projected targets for year 2020<sup>4</sup>.

One of the underlying reasons for not achieving the sustainability target can be related to the wide adoption of CHP technology in the sector. Since year 2003, the availability of CHP technology together with the liberalization of the electricity market allowed growers to obtain extra revenues by delivering excess electricity to the grid. Growers could shift their electricity load to periods with high spot market prices, which led many grower to adopt CHP technology<sup>5</sup>. The rapid uptake of CHP technology in the sector, due to its clear financial benefits<sup>3</sup>, has out competed other potential and sustainable energy sources. This resulted in the sector not realizing the targets set for using sustainable energy sources.

CHP technology consumes large quantities of natural gas, which is not considered to be a sustainable source of energy. Furthermore it has been recognized that natural gas dependency translates into vulnerability for a number of reasons: depleting national resources, the problem of security of supply from exporting countries, and increasing (or at least variable or unpredictable) prices. Furthermore, some growers have realized that “sustainably grown crop” is a label that may distinguish their product and bring in higher revenue. As a consequence, both the sector and government are actively seeking to promote and accomplish an “energy transition” of the sector.

## AIM

The energy-related literature in horticulture research has mainly contributed towards proposing new design methods in cultivation to reduce energy demands<sup>6</sup>, produce less emissions<sup>7</sup> or to build the structure with such materials that minimize heat loss from the greenhouse<sup>8</sup>. Some literature has explored new energy sources and the economic potential

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6 Zwart, H. F. D. (1996). Analyzing energy-saving options in greenhouse cultivation using a simulation model (Doctoral dissertation, Landbouwniversiteit te Wageningen).

7 van't Ooster, A., Van Ieperen, W., & Kalaitzoglou, P. (2010, August). Model study on applicability of a semi closed greenhouse concept in Almeria: effects on greenhouse climate, crop yield and resource use efficiency. In *XXVIII International Horticultural Congress on Science and Horticulture for People (IHC2010): International Symposium on 927* (pp. 51-58).

8 Vanthoor, B. H. E., Stanghellini, C., Van Henten, E. J., & De Visser, P. H. B. (2011). A methodology for model-based greenhouse design:

of harvesting them for commercial cultivation<sup>4</sup>. In retrospect surprisingly, a survey of some Dutch firms (including a few horticulture related firms) found that energy-saving investment decisions will not have a significant impact on profitability and competitive position of the firms<sup>9</sup>. Meanwhile, to the best of our knowledge, the views and opinions of growers, who are often the main investors and adopters of new technologies in horticulture industry, have not yet been investigated. Therefore, in this study we will focus on growers and their decision-making.

Greenhouse growers have an entrepreneurial attitude and are involved in tight competition in the vegetables and flowers sector<sup>10</sup>. They are mostly pro- innovation professionals and capable of assessing different proposed measures<sup>11</sup>. In the past few years, the three energy sources proposed (i.e. solar thermal energy, geothermal energy and biogas ) have been installed and tested in a small number of greenhouses in the Netherlands. Through educational gatherings and symposiums (e.g. EnergieK2020 event organised by initiative called: KasalsEnergiebron), experts have revealed practical examples of these alternative sources being applied to different greenhouses and demonstrated to growers that such sources can provide full or partial substitutes for natural gas.

Based on known characteristics about growers, in this research we conduct a survey on them to gather their state-of-mind and their judgement as a hypothetical investor on the alternative energy sources/technologies proposed. We set up a stated-choice experiment among a sample of Dutch growers, where we ask their opinions and their preferences about the three alternative energy sources and their willingness to adopt such innovative measures in the (near) future. The experiment consists of offering different scenarios to growers and asking them to select the most desired alternative energy based on their attributes. Furthermore, we ask about growers' attitudes on environmental matters and on pollution emitted from their greenhouse when burning fossil fuels. We jointly analyse growers' choices on alternatives and their attitudes on emissions to the environment, to infer a deeper understanding of their opinions and preferences.

The societal contribution of this work is that these findings can contribute to our understanding of the relationship between people's attitudes and stated preferences regarding environmental values and policies. At a practical level, this work provides some recommendations to the governing bodies to implement tailored policies that aim to steer different sectors in the horticulture industry towards a more environmental and sustainable way of growing their crops.

## METHOD

The main method used, in this research, to estimate preferences of growers is based on Discrete Choice Models (DCM), which has been introduced by McFadden in 1974. These models have been used to explain preferences of individuals and predict market shares for products and services in many domains such as transportation, health care, consumer choice, and environmental economics<sup>12</sup>. With the information obtained from choice experiments, one can estimate coefficients that quantitatively describe the importance of different attributes to individuals (i.e. growers).

In choice models, the analyst represents the decision making procedure of people as a utility maximization exercise, whereby each individual tries to maximize his/her utility from the alternative options that are offered to him/her. This is based on random utility theory where individual  $i$  gains utility  $U$  from each alternative option  $e$ , shown as:  $U_{ie}$ . The utility is further defined as:  $U_{ie} = V_{ie} + \epsilon_{ie}$ , where the first part  $V_{ie}$  is the deterministic part, which is calculated from the choices that individuals make when observing the available sets of alternatives and  $\epsilon_{ie}$  is the vector of coefficients, and  $e$  is a vector of alternatives. The  $\epsilon_{ie}$  is the random component, which is assumed to be identically distributed extreme values [type I extreme value]<sup>13</sup>.

During the design of a choice experiment, several choice sets are created. In each choice set, constant numbers of alternatives (i.e. profiles of energy sources) with different values for each attribute are listed. The three alternatives were three energy sources: solar thermal energy, biofuel based energy, geothermal energy. Four constant attributes have been considered for each alternative; however, the specific values for attributes are varied. Table 1 shows the alternatives and attributes that are considered for this study and the range for each attribute are given on this table.

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Part 1, a greenhouse climate model for a broad range of designs and climates. *Biosystems Engineering*, 110(4), 363-377.

9 De Groot, H. L., Verhoef, E. T., & Nijkamp, P. (2001). Energy saving by firms: decision-making, barriers and policies. *Energy Economics*, 23(6), 717-740.

10 van der Veen, R., 2012. Case study 'CHP diffusion in Dutch greenhouses'. Final report, Delft University of Technology, faculty of Technology Policy and Management.

11 Schrauwen, N. (2012). Innovativeness of innovation (Doctoral dissertation, Master's thesis, TU Delft. 167).

12 Chorus, C. G. (2012). Random Regret-based discrete choice modelling: A tutorial. Springer.

13 Train, K. (2009). Discrete choice methods with simulation. Cambridge university press.

**Table 1 Alternatives, attributes, and ranges for attributes for the choice experiment**




Alternatives	Solar thermal energy	Bio-fuel energy	Geothermal energy
<b>Attributes</b>			
Beginning investment /m <sup>2</sup>	65-80 €/m <sup>2</sup>	20-25 €/m <sup>2</sup>	80-200 /m <sup>2</sup>
Amount of natural gas saved [m <sup>3</sup> a.e. / (m <sup>2</sup> jr)]*	10-11 [m <sup>3</sup> a.e./ (m <sup>2</sup> jr)]	8-13 [m <sup>3</sup> a.e./ (m <sup>2</sup> jr)]	21-40-120 [m <sup>3</sup> a.e./ (m <sup>2</sup> jr)]
Additional electricity required (kWh/m <sup>2</sup> )	25-27 kWh/m <sup>2</sup>	2-3 kWh/m <sup>2</sup>	7-11 kWh/m <sup>2</sup>
Emission savings (gr/m <sup>2</sup> )	6-7 gr/m <sup>2</sup>	22-31 gr/m <sup>2</sup>	32-66 gr/m <sup>2</sup>

\* cubic meters of natural gas saved per meter squared of greenhouse in duration of one year

The choice experiment is implemented in the form of a survey. In our study, the survey is performed in two ways: 1) an online questionnaire with the web-link sent to email addresses of growers and 2) face-to-face interviews with growers who participated in a horticulture-related trade exhibition.

The survey has three distinct parts. The first part of the survey collects some demographic information from growers and some questions about current crop cultivated, energy source and other information about the type of greenhouse. The objective of this part is to check for the representativeness of growers in the sample. The second part of survey collects the preferences of growers from the alternative energy sources offered in several choice sets; the third part asks questions about growers' attitudes related to pollution caused by cultivation. The number of choice sets given to each respondent is constant and it is determined during the design of the choice experiment based on the number of selected alternatives, numbers of attributes defined and the levels attached to attributes. Table 2 shows an example choice set as seen by respondents (the English translated version).

**Table 2 An example choice set**

	Solar thermal energy	Bio-fuel energy	Geothermal energy
Beginning investment €/m <sup>2</sup>	65 €/m <sup>2</sup>	21 €/m <sup>2</sup>	150 €/m <sup>2</sup>
Amount of natural gas saved [m <sup>3</sup> a.e./ (m <sup>2</sup> jr)]	10 [m <sup>3</sup> a.e./ (m <sup>2</sup> jr)]	12 [m <sup>3</sup> a.e./ (m <sup>2</sup> jr)]	40 [m <sup>3</sup> a.e./ (m <sup>2</sup> jr)]
Additional electricity required (kWh/m <sup>2</sup> )	27 kWh/m <sup>2</sup>	3 kWh/m <sup>2</sup>	10 kWh/m <sup>2</sup>
Emission savings (gr/m <sup>2</sup> )	7 gr/m <sup>2</sup>	31 gr/m <sup>2</sup>	55 gr/m <sup>2</sup>
Which Energy source do you prefer?			

Once the survey is completed by a sufficient number of respondents, statistical models such as Multi-Nomial Logit (MNL) are used to estimate growers' preference by calculating parametric coefficients. These coefficients tell us which alternative is most desirable and which attribute has most impact on the growers' total utility function (the effects of the attributes are assumed to be linear). A software package called BIOGEME is used to calculate the coefficients of different attributes based on MNL model from the choice data<sup>14</sup>. The values of these coefficients indicate the slope of utility curve. The MNL is selected based on the assumption that the utility as obtained from the choices of respondents is composed of a systematic non-random part (also known as observed part of utility) and a random error part. The other assumption was that the additional random error term would be independently and identically distributed (IID)<sup>15</sup>.

14 Bierlaire, M. (2003). BIOGEME: A free package for the estimation of discrete choice models , Proceedings of the 3rd Swiss Transportation Research Conference, Ascona, Switzerland.

15 Hensher, D. A., Rose, J. M., & Greene, W. H. (2005). Applied choice analysis: a primer. Cambridge University Press.

The idea of choice-modelling is that, while growers choose among energy alternatives, they implicitly revealed their preferences on the alternatives and attractiveness of the attributes. Furthermore, based on growers' background characteristics and the type of horticulture, they can be clustered into groups that have common characteristics. Distinct utility functions are calculated for each cluster and hence the heterogeneity among different type of growers is investigated.

## RESULTS

Although the online survey is still ongoing and more data from growers are expected, we are able to provide some preliminary results based on data already gathered from growers. The most influential attribute on growers opinions is the "amount of natural gas saved" per energy resource, whereas, our intuition was that "beginning capital" would be most influential attribute. The latter attribute came only as second most influential attribute. Emission savings appear to be the attribute least important to the growers.

Those respondents that grew crops with intensive heat demand (e.g. tropical pot plants) even put more emphasis on the quantity of natural gas saved per meter squared in a year. In contrast, those growers who require a lot of lighting in their cultivation process were more concerned with the "additional electricity required" attribute.

With this type of analysis, it is revealed that different solutions are preferred for different types of cultivations. For instance, those growers with intensive heat requirements for their crops are more inclined to invest on geothermal energy, whereas those who required more light in their greenhouses are willing to invest in a biofuel alternative (in comparison to the rest of the growers). The reason behind this behaviour is that with investing in biofuels, these growers do not need to buy a large quantity of electricity from the grid, which will reduce their production costs.

At a more abstract level and when considering alternatives, the geothermal energy has been chosen as most favourite alternative amongst the three alternatives for delivering a high quantity of heat and for requiring less electricity usage, while this source of energy also provides the highest emission savings among the alternatives.

## CONCLUSION

This research employs a proven methodology called discrete choice modelling and applies it in the field of horticultural research. The opinion and preferences of greenhouse growers are investigated regarding use of alternative energy sources in Dutch greenhouses. Also the attitude of these growers with respect to emissions from burning natural gas are measured and reflected in their choices. The most important aspect relating to energy use in greenhouses are thought to be heat, electricity and initial investment on new energy sources.

Different types of crops dominate preferences of growers and their approaches towards the issue of energy alternatives. In the absence of fossil fuels, if the crop requires a large amount of heat, then growers are more interested in geothermal energy and if the crops require electricity for lighting then growers tend to go for bio-fuels. These findings capture the mind-set of growers and their probable approach towards the introduction of alternative and sustainable energy sources, given that fossil fuels become scares or too expensive.

Furthermore, the outcomes of this research can be helpful for infrastructure decision makers and planners. The results confirm that different sort of cultivations have different utility requirements. Therefore, the decision to provide heat, electricity or CO<sub>2</sub> for horticultures can be based on the type of crops that are cultivated in a given area. Also in this research we intend to provide policy recommendations to further guide/steer Dutch greenhouse growers to move towards alternative and sustainable energy sources, and thus help shape their energy transition.

## ACKNOWLEDGEMENT

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# Spatially and Temporally Explicit Energy System Modelling to Support the Transition to a Low Carbon Energy Infrastructure – Case Study for Wind Energy in the UK

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<http://discovery.ucl.ac.uk/1469399/>

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## ABSTRACT

Renewable energy sources and electricity demand vary with time and space and the energy system is constrained by the location of the current infrastructure in place. The transitioning to a low carbon energy society can be facilitated by combining long term planning of infrastructure with taking spatial and temporal characteristics of the energy system into account. There is a lack of studies addressing this systemic view. We soft-link two models in order to analyse long term investment decisions in generation, transmission and storage capacities and the effects of short-term fluctuation of renewable supply: The national energy system model UKTM (UK TIMES model) and a dispatch model. The modelling approach combines the benefits of two models: an energy system model to analyse decarbonisation pathways and a power dispatch model that can evaluate the technical feasibility of those pathways and the impact of intermittent renewable energy sources on the power market. Results give us the technical feasibility of the UKTM solution from 2010 until 2050. This allows us to determine lower bounds of flexible elements and feeding them back in an iterative process (e.g. storage, demand side control, balancing). We apply the methodology to study the long-term investments of wind infrastructure in the United Kingdom.

**Keywords:** Energy System Model, Dispatch Model, Optimisation, Wind Energy, Spatially Explicit, Temporally Explicit

## INTRODUCTION

Under the Renewable Energy Directive<sup>1</sup>, the European Commission (EC) implemented the target to increase the share of renewable energy in gross final energy consumption from 8.5% in 2005 to 20% in 2020. Further, in its Framework for Climate and Energy Policies the EC proposed a reduction in greenhouse gas emissions of 40% below the 1990 level and an increase in the share of renewable energy to at least 27% by 2030<sup>2</sup>. These targets imply an increase of distributed, variable power generation. Transitioning to this low carbon energy future needs long-term planning and technically feasible solutions. The economic modelling of electricity markets is not possible without accounting for technical constraints. Investment decisions regarding renewable energy generation, transmission and storage are interconnected. Renewable energy sources (RES) and electricity demand vary with time and space and the energy system is constrained by the location of the current infrastructure in place. A large-scale deployment of renewable energy generation can be facilitated by combining long-term planning for these infrastructure investments with seasonal, daily and short-term dynamics of supply and demand<sup>3</sup>.

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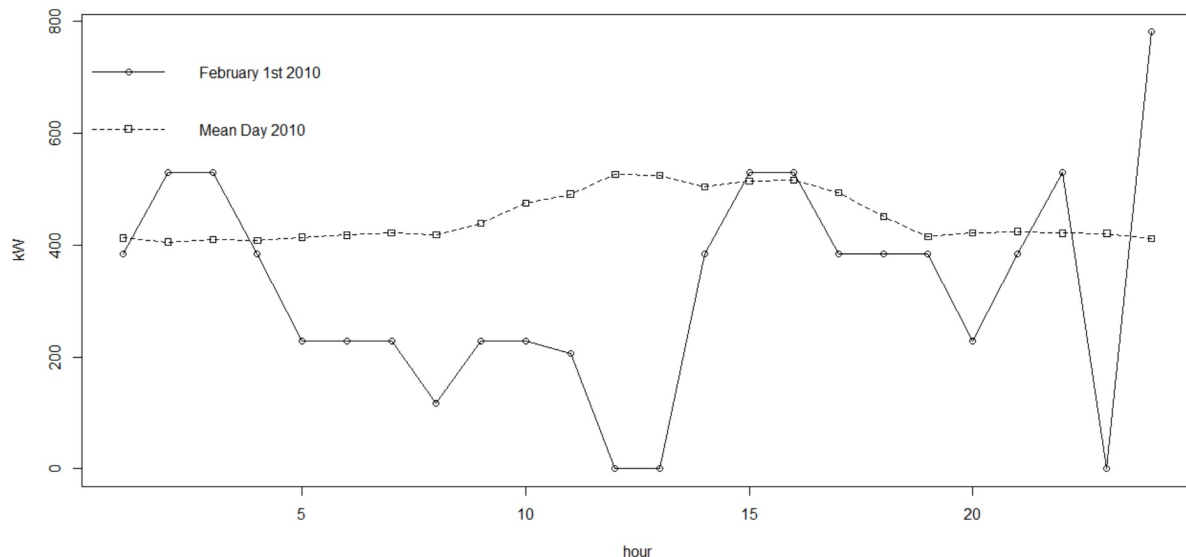
1 European Commission. Directive 2009/28/EC of the European parliament and of the council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC". (2009).

2 European Commission. A policy framework for climate and energy in the period from 2020 to 2030. (2014). at <[http://ec.europa.eu/energy/doc/2030/com\\_2014\\_15\\_en.pdf](http://ec.europa.eu/energy/doc/2030/com_2014_15_en.pdf)>

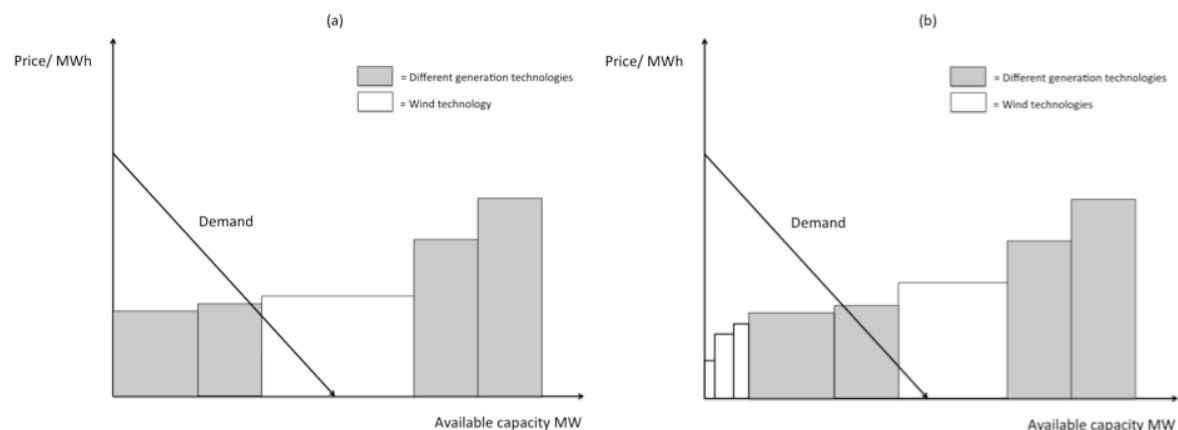
3 Haller, M., Ludig, S. & Bauer, N. Decarbonization scenarios for the EU and MENA power system: Considering spatial distribution and short term dynamics of renewable generation. Energy Policy (2012). doi:10.1016/j.enpol.2012.04.069

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Energy system models integrate several components of the system. However, they have a simplified time and geographical resolution<sup>4,5</sup>. This is a trade off between technical detail and level of integration which sacrifices detailed modelling of grid and dispatch in order to gain long-term insights for the whole energy system<sup>6</sup>. Therefore, the representation of RES in energy systems models is usually highly stylized<sup>7</sup>. When introducing geographically differentiated availabilities in the energy system model we would generally consider a supply cost curve. Consequently, only regions with high enough availabilities would be considered as possible in the solution<sup>5</sup>. For example, figure 1 illustrates the difference in hourly wind power output between a randomly selected day in one region and a mean day for 2010 using NCEP Climate Forecast System Reanalysis data<sup>8</sup> and own analysis as described under the Methodology section.



**Figure 1** Wind energy output per 2.5MW turbine for one randomly selected day and region in England and Wales vs. the mean over all days and regions in England and Wales



**Figure 2** Effects of the spatial resolution on the ordering of a supply curve in an energy system model: (a) model with one wind region, (b) model with four wind regions<sup>9</sup>

4 Pfenninger, S., Hawkes, A. & Keirstead, J. Energy systems modeling for twenty-first century energy challenges. *Renewable and Sustainable Energy Reviews* 33, 74–86 (2014).

5 Simoes, S., Huld, T., Mayr, D., Schmidt, J. & Zeyringer, M. The impact of location on competitiveness of wind and PV power plants – case study for Austria. in (2013).

6 Sullivan, P., Krey, V. & Riahi, K. Impacts of considering electric sector variability and reliability in the MESSAGE model. *Energy Strategy Reviews* 1, 157–163 (2013).

7 Ludig, S., Haller, M., Schmid, E. & Bauer, N. Fluctuating renewables in a long-term climate change mitigation strategy. *Energy* 36, 6674–6685 (2011).

8 Saha, S. et al. The NCEP Climate Forecast System Reanalysis. *Bull. Amer. Meteor. Soc.* 91, 1015–1057 (2010).

Figure 2 shows the effects of using different spatial resolutions represented by a single technology for one region (a) and several wind technologies for several regions on the supply curve of an energy system model. In Figure 2 (a) using one average wind region makes it too expensive to be included in the supply curve which meets demand. Differently, in Figure 2 (b) three wind locations are part of the solution<sup>9</sup>. A similar graph can be drawn showing the effects of the temporal resolution on the ordering of a supply curve in an energy systems model.

If using geographically aggregated renewable resource data in a dispatch model, the choice of flexible instruments will be under- or overestimated. Averaging wind availability and demand does not capture events of e.g. low wind availability and high demand when the usage of backup plants or stored electricity is necessary.

Most studies do not include the systemic view necessary<sup>3</sup> combining long-term planning with an adequate representation of the spatial and temporal characteristics of RES to provide sufficient insights into the transition to a low carbon infrastructure. Recently, there have been first approaches for more detailed temporal modelling in order to account for fluctuating RES: Kannan and Turton<sup>10</sup> introduce dispatch elements into the Swiss TIMES model. They implement 4 seasonal, 3 daily and 24 hourly time slices. They conclude that this approach gives more detail but cannot replace a dispatch model. Ludig et al.<sup>7</sup> introduce a higher temporal resolution into the LINES model for Germany.

Others such as Pina et al.<sup>11</sup>, Deane et al.<sup>12</sup> and Welsch et al.<sup>13</sup> developed hybrid modelling approaches soft-linking energy system models with temporally detailed power system models. Their approach results from accepting that greater insights can be gained by drawing on the strengths of different models<sup>12</sup>.

All studies we reviewed focus on a better description of the power sector section by improving the temporal resolution but disregard the modelling of spatial characteristics of RES. Both elements are important as intermittent RES and demand vary with time and in space due to the small spatial resolution over which these vary. Further, without considering the location of transmission and generation capacities, effects on the transmission grid and the need for its extension cannot be evaluated. We conclude from our review that there is a lack of research methodologies able to answer the following questions: What are the cost effective, technically feasible long term decarbonisation strategies leading to a low carbon power system? What is the role of flexible elements in the energy system to support a large-scale integration of RES?

We therefore propose a hybrid-modelling approach that addresses both temporal and spatial characteristics of RES by combining an energy system model with a power dispatch model. Energy system models give a more comprehensive overview of the entire sector including its long term planning. Power systems models are better suited to high resolution modeling of the electricity sector studying technical feasibilities and market implications but they usually do not take planning decisions. They thus rely on scenarios or inputs from other models. A combination of these two approaches can give valuable insights into the power sector and examining the technical feasibility and market implications of the results from a long term planning model.

## UK CASE STUDY

We apply the model to the UK, which is in the process of integrating high shares of intermittent RES into its system. Thus, it is a good case study. The target share of energy from RES in gross final energy consumption amounts to 15% in 2020 from 1.3% in 2005<sup>1</sup>. The UK government estimates offshore wind to represent 37%, onshore wind 29%, ocean energy 3% and solar PV 2% of gross renewable electricity consumption in 2020<sup>14</sup>. According to the Department of Energy & Climate Change<sup>14</sup> the UK has the best wind, wave and tidal resources in Europe. Wind and tidal energy sources are geographically diverse over varying terrain, meaning that analysis of spatial variability is

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9 Simoes, S., Zeyringer, M., Mayr, D., Huld, T. & Nijs, W. Impact of modelling geographical disaggregation of wind and PV electricity generation in large energy system models: a case study for Austria. *submitted to Energy* (2014).

10 Kannan, R. & Turton, H. A Long-Term Electricity Dispatch Model with the TIMES Framework. *Environ Model Assess* **18**, 325–343 (2013).

11 Pina, A., Silva, C. A. & Ferrão, P. High-resolution modeling framework for planning electricity systems with high penetration of renewables. *Applied Energy* **112**, 215–223 (2013).

12 Deane, J. P., Chiodi, A., Gargiulo, M. & Ó Gallachóir, B. P. Soft-linking of a {Citation}power systems model to an energy systems model. *Energy* **42**, 303–312 (2012).

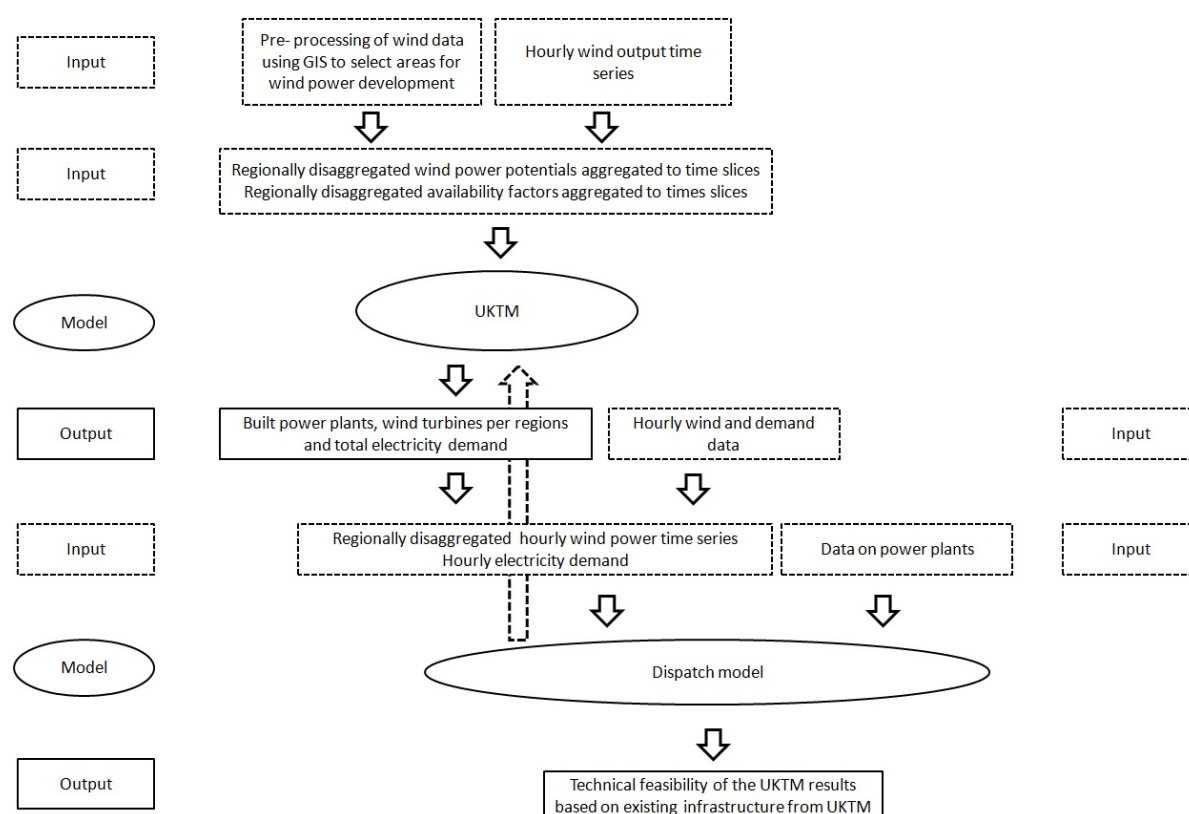
13 Welsch, M. et al. Modelling elements of Smart Grids – Enhancing the OSeMOSYS (Open Source Energy Modelling System) code. *Energy* **46**, 337–350 (2012).

14 Department of Energy & Climate Change. National Renewable Energy Action Plan for the United Kingdom Article 4 of the Renewable Energy Directive 2009/28/EC 1. (2010).

interesting. UK electricity demand is centered in the South, whereas the resource potential is concentrated be found in the North: High wind speed regions and the main tidal energy opportunities are both found in Scotland<sup>15, 16</sup>. As wind energy will represent the largest share of variable RES we concentrate in this modelling exercise solely on this resource. There is a limited number of studies for the UK considering spatial and temporal characteristics of variable renewables and demand and their interaction: Sinden<sup>15</sup>, Green and Vasilakos<sup>17</sup>, Coker et al.<sup>18</sup> and Iyer et al.<sup>19</sup>

## METHODOLOGY

We soft-link two models in order to analyse long term investment decisions in generation, transmission and storage capacities, and the effects of short-term fluctuation of renewable supply: The national energy system model UKTM (UK TIMES model) and a dispatch model, both developed at the UCL Energy Institute. This approach allows us to determine the technical feasibility of the UKTM solution until 2050. Further, the dispatch model gives additional insights into the electricity market. The modelling process is illustrated in Figure 3 and will be explained in more detail in the following paragraphs. The dashed arrow refers to future work.



**Figure 3 Graphical representation of the modeling approach**

UKTM is a linear optimization bottom-up technology-rich model based on the TIMES model generator. It minimizes total energy system costs required to satisfy the exogenously set energy service demands subject to a number of additional constraints<sup>20</sup>. UKTM contains 16 time slices: 4 seasons and 4 intraday (day, evening, late evening, night)

15 Sinden, G. Characteristics of the UK wind resource: Long-term patterns and relationship to electricity demand. *Energy Policy* **35**, 112–127 (2007).

16 IPCC. *Renewable Energy Sources and Climate Change Mitigation Special Report of the Intergovernmental Panel on Climate Change*. (Cambridge Univ Pr, 2011). at <[http://srren.ipcc-wg3.de/report/IPCC\\_SRREN\\_Full\\_Report.pdf](http://srren.ipcc-wg3.de/report/IPCC_SRREN_Full_Report.pdf)>

17 Green, R. & Vasilakos, N. Market behaviour with large amounts of intermittent generation. *Energy Policy* **38**, 3211–3220 (2010).

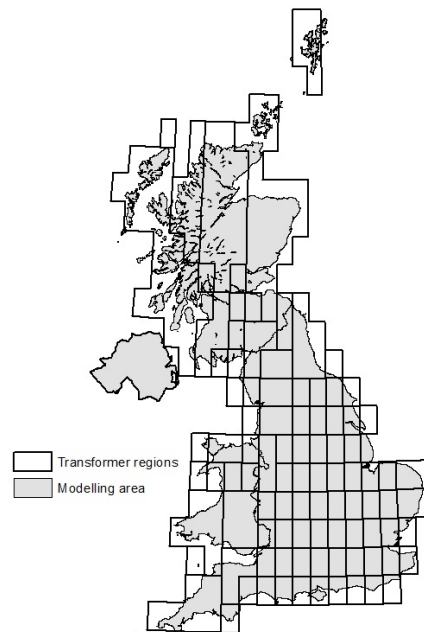
18 Coker, P., Barlow, J., Cockerill, T. & Shipworth, D. Measuring significant variability characteristics: An assessment of three UK renewables. *Renewable Energy* **53**, 111–120 (2013).

19 Iyer, A. S., Couch, S. J., Harrison, G. P. & Wallace, A. R. Variability and phasing of tidal current energy around the United Kingdom. *Renewable Energy* **51**, 343–357 (2013).

20 Loulou, R. & Labriet, M. ETSAP-TIAM: The TIMES integrated assessment model Part I: Model structure. *Computational Management*

and one region (UK). The model comprises a time period from 2010 (the base year) to 2050 with one model period covering 5 years (represented by one representative year). More information on UKTM can be found in Daly et al.<sup>21</sup> and on the TIMES model generator in Loulou and Labriet<sup>20</sup> and in Loulou<sup>22</sup>.

Similar to other dispatch models<sup>23,24</sup>, our power system model maximizes welfare or, in other words, minimizes annual variable electricity production costs. Costs are defined for each electricity generation source as the sum of the variable operation and maintenance costs and fuel costs. In addition, we also include CO<sub>2</sub> emissions. Input data are the power plants resulting from UKTM and variable electricity production costs per plant. For the dispatch model we combine them with technical information such as start costs and ramping rates. Other data are hourly demand time series and hourly resource time series. In order to be able to at a later stage assess grid infrastructure investments we divide the UK into transformer segments. Therefore, we distribute each grid cell (0.5° x 0.5°) to the closest transmission transformer<sup>25</sup>. This gives us 90 regions as illustrated in Figure 4.



**Figure 4 The 90 transformer regions**

In the scope of this analysis, we use highly spatially and temporally resolved time series for potential sites of onshore wind power installations. We obtained wind speed data from the NCEP - CFSR climate reanalysis (National Centre for Climate Prediction Climate Forecast System Reanalysis)<sup>8</sup>. We interpolate the meteorological data to a 0.5° x 0.5° decimal grid. Wind speed is provided at 10 m above the Earth's surface by NCEP – CFSR. This was adapted to turbine hub height using the power law, and a Hellman exponent of 1/7 onshore and 1/9 offshore. This dataset gives us hourly wind power output for a 2.5 MW turbine from 2000 until 2010 in kW. For this preliminary study we use the wind data for the year 2010. We calculate the availability factor of wind energy for each of the 16 UK time slices. The availability factor in TIMES describes the percentage of the year in which the technology is functional. The total wind potential per grid cell is calculated by subtracting cities, roads, protected areas and water bodies from the total available area in each grid cell. We model a wind turbine of the size of 2.5 MW. We assume that the distance between

*Science* **5**, 7–40 (2008).

<sup>21</sup> Daly, H. E., Dodds, P. E. & Fais, B. The UK TIMES Model Documentation V1.00. (2014).

<sup>22</sup> Loulou, R. ETSAP-TIAM: The TIMES integrated assessment model. Part II: Mathematical formulation. *Computational Management Science* **5**, 41–66 (2008).

<sup>23</sup> Brancucci Martínez-Anido, C. et al. Medium-term demand for European cross-border electricity transmission capacity. *Energy Policy* **61**, 207–222 (2013).

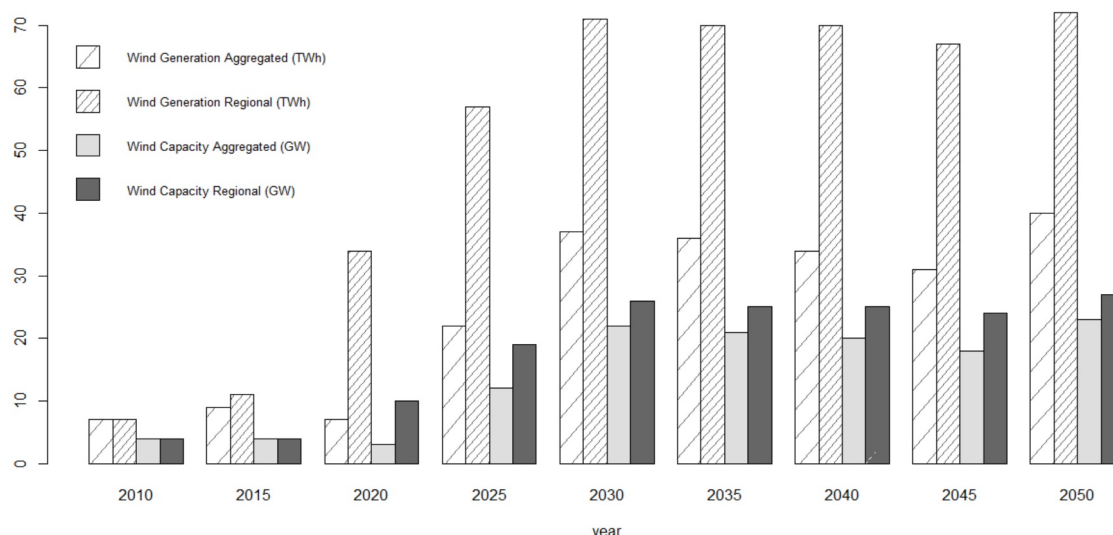
<sup>24</sup> Weigt, H., Jeske, T., Leuthold, F. & von Hirschhausen, C. 'Take the long way down': Integration of large-scale North Sea wind using HVDC transmission. *Energy Policy* **38**, 3164–3173 (2010).

<sup>25</sup> Nationalgrid. Transmission Network: Shape files. at <<http://www2.nationalgrid.com/uk/services/land-and-development/planning-authority/shape-files/>>

two wind turbines has to be at least five times the rotor diameter. The rotor diameter of a 2.5 MW turbine amounts to 90 meters<sup>26</sup>. This translates to an area of approximately 1 km<sup>2</sup> needed per wind turbine. These assumptions results in a total wind power potential of 114 GW. Availability factors vary between 3% and 71% per time slice and region. On average the time slice showing the highest AF is autumn night with 29%. We locate the existing plants in each grid cell using the DECC planning database on renewable generation<sup>27</sup> and allocate them to the wind power time series. This gives us the yearly wind power output for each turbine. We run the UKTM in a low GHG emission scenario meaning a reduction in GHG emissions of 80% compared to 1990 levels. For comparison, we perform two runs: an aggregated run with one single region and a regional run with 90 wind regions based on the transformer segments. In a next step we use the results on all built power plants including built wind turbines per region and total electricity demand as an input into the dispatch model. We use the 2010 energy demand as provided by Nationalgrid<sup>28</sup>. Assuming that its shape will not change we scale the hourly values to the total electricity demand for 2050 resulting from UKTM. As we know where UKTM builds the wind turbines we can again allocate the wind time series to get the hourly electricity production per wind turbine. We then run the power dispatch model for the year 2050. The hourly dispatch enables us to study the technical appropriateness of the solution given by UKTM assuming no infrastructure change and define upper bounds and lower limits, which can be fed back in an iterative process.

## RESULTS, CONCLUSIONS AND OUTLOOK

Figure 5 shows that the spatial disaggregation of wind energy resources leads to a higher share of wind energy in the UKTM runs: In the aggregated scenario, the total wind capacity installed in 2050 is 23GW and 40GWh are generated. In the regional scenario 27GW of wind are installed and 72GWh are produced in 2050.



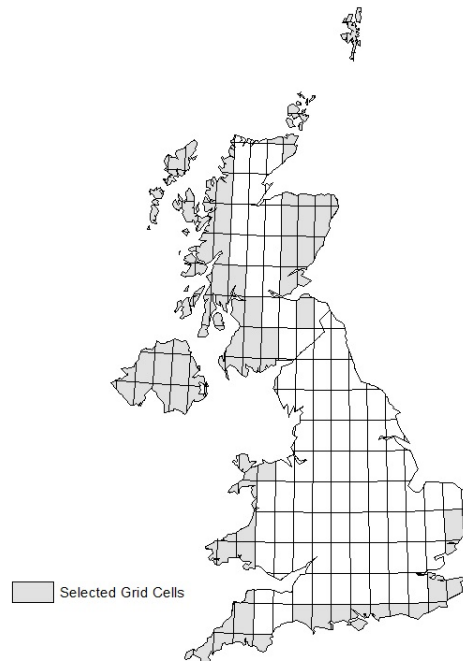
**Figure 5 Wind generation and capacity per year for the aggregated and regional run**

In the disaggregated run 27 regions out of 90 are selected. As figure 6 illustrates the selected regions are found around the coastal areas of England and Wales, in Scotland and Northern Ireland with higher wind availabilities.

<sup>26</sup> Fraunhofer Institute. Windmonitor. (2014). at <[http://windmonitor.iwes.fraunhofer.de/windwebdad/www\\_reisi\\_page\\_new.show\\_page?page\\_nr=73&lang=en&owa=&owa\\_own\\_header=0](http://windmonitor.iwes.fraunhofer.de/windwebdad/www_reisi_page_new.show_page?page_nr=73&lang=en&owa=&owa_own_header=0)>

<sup>27</sup> Department of Energy & Climate Change. DECC Planning Database- Montly Extract. (2014). at <<http://restats.decc.gov.uk/app/reporting/decc/monthlyextract>>

<sup>28</sup> Nationalgrid. Demand\_Jan 2010 to December 2012. <http://www2.nationalgrid.com/UK/Industry-information/Electricity-transmission-operational-data/Data-Explorer/>



**Figure 6 Regions selected by the UKTM**

Preliminary runs using the dispatch model show compared to UKTM higher wind curtailment (45% vs. 37%). In 5% of the hours supply does not fulfil demand. These results indicate that the energy system model installs a too high amount of baseload capacity and not enough flexible generation for the system to operate without disconnecting demand. In our case study the energy system model installs 21 GW of nuclear until 2050 (total installed capacity amounts to 73GW in both runs). In both runs the total electricity generation from nuclear in 2050 amounts to 177 TWh of nuclear in both runs (total electricity production is 332 TWh in the regional and 311 in the aggregated run). In the aggregated run in 2050 3% of the total generation comes from gas (0% in the regional run) compared to 47% in 2010.

Our methodology allows to better represent the power sector in energy system models. This will become increasingly important when evaluating high shares of fluctuating RES. The modelling approach combines the benefits of two models: an energy system model to analyse decarbonisation pathways and a power dispatch model which can evaluate the technical feasibility of those pathways and the impact of intermittent RES on the power market.

In a next step we will run the dispatch model from 2010 until 2050. Further, we will conduct a sensitivity analysis changing the wind resource years and the shape of the demand profile allowing to account for a large scale deployment of e.g. electric vehicle or heat pumps. Further research will focus on feeding the results from the dispatch model back to the energy system model by introducing upper bounds (e.g. maximum wind capacity without backup capacity) and lower limits (e.g. storage) and running the two models in an iterative process. We will include an algorithm to extend the existing electricity grid<sup>29</sup> based on the price difference in two nodes into the dispatch model. As a result we will be able to not only include costs for flexible elements but also for line extensions into UKTM.

<sup>29</sup> Leuthold, F. Economic Engineering Modeling of Liberalized Electricity Markets: Approaches, Algorithms, and Applications in a European Context. (Dresden University, 2010).





# Tour-based Travel Mode Choice Estimation based on Data Mining and Fuzzy Techniques

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## ABSTRACT

This paper extends tour-based mode choice model, which mainly includes individual trip level interactions, to include linked travel modes of consecutive trips of an individual. Travel modes of consecutive trip made by an individual in a household have strong dependency or co-relation because individuals try to maintain their travel modes or use a few combinations of modes for current and subsequent trips. Traditionally, tour based mode choice models involved nested logit models derived from expert knowledge. There are limitations associated with this approach. Logit models assumes i) specific model structure (linear utility model) in advance; and, ii) it holds across an entire historical observations. These assumptions about the predefined model may be representative of reality, however these rules or heuristics for tour based mode choice should ideally be derived from the survey data rather than based on expert knowledge/judgment. Therefore, in this paper, we propose a novel data-driven methodology to address the issues identified in tour based mode choice. The proposed methodology is tested using the Household Travel Survey (HTS) data of Sydney metropolitan area and its performances are compared with the state-of-the-art approaches in this area.

**Keywords:** Travel Mode Choice, Data Mining, Travel Mode Choice, Fuzzy Sets

## INTRODUCTION

One of the fundamental processes that shape urban landscapes is people's travel behaviour. Hence, a thorough understanding of travel behaviour is crucial for effective transportation and land use planning in urban environments. Travel mode choice is an important aspect of travel behaviour, and also one of the four steps in transportation demand estimation for urban planning. It refers to the procedure of assigning available travel modes (e.g. car, walk, bus, and train) to each individual's trips in a household based on personal, activity and environmental attributes.

Travel mode choice has received a significant research attention. From a modelling perspective, travel mode choice has been primarily studied using discrete choice models (reference). Such models include probit models<sup>1</sup>, multinomial logit (MNL) models<sup>2</sup> and nested logit models<sup>3</sup>. However, discrete choice models have received stringent criticisms due to their inherent limitations such as i) specific model structure needs to be specified in advance, which ignores partial relationships between explanatory variables and travel modes for subgroups in a population; ii) inability to model

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1 Gaudry, M.J.I. (1980) 'Dogit and logit models of travel mode choice in Montreal', *Canadian Journal of Economics*, vol. 13, pp. 268-279

2 McFadden, D. (1973) 'Conditional Logit Analysis of Qualitative Choice Behavior', *Frontiers in Econometrics*, P. Zarembka, ed., Academic Press, New York, NY

3 Daly, A. and Zachary, S. (1979) 'Improved multiple choice models', in: D. Hensher and Q. Dalvi (eds), *Identifying and measuring the determinants of mode choice*, Teakfield, London, pp. 335-357

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complex non-linear systems, which represent complex relationships involved in human decision making; and iii) they check only for conditions that hold across an entire population of observations in the training dataset and patterns cannot be extracted from a subgroup of observations<sup>4</sup>.

Meanwhile, machine learning has emerged as a superior means in travel mode choice research by which travel mode choice can be better predicted while alleviating aforementioned shortcomings<sup>4,5,6,7</sup>. For example, Xie et al.<sup>4</sup> reported that Artificial Neural Networks (ANN) achieved better results compared to MNL based on a comparative study conducted using work-related travel data. Similarly, Rashmidatta<sup>8</sup> has compared nested logit model and ANN model for long distance travel mode choice selection, and illustrated the better performance of ANN over other models. Furthermore, there are other studies that compare and contrast the performance of machine learning techniques with other traditional models, and propose to use machine learning techniques such as ANN and DT for travel mode choice prediction<sup>9,5,6,7,10</sup>.

In addition to the differences in methods used, research into travel mode choice exhibits variations in terms of the predicted trip type, i.e., independent trips verses tour-based (linked) trips and data type used. It is important to understand these variations prior to establishing innovative aspects of this study. We identify three types of trips, (a) independent trips, (b) linked trips of an individual, and (c) linked trips of individuals within a household. To predict these trip types, researchers have used crisp or fuzzy data or a mix of crisp and fuzzy data. In this study, we use machine learning techniques to predict both independent trips and linked trips of an individual using a mix of crisp and fuzzy data. We are unaware of any other study where a mix of crisp and fuzzy data is used to for predicting the modes for tour-based linked trips. This methodological advance is rightly justified in results we achieved as explained in a later section. Table 1 serves three purposes: it summarizes existing research in travel mode choice, puts this study in perspective and identifies future research directions. The overall objective of this study is to achieve higher accuracy in travel mode choice predictions using machine learning algorithms.

## PROPOSED MODELLING METHODOLOGY

This section details proposed modelling methodology in this paper for the travel mode choices of an individual in a household based on a travel survey. As mentioned in Section 1, travel mode choice problem has been studied largely using discrete choice models such as probit model, multinomial logit (MNL) model and nested logit models. Major limitations in these studies are i) predefined utility model with all the explanatory variables included ignoring partial relationships; ii) inability to model non-linear relationships; and, iii) models cannot be extracted from a subset of observations. This led us to explore methods in the area of machine learning, artificial neural networks (ANN) and decision trees (DT), to overcome the aforementioned limitations. These methods have predominantly been used for problems related to classification based on historical data or evidence.

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4 Xie, C., Lu, J., and Parkany, E. (2003) 'Work Travel Mode Choice Modeling Using Data Mining: Decision Trees And Neural Networks', *Transportation Research Record: Journal of the Transportation Research Board*, No. 1854, pp. 50-61

5 Reggiani, A. and Tritapepe, T. (2000) 'Neural networks and Logit models applied to commuters' mobility in the Metropolitan area of Milan', in: V. Himanen, P. Nijkamp and A. Reggiani, (eds), *Neural networks in Transport Systems*, Aldershot, Ashgate, pp. 111-129

6 Cantarella, G.E. and De Luca, S., (2003) 'Modeling transportation mode choice through artificial neural networks', in *Fourth International Symposium on Uncertainty Modeling and Analysis, ISUMA 2003*, pp.84-90, 24-24 Sept. 2003

7 Shmueli, D., Salomon, I. and Shefer, D. (1996) 'Neural network analysis of travel behavior: evaluating tools for prediction', *Transportation Research Part C: Emerging Technologies*, Vol. 4 (3), pp. 151-166.

8 Rasmidatta, I. (2006) 'Mode Choice Models for Long Distance Travel in USA', PhD Thesis, University of Texas at Arlington, USA

9 Nijkamp, P., Reggiani, A., and Tritapepe, T. (1996) 'Modelling inter-urban transport flows in Italy: A comparison between neural network analysis and logit analysis', *Transportation Research Part C: Emerging Technologies*, Vol. 4, No. 6, pp. 323-338.

10 Hensher, D.A. and Ton, T.T. (2000) 'A comparison of the predictive potential of artificial neural networks and nested logit models for commuter mode choice', *Transportation Research Part E: Logistics and Transportation Review*, Vol. 36, No. 3, pp.155-172.

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**Table 1. Classification of state of the art approaches in mode choice**

	Data Type	Discrete Choice Models		Machine Learning	
		Crisp Data	Crisp & Fuzzy Data	Crisp Data	Crisp & Fuzzy Data
Trip Type					
Independent Trips	1,2,3,10	1	4,5,6,7,10	2	
Linked Individual Trips (tour-based)	3	-	4	This Study	
Linked Household Trips	11	-	Future Work	Future Work	

Following section mainly presents the data processing and fuzzy analysis of dataset for modelling and prediction. These steps are used for ANN and DT for learning and prediction.

### Data processing to link consecutive trips of an individual

Travel mode choice can be understood as the travel mode to which traveller pre-commit given a particular purpose (shopping, work, school) and other travel details (departure times, arrival times, origin, destination, etc). Majority of the traditional literature focuses on individual trip, i.e., the travel between a pair of origin and destination. In this type of modelling, each trip is considered as an independent event, for which an individual has to make independent decision about travel mode. However, due to complexity of patterns of trip of an individual, assumption about each trip to be independent does not hold well. Furthermore, Cirillo and Axhausen<sup>11</sup> suggested that individuals maintain their mode during a tour (a sequence of trips starting and ending at the same place, i.e., home → work → shopping → home), especially if they use an individual vehicle (car, motorcycle or bicycle). Following the assumption that there is strong dependency between travel modes adopted in consecutive modes, this subsection considers consecutive trip modes (in a tour) for modelling and prediction.

Travel surveys are increasingly used in most of the metropolitan cities to understand the people's travel behaviour and demand for transport planning. These travel surveys record socio-economic characteristics, demographic characteristics, household attributes, travel details/diary, purpose, departing and arriving times, and travel modes, among others. These records are used by planner to design or change existing transport plans. This paper will utilize these travel surveys to model mode choices of an individual given other attributes.

<sup>11</sup> Dell'Orco, M, Circella, G & Sassanelli, D (2007) 'A hybrid approach to combine fuzziness and randomness in travel choice prediction', *European Journal of Operational Research*, vol. 185, 2007, pp. 648-658

Let  $(X, Y)$  be a survey dataset of trips made by  $L$  travelers, where  $(x^{lm}, y^{lm})$  represents the  $m$ -th trip made by the traveller  $l$ ,  $m \in \{1, 2, \dots, M_l\}$ ,  $l \in \{1, 2, \dots, L\}$ . Without loss of generality, suppose  $x^{lm} = (x_1^{lm}, x_2^{lm}, \dots, x_n^{lm})$  and  $y^{lm} = (y_1^{lm}, y_2^{lm}, \dots, y_o^{lm})$  where each  $x_i$  ( $i = 1, \dots, n$ ) is called an explanatory attribute and each  $y_k$  ( $k = 1, \dots, o$ ) is a Boolean decision variable which indicates a possible travel mode.

In order to describe consecutive trips, we introduce an additional set of explanatory variables, which consider the mode choice adopted by the individual in previous trip, apart from  $x^{lm}$  to model the travel mode choices. The additional variable set is represented as  $x'_{lm}$  and it contains the mode choice of previous trip on a particular tour, i.e.,  $y^{l(m-1)}$ . Formally,

$$x'_{lm} = \begin{cases} \mathbf{0} & m = 1 \\ y^{l(m-1)} & m \in \{2, \dots, M_l\} \end{cases} \quad (1)$$

Since, the first trip (i.e.,  $m = 1$ ) does not have information about the previous trip mode choice ( $y^{l0}$ ), we use a dummy vector  $\mathbf{0} = (0, \dots, 0)$  to represent that. In other words we treat first trip on an individual independent and the rest of the trips to be dependent on previous trip in a tour.

The modified travel survey dataset includes  $x^{lm}$  and  $x'_{lm}$  as an explanatory set of variables to model the responses in  $y^{lm}$  for all  $l \in \{1, 2, \dots, L\}$ ,  $m \in \{1, 2, \dots, M_l\}$ . Now, this dataset is used with ANN and DT for modeling the travel mode choices of an individual in his tour.

## FUZZY DATA FOR MODE CHOICE

Fuzzy set was introduced by Zadeh<sup>12</sup> as a tool for processing uncertainty in real application systems which involve human perceptions of vague concepts such as “young person” and “big heap”. Since then, fuzzy set has been successfully used in engineering, control systems, and decision making<sup>13</sup>. Recently, it has been used in travel demand modelling<sup>12</sup>. Considering that a travel mode choice is a decision making on the basis of a set of uncertain factors including travel cost, travel time, purpose, as well as individual demographic characteristics, we argue that using fuzzy sets can better describe a person’s choice of a specific travel mode.

Travel mode choice is affected by many uncertain factors. A typical factor is the travelling period. In Sydney metropolitan area, a traveller who drives to Central Business District (CBD) during the morning peak hours is very likely to experience traffic congestions and delays. However, if the traveller makes the same trip by train during the same period, the traffic congestion has minimal impact on this trip. A traveller’s demographic characteristics may also affect his or her choice of a specific travel mode. A frequent traveller prefers driving a car to taking a public transport because of the flexibility the former offers for subsequent trips. In these examples, “morning peak hours” and “frequent traveller” are uncertain concepts whose meanings are easily understood but are hardly defined in an accurate way. Hence, using fuzzy set is an alternative to describe these uncertain concepts and related factors of them.

Fuzzy set can provide better description of and insight into a specific travel mode choice. Generally, a travel mode choice can be described as an “IF-THEN” expression such as: IF the depart time is 06:30 and the travel distance is 20.5km, THEN the travel mode is car-driving. Although this kind of description is accurate from modelling and the data point of view, it lacks the insight, particularly, in the presence of tens of similar expressions. Using fuzzy set, we can provide an intuitive and better expression as: IF the depart time is early morning and the travel time is long, THEN the travel mode is car-driving. Hence, we can combine multiple expressions into an easily understandable description and provide insight into the mode choice. Details of operations and algorithms of fuzzy sets are not included which can be found in<sup>14</sup>. Based on the features of fuzzy sets, we introduce several fuzzy attributes to replace some variables used in travel behaviour survey.

12 Yaldi, G., Taylor, M.A.P., and Yue, W. (2010) ‘Examining the possibility of fuzzy set theory application in travel demand modelling’, *Journal of the Eastern Asia Society for Transportation Studies*, Vol. 8, pp. 579-592

13 Miller, E. J., Roorda, M. J., and Carrasco, J. A. (2005) ‘A tour-based model of travel mode choice’, *Transportation*, Vol. 32, No. 4, pp. 399-422. doi:10.1007/s11116-004-7962-3

14 Biagioni, J. P., Szczurek, P. M., Nelson, P.C., and Mohammadian, A. (2008) ‘Tour-based mode choice modeling: Using an ensemble of conditional and unconditional data mining classifiers’, in *Transportation Research Board 88th Annual Meeting*, January 11-15, Washington, DC.

## CASE STUDY

### Dataset description

The household travel survey (HTS) data is the largest and most comprehensive source of information on personal travel patterns for the Sydney Greater Metropolitan Area (GMA), which covers Sydney, the Illawarra Statistical Divisions and the Newcastle Statistical Subdivision. The data is collected through face to face interviews with approximately 3000-3500 households each year (out of 5000 households in the Sydney GMA randomly invited to participate in the survey). Details recorded include (but are not limited to) departure time, travel time, travel mode, purpose, origin and destination, of each of the trips that each person in a household makes over 24 hours on a representative day of the year. Socio-demographic attributes of households and individuals are also collected.

### Fuzzy sets of travel mode choice variables

Based on the analysis of the character of exploratory variables of the dataset, we defined fuzzy sets for each of the two selected variables which are “depart\_time” and “household\_income”.

In the survey dataset, the “depart\_time” variable is recorded in minutes from 00:00 to 23:59 for the day. Following a Transport for NSW technical documentation (Bureau of Transport Statistics 2011), four fuzzy sets are defined for “depart\_time” over the 24-hour period, which are “morning peak” (*M*), “evening peak” (*E*), “inter-peak” (*I*), and “evening/night period” (*N*).

In the survey dataset, the variable “household\_income” indicates the annual approximate household income which ranges from –AU\$5005.74 to AU\$402741. Due to the spread of income, it is hard to get insight of the influence of the variable on travel mode choice. Hence, we introduced three fuzzy sets to depict easily understandable concepts which are consistent with people’s ordinary experience on household income levels. The three fuzzy sets are “low income” (*LI*), “middle income” (*MI*), and “high income” (*HI*), based on related information from the Australian Bureau of Statistics and the Australian Taxation Office<sup>15</sup>.

Following section discusses the results obtained from applying proposed methodology to the case study presented in this section.

## RESULTS AND DISCUSSION

The presented method has been implemented and tested on a 100k sample which is randomly selected from a dataset for Sydney Household Travel Survey conducted by BTS, Transport for New South Wales (TfNSW), Australia. We partitioned the 100k sample into three subsets, i.e., a training dataset (30%), a testing dataset (35%) and a validation dataset (35%). The performance measure used for the comparison of classifiers is taken to be the percentage of records correctly identified (PCI). Total 4 experiments (shown in Table 2) have been conducted based on different empirical settings (on DT and ANN) which are:

**Table 2. Experiments based on DT, ANN**

Experiment	Empirical Settings		PCI (%)	
	Fuzzy sets	Dependent trip	DT	ANN
1	N	N	64.71	68.1
2	Y	N	67.67	68.7
3	N	Y	85.63	85.9
4	Y	Y	86.17	86.8

15 Cirillo, C. and Axhausen, K. W. (2002) ‘Mode choice of complex tours: A panel analysis’, Arbeitsberichte Verkehrs- und Raumplanung, Vol. 142, Zurich: Institut für Verkehrsplanung, Transporttechnik, Strassen und Eisenbahnbau (IVT), ETH Zurich

**Experiment 1:** We use travel\_mode as decision variable and the others as explanatory variables. Under this setting, we test independent trip modelling and use this result as a benchmark for the following tests.

**Experiment 2:** Replacing the explanatory variables “hh\_income” and “depart\_time” by their fuzzy sets in Experiment 1. Under this setting, we test the performance of fuzzy sets in travel mode choice modelling.

**Experiment 3:** We add attribute “pre\_mode\_new” as an additional exploratory attribute to experiment 1 and test the performance of travel mode choice modelling based on linked trips.

**Experiment 4:** We add attribute “pre\_mode\_new” as an additional exploratory attribute to experiment 2 and test the performance of linked trips modelling based on consecutive trip under fuzzy set settings.

Table 2 gives the empirical settings and PCI of the eight experiments. Some observations from this table are:

A. Using dependent trips in a tour achieves higher PCI. For example, the PCI of experiment 1, 2 for both ANN and DT increases significantly from 64.71% to 85.63% in DT and 69.30% to 84.7% in ANN.

**Table 3. Mode shares for ANN prediction**

Travel Modes	HTS data	DT Prediction	ANN Prediction
Car_driver	40.95%	43.50%	43.11%
Car_passenger	20.65%	30.76%	19.05%
Public_transport	8.37%	7.54%	7.74%
Walk	29.26%	17.68%	29.55%
Bicycle	0.77%	0.53%	0.53%

B. Using fuzzy sets as opposed to crisp numbers gives higher PCI to ANN and DT. Experiments 1 & 2 for DT and 3 & 4 for ANN justify the use of Fuzzy sets. C. ANN performs better than the DT for all the experiments.

Based on the experiments, we can claim that our method can improve the PCI of travel mode choice. Table 3 illustrates the mode shares predicted by proposed approach considering ANN with fuzzy sets and tour based trips and it is compared with the original mode shares from HTS data. It illustrates that the mode shares from proposed approach are consistent with that from HTS data.

## DISCUSSION AND CONCLUSIONS

This paper describes a novel methodology for travel mode choices based on data mining methods such as ANN and DTs combined with fuzzy sets. The proposed method considers (i) expert judgments by using fuzzy sets instead of crisp numbers for some explanatory variables; and, (ii) using the tour-based model that uses travel modes for previous trips as one of the predictor variables for current trip's mode choice. The proposed methodology is tested on a real dataset to evaluate the performance of classifiers for travel mode choice modelling. The results from various analysis conducted in this paper suggest that the use of fuzzy sets and tour-based model for mode choice achieves higher performances. In future, this work can be extended to include other explanatory variables, new fuzzy sets, and linking the individuals in the household to achieve higher classification performances.

# Infrastructure and Extreme Events





# Planned Adaptation in Design and Testing of Critical Infrastructure: The Case of Flood Safety in The Netherlands

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## ABSTRACT

In the Netherlands, dykes and other primary water defence works are assets that are essential to keep the society and economy functioning, by protecting against flooding from sea and rivers due to extreme events. Given that 55% of the country is at risk of flooding, primary water defence works belong to its critical infrastructure. Many factors influence the risk and impact of flooding. Besides physical factors (e.g., landscape design, climate change) also socio-economic factors (e.g., population, assets) are important. Given that these factors change and feature complex and uncertain behaviour in past and future, the design and regulation of this critical infrastructure will have to be flexible enough to be able to deal with such changes. 'Planned Adaptation' refers to regulatory programmes that plan for future changes in knowledge by producing new knowledge and revising rules at regular intervals. This study describes the emergence of the next generation of Dutch primary water defence infrastructure, which through the stepwise implementation of Planned Adaptation for design and testing of primary water defence works in the mid-1990s has moved beyond the Delta Works approach of 1953 and subsequent unplanned adaptations. This has prepared the ground for the recent introduction of Adaptive Delta Management, which makes an integral part of the new Delta Plan for the Netherlands that was published on 16 September 2014 and which is also analysed in this study.

**Keywords:** Water Defence Works; Critical Infrastructure; Dealing With Uncertainty; Planned Adaptation; Delta Plan

## INTRODUCTION

After the coastal flooding disaster of 1953, the Netherlands embarked on a major multi-decade civil engineering effort to increase the protection against storm surges through the Delta Works and strengthening of the coast (dunes and dykes) – high safety standards were set in this process (e.g., for some parts of the country, protection against 1 in 10,000 year events). Also peak river discharges were re-assessed and river dykes were raised. While a significant amount of knowledge about the necessary heights and strengths of dunes and dykes was generated during that period, no system was put into place to systematically refine and update this knowledge and the resulting 'hydraulic requirements', engineering standards that correspond to the set safety standards, for the different locations along the coast. In 1989, when the Delta Works were considered to have nearly reached their completion, a five-year cycle of re-assessment of the safety of the primary water defence works was proposed along with continuous research funding to generate the required knowledge updates in a planned manner rather than in the ad hoc manner of earlier decades. The first cycle started in 1996 and the fourth cycle will run from 2017 (the cycle length has changed from five to six years to twelve years). The fourth cycle will be based on the new safety standards that have been proposed in 2014 and that will make use of renewed test and design criteria. This study argues that this system, which operates under the Water Act, has become fairly successful in generating new knowledge and making corresponding changes in the hydraulic requirements. For instance, new knowledge about wave heights along the coast have led

to significant investments in the heightening of coastal defences, and new insights into dyke failure mechanisms (in particular, 'piping') have led to a fundamental restructuring effort for dykes. Furthermore, by introducing a new risk-based approach to flood safety and a monitoring and evaluation programme that can lead to revisions of the new approach at regular intervals, science, engineering and public policy have been brought closer together in the new Delta Plan for the Netherlands that was released on 16 September 2014.

In this study, the Dutch science/engineering–policy process for setting safety standards and translating them into engineering standards for primary water defences is examined. We investigate to what extent we can see Planned Adaptation happening in this process. The term 'Planned Adaptation' is used to describe two features of a policy process: [a] there is a prior commitment to subject an existing policy to *de novo* re-evaluation and [b] systematic effort is made to mobilise new factual information for use when the re-evaluation takes place.<sup>1</sup>

## THE PERIOD BEFORE THE WATER DEFENCE ACT (1916–1995)

It took a long time before the knowledge needed to give the Netherlands protection from sea inundations started to become gathered in a systematic manner. After the flooding in 1916, for instance, a *Rijkswaterstaat* (Directorate-General for Public Works and Water Management) committee had studied whether such flooding could happen again and concluded – based on knowledge available then – that that was not the case. This 1916 judgement was not revisited until 1938, when a civil engineer in *Rijkswaterstaat*, Johan van Veen, just could not believe that no new knowledge had become available that would make a re-assessment worthwhile. He initiated a study of existing dykes and found that these did not suffice by far, largely because of local factors that had not been taken into account. This led to the *Viereilandenplan* (Four Islands Plan) of 1938, which mapped out where higher or new dykes were needed and where dams should be built. It was not immediately implemented, but – as is typically the case in the Netherlands – first a committee was formed, the *Stormvloedcommissie* (Storm Surge Commission).

By the 1940s it had become clear to engineers from *Rijkswaterstaat* and the Storm Surge Committee that many dykes were still too low and too weak to withstand the severe storm surges that were likely to come. During the Second World War a lot of land had been put under water on purpose by both the Germans and the Allied Forces. In the Battle of the Scheldt for example, in October/November 1944, the island of Walcheren at the mouth of the West Scheldt remained in German hands and to break their defence sea dykes were bombed. After the war the Dutch were able to quickly regain the land (sometimes after surmounting huge technical difficulties) and they started to believe more and more that many desired physical and social changes in the Netherlands could be effected by choosing the right government policies and engineering approach ('*maakbaarheid*'). A plan by van Veen was even presented to close off most of the delta and reduce the coastline to the length it had in the year 800. This would lead to a significant amount of new land and a high level of safety. This plan did not get enough support within *Rijkswaterstaat*, though. He was even fired as secretary of the Storm Surge Commission. Still, the implementation of his Four Islands Plan was continued with the closing of the Den Briel Meuse in 1950.

But the Netherlands were too late with raising and fortifying all the dykes for which this was deemed necessary according to the Storm Surge Commission. The knowledge that was available about the risks had not been acted upon soon enough; the country was 'slapped in the face'. In February 1953, a storm surge disaster occurred, generally known in the Netherlands as 'The Disaster'. Though the number of casualties was not very high as compared with earlier disasters (1,836 people drowned as compared to tens of thousands in earlier floods in the 1500s for instance), the effects were traumatic – at the individual level, for the Netherlands as a country, and for the coastal engineering profession.<sup>2</sup> Very quickly after this disaster the first Delta Commission was installed and came up with a drastic reaction: the *Deltaplan* (Delta Plan) which in the end would turn out to take more than three decades to complete. This plan was a somewhat weakened version of the earlier plan proposed by van Veen for a complete closure of the Dutch coast. In 1955, the first Delta Commission proposed protection levels in connection with the *Deltaplan*. This made it possible to calculate the 'hydraulic requirements' for each segment of primary water defence (for instance, the once in ten thousand years combinations of water heights, that is sea level plus tide plus storm surge) and waves that the dykes in Holland are required to withstand; the hydraulic requirements are technically formulated as boundary conditions somewhat away into the water from the water defence work.

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1 McCray, L. E., Oye, K.A. & Petersen, A. C. *Technol. Forecast. Soc. Change* 77, 951–959 (2010).

2 Bijker, W. E. *Soc. Stud. Sci.* 37, 143–151 (2007).

Over the 20th century there have been large, *unplanned* changes to the methods for determining hydraulic requirements. Before The Disaster of 1953 the norm for the height of a water defence work was determined by adding to the highest observed water level a fixed additional height: 0.5 or 1 m. For dykes exposed to waves more would be added. Already in 1939, the Storm Surge Commission pointed out that this method was fundamentally wrong; statistically speaking there could always be a higher water level than the highest level observed and also sea-level rise was contributing to higher water levels. The Disaster of 1953, which was caused by a combination of high water and structural failure, proved the correctness of this conclusion, which until then had not been adopted by the governments involved (the national government, the provinces and the water boards). The Delta Commission, in its final report of 10 December 1960, advised to create a national system of flood protection based on well-founded norms and guidelines. For Randstad Holland, the Delta Commission advised to base the design of water defence works on a water level of NAP (Amsterdam Ordnance Datum) + 5 m at Hoek van Holland, a seaward point, and corresponding levels elsewhere along the coast. These water levels match the storm surge water levels for which the chance that they are exceeded is 1:10,000 per year, on average. In addition, the first Delta Commission advised to take into account a *relative* sea level rise (that is, including the geological land subsidence effect) of 0.2 meter per century for the life span of the designed water defence work. The first Delta Commission also offered practical guidance on how designs could guarantee defence against the mentioned storm surge water levels: for example, by stating that 2% of the waves that can be expected for the indicative water level may run over the water defence work. Several years later, the *Technische Adviescommissie voor de Waterkeringen* (Technical Advisory Commission for the Water Defence Works) would be charged with further developing technical guidance.

### THE INTRODUCTION OF PLANNED ADAPTATION WITH THE WATER DEFENCE ACT (1995)

In December 1995, the *Wet op de waterkering* (Water Defence Act) was accepted. This act provided both a statutory basis for the safety levels adopted after the 1955 Delta Commission proposal and a five-year review cycle of the hydraulic requirements associated with those fixed safety levels. In 2009 the act has been transformed without any substantive changes – except for a change in cycle length to six years, see below – into a part of the new *Waterwet* (Water Act). The main reason for introducing planned adaptation was that with the completion of the Delta Works, if not a system of Planned Adaptation were introduced, the safety of Dutch water defence could gradually deteriorate and the Dutch could become ‘slapped in the face’ again by a major catastrophe. One must remember here that 55% of the Netherlands is at risk of flooding from sea and rivers. Now that the safety levels set in 1955 had been met at the end of the 1980s, these safety levels have to be maintained. Dutch policy documents often stipulate that a deterioration of safety levels should ‘never occur’ anymore. In the aftermath of the Delta Works, the research funding and research infrastructure could continue to be used for Planned Adaptation, which may trigger small or large water defence engineering projects depending on how the standards evolve.

The proposal for the Water Defence Act was sent to Parliament by Minister Neelie Smit-Kroes (the later European Commissioner Neelie Kroes) in April 1989. There were some discussions surrounding the Act related to role of the national government and the distribution of costs over different actors. But there was no discussion at all about the need for scheduled reviews of the hydraulic requirements. In the Netherlands, the government and all actors involved in water defence policy and regulation just did not want a repeat of being too slow to respond to changing conditions and emerging knowledge now that the *Deltaplan* had been fully realised. Surely, The Disaster of 1953 and the drastic multi-decade response to it constitute an example of Unplanned Adaptation. When this effort was nearly finished, all relevant actors involved in coastal and river defence shared the concern that mismatches between actual and required defence might gradually develop. In order to prevent this from happening, the Dutch government said a system should be put in place that would guarantee *both* a regular updating of hydraulic requirements *and* other safety criteria and a regular test of whether the water defence works satisfy all the safety criteria. As a corollary, the government took up to allocate a larger fraction of research money spent on water defence engineering research for providing the knowledge needed to better calculate the hydraulic requirements and other safety criteria. In due time, a targeted research program would be set up, directly connected to the review cycles. Thus, Planned Adaptation was introduced in Dutch flood safety management.

When one introduces Planned Adaptation, one has several options for designing the processes securing the regular updates of the policy. One option is to monitor continuously and lay down in an agreement or convention what the thresholds for the most critical criteria are and what actions logically follow from reaching these values, e.g. adjusting safety standards or underlying criteria. In this option there is no a priori fixed cycle length; adjustment is considered

when the conditions justify the efforts involved. Another option is to fix the cycle length. At regular intervals all relevant data are analysed to determine if an update of safety levels or of underlying criteria is necessary. In this option obviously one has to choose a cycle length. In the Water Defence Act the frequency of re-assessing the hydraulic requirements was synchronised with the frequency of safety ‘testing’, where officials actually go out and assess the safety of existing structures by following an assessment protocol – this regular testing was the other major innovation introduced with the Water Defence Act. Both frequencies were set at once every five years. In the Explanatory Memorandum of 1989 this period was presented as a compromise between staying up-to-date with respect to guaranteeing the safety norm (new research can be well expected to deliver and corroborate new insights in just a few years’ period) and being able to incorporate changes in requirements into the planning of water defence works maintenance (for the latter, policy makers in coastal defence typically prefer changes in hydraulic requirements less than once in a decade).

## THE DELTA PROGRAMME AND ADAPTIVE DELTA MANAGEMENT (2014 DELTA DECISIONS)

In 2008, the second Delta Commission was installed. After one year it published its proposal and was abrogated. The commission advised, amongst other things, to establish a ‘Delta Programme’ uniting all levels of government and focusing on water safety and fresh water supply. This was done and the Delta Programme was tasked to focus on the *prevention* of a disaster, thus breaking from the past where big interventions were most often *reactions* to a disaster. The programme started in 2010, is led by a government commissioner and has an annual budget of 1 billion euro. While the Delta Commission had focused on the urgency to prepare for climate change, climate change became less central to the Delta Programme: in effect, it became one of the elements that established the necessity to deal with the Dutch Delta now.<sup>3</sup>

Based on a significant amount of targeted research, the Delta Programme has proposed new, regionally differentiated safety standards in September 2014: everyone living behind dykes and dunes in the Netherlands can count on a protection level of  $10^{-6}$  or higher by 2050:

“The Delta Commissioner proposes that a risk-based approach be applied in water policy. This means taking into account the risk of flooding and the ensuing consequences. He is also proposing new standards for flood defences. These new standards are aimed at reducing the risk of death due to floods anywhere in the Netherlands to 1:100,000 (0.001 per cent) a year. A higher level of protection will apply in certain places where many casualties or significant economic loss could occur, or where “vital infrastructure” could be disrupted and affect the whole country (for example, the gas hub in Groningen). The aim is for all primary flood defences to meet the new standards in 2050.”<sup>4</sup>

These risk-based safety standards will subsequently be translated into the corresponding hydraulic requirements for the re-assessment cycle that starts in 2017 and will be enforced under the Water Act. The Delta Plan (or, more precisely, ‘Delta Decisions’) of 2014 also proposes Planned Adaptation with a frequency of 12 years, when each time a full assessment will be made to whether the hydraulic requirements need to be adjusted if the underlying assumptions have changed materially – the safety standards themselves had not changed since 1955 and the new uniform risk-based standard may be expected to be kept more or less constant for the next few decades too.

The approach of Planned Adaptation also guides the way the new Delta Program frames ‘Adaptive Delta Management’ in the light of the projected sea-level rise and changes in river run-off associated with climate change over the 21st century and beyond, as well as other (socio-economic) developments:

“A key principle of the proposed Delta Decisions and preferential strategies is that it should also be possible to take additional measures in the long term (after 2050) to address the challenges following from climatological and socio-economic developments. The options for these are ready. These have been included in the adaptation paths of the preferential strategies.”<sup>5</sup>

There are three significant examples of Adaptive Delta Management decisions where given the uncertainties options for after 2050 are consciously kept open through spatial policy, thus at some cost (even these costs are to be minimised). Both the options themselves and keeping them open are subject to planned re-assessments based on new knowledge that will be gathered in the future. The three examples of the options are:

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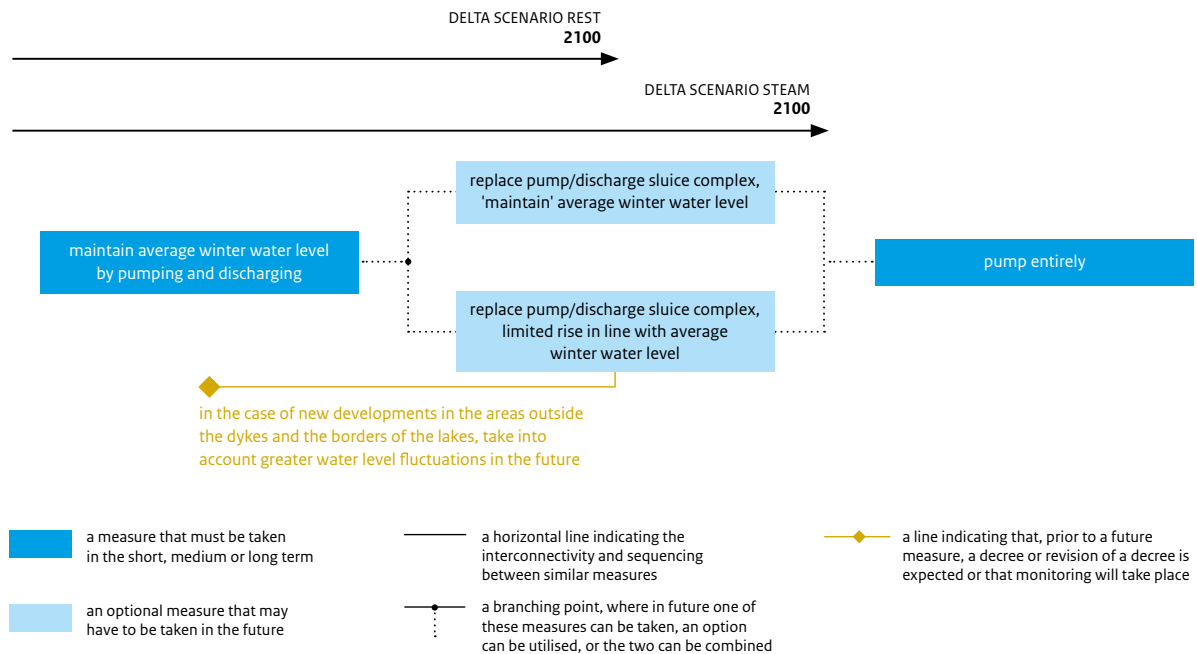
3 Zegwaard, A., Petersen, A. C. & Wester, P. *Climatic Change* (in press).

4 Delta Commissioner, *Delta Programme 2015*, web announcement (Delta Commissioner, The Hague, The Netherlands, 16 September 2014); available at [www.deltacommissaris.nl/english/delta-programme/delta-programme-2015](http://www.deltacommissaris.nl/english/delta-programme/delta-programme-2015)

5 Delta Commissioner, *Delta Programme 2015* (Delta Commissioner, The Hague, The Netherlands, 16 September 2014); available at [www.deltacommissaris.nl/english/delta-programme/publications](http://www.deltacommissaris.nl/english/delta-programme/publications)

- to allow the winter water level in the IJsselmeer region to rise with the sea level to a limited extent;
- if necessary, to change the discharge distribution across the Rhine distributaries;
- to use Rijnstrangen as a retention area.

The basic philosophy behind Adaptive Delta Management is to choose strategies and measures that can give the Netherlands flexibility in the way they respond to new measurements and insights, by stepping up efforts if necessary or changing strategy, while already having everything at hand (see, e.g. Figure 1).



**Figure 1. IJsselmeer region, adaptation path for preferential strategy for flood risk management**

Finally, Adaptive Delta Management will require proper monitoring of effects and, based thereon, regular evaluation of the strategies followed. Therefore, the Delta Commissioner will direct the development of a monitoring and evaluation system that matches with the adaptive and area-based approach advocated by the new Delta Plan.



# An Analysis of the Vulnerability of Power Grids to Extreme Space Weather Using Complex Network Theory

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## ABSTRACT

Space weather can affect critical infrastructures, causing damage to systems and resulting in failures or service disruptions. Of particular concern is the long-distance high-voltage power grid due to its vulnerability to geomagnetic storms. The induction of Geomagnetically Induced Currents (GICs) in the power network can damage equipment, push high-voltage transformers into their non-linear saturation range, or trip protection systems due to harmonics. These effects can lead to grid collapse.

Recently, several studies were commissioned in the U.S. to assess the power grid's vulnerability to extreme space weather and to investigate the potential consequences of prolonged blackouts on society. These studies highlighted a potentially major impact on the North American transmission grid and its components.

This study aims at identifying the vulnerability of the European power transmission grid with respect to extreme space weather by using complex network theory. We try to understand the spatial distribution and magnitude of GIC loading and the impact on grid operations potentially incurred. In a later step, this study will continue to estimate the impact of extreme space weather on society in Europe via the interdependencies of critical infrastructures with the power grid.

**Keywords:** Space Weather, Geomagnetic Induced Currents, Vulnerability, Complex Network Theory, Power Grids

## INTRODUCTION AND RATIONALE

Space weather driven by solar disturbances can affect ground- and space-based critical infrastructures, potentially causing damage to systems and resulting in failures or service disruptions<sup>1</sup>. Of particular concern is the long-distance high-voltage power grid due to its vulnerability to geomagnetic storms that can develop when solar coronal mass ejections (CME) interact with the Earth's magnetosphere. The subsequent induction of Geomagnetically Induced Currents (GICs) in the power network can damage or destroy equipment, push high-voltage transformers into their non-linear saturation range, or trip protection systems due to harmonics. These effects lead to voltage instability that can eventually result in grid collapse<sup>2,3</sup>.

The collapse of the Hydro-Quebec transmission network during the severe geomagnetic storm in 1989 was a wake-

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1 Daglis, I.A. (ed.), Effects of space weather on technology infrastructure, Springer, ISBN 1-4020-2748-6 2005.

2 Krausmann E., Andersson E., Murtagh W. and Mitchison N., Space weather and power grids: findings and outlook, EUR 26370, ISBN 978-92-79-34812-9, 2013.

3 Schrijver, C.J. and Mitchell S.D., Disturbances in the US electric grid associated with geomagnetic activity, *J. Space Weather and Space Climate*, 3, A19, 2013.

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up call for the power industry world-wide and it is testimony to the vulnerability of the power grid to space weather effects. The Hydro-Quebec blackout also affected industrial production in a number of other sectors, drawing attention to the potential for significant ripple effects in case of a power outage<sup>4</sup>.

Recognizing the risks associated with the impact of a geomagnetic storm on the power grid, recently, several studies were commissioned in the U.S. to assess the power grid's vulnerability to extreme space weather and to investigate the potential consequences of prolonged blackouts on society<sup>5,6,7,8</sup>. These studies highlighted a potentially major impact on the North American transmission grid and its components, in particular high-voltage transformers. With manufacture lead times of 12 to 18 months, these grid elements would be the bottleneck for rapid recovery. Numerous other critical infrastructures would also be disrupted until grid operations could be re-established<sup>9</sup>.

An extreme geomagnetic storm such as the 1859 Carrington event, the largest geomagnetic storm on record, would encompass North America but also a significant part of Europe<sup>10</sup>. Various analyses on the European power grid were carried out regarding the reliability of the network in general<sup>11</sup>, or the vulnerability to local failures and intentional attacks<sup>12,13</sup>. However, hardly any information exists on the vulnerability of the European power grid to extreme space weather or the consequences of impact, including interdependencies with other critical infrastructures.

This study, which is work in progress, aims at identifying the vulnerability of the European power transmission grid with respect to extreme space weather by using complex network theory. We try to understand the spatial distribution and magnitude of GIC loading and the impact on grid operations potentially incurred. In a later step, this study will continue to estimate the impact of extreme space weather on society in Europe via the interdependencies of critical infrastructures with the power grid.

## METHODOLOGY

When considering space weather effects on power networks, several issues have to be considered. For example, power grids are designed according to the N-1 criterion which stipulates that the system should tolerate any single failure and still maintain its function<sup>14</sup>. Geomagnetic storms extend over vast geographic areas and their impact can involve wide portions of the electrical networks: it is therefore important to look beyond the N-1 criterion and analyze the effects of several simultaneous failures over possibly spatially extended areas. Moreover, the geophysical characteristics of the location of the power grid also act as a source of vulnerability during space weather events: soil resistivity affects the propagation of magnetic disturbances resulting in induced large currents in long electrical transmission lines.

A vulnerability analysis therefore needs to adopt an approach which covers different perspectives, each dealing with the different aspects of power-grid vulnerability to extreme space weather. These perspectives are: global vulnerability

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4 Boteler, D.H., Assessment of geomagnetic hazard to power systems in Canada, *Natural Hazards*, 23, 101-120, 2001.

5 National Research Council, Severe Space Weather Events—Understanding Societal and Economic Impacts, Workshop Report, ISBN 978-0-309-12769-1, 2008.

6 Kappenman J., Geomagnetic storms and their impacts on the US power grid, Meta – R- 319 Report, 2010.

7 JASON, Impact of severe space weather on the electric grid, JSR-11-320, The MITRE Corporation, 2011.

8 NERC, 2012 Special Reliability Assessment Interim Report: Effects of Geomagnetic Disturbances on the Bulk Power System, North American Electric Reliability Corporation, 2012.

9 National Research Council, Severe Space Weather Events—Understanding Societal and Economic Impacts, Workshop Report, ISBN 978-0-309-12769-1, 2008.

10 Pulkkinen A., Bernabeu E., Eichner J., Beggan C. and Thompson A.W.P., Generation of 100-year geomagnetically induced current scenarios, *Space Weather*, Vol. 10, S04003, 2012.

11 Brancucci Martinez-Anido C., Bolado R., De Vries L., Fulli G., Vandenbergh M. and Masera M., European power grid reliability indicators, what do they really tell?, *Electric Power System Research*, 90, 79-84, 2012.

12 Rosas-Casals M., Valverde S. and Solé R., Topological vulnerability of the European power grid under errors and attacks, *Int. J. Bifurcation and Chaos*, 17, 2007.

13 Rosas-Casals M. and Solé R., Analysis of major failures in Europe's power grid, *Electrical Power and Energy Systems*, 33, 805-808, 2011.

14 IRGC, White paper on managing and reducing social vulnerabilities from coupled critical infrastructures, International Risk Governance Council, Geneva, 2006.



analysis, critical component analysis and geographical vulnerability analysis<sup>15</sup>. Global vulnerability analysis is carried out by exposing the system to strains of different intensity and orientation and estimating the negative consequences that arise. This is achieved, for example, by imposing different geomagnetic storm scenarios and estimating the resulting GICs in the system. Critical component analysis aims at estimating the consequences of single component failure or of a set of components failure, in order to identify those components that give rise to the largest negative consequences, i.e. those that are the most critical. Geographical vulnerability analysis consists of studying how space weather interacts with the geographic characteristics of the location of the system and of its components.

Vulnerability analysis requires the structure and behavior of the power grid to be modeled. There are many ways for doing this, depending on the physical and dynamical aspect of the system function to capture. Advanced models, such as those used in system engineering, are superior in capturing the physical behavior of the system but have a high computational cost for the kind of analysis carried out in these studies. In contrast, abstracted models, i.e. purely connectivity-based/topological models are used within the field of graph theory. They are computationally very fast but may not capture the relevant behavior of the system.

For modeling the electric power grid, a complex network theory approach has been chosen. The complex network approach distinguishes between a structural and a functional model of the system. Inspired by the field of network theory, the structural model captures the structural properties and consists of an abstract representation of the system: components of the power grid, for example bus-bars, are represented as nodes and connections; transmission lines, for example, are represented as edges. The functional model, which is inspired by system engineering, accounts for the physical properties and constraints of power systems and represents the response of the system when it is exposed to strains, such as currents caused by geomagnetic storms<sup>16</sup>.

This work proposes an approach that includes extended centrality measures to assess the structural vulnerability of power grids. It is intended as a first step to estimate the impact of extreme space weather effects on power grids and their potential consequences on interdependent critical infrastructures.

## PRELIMINARY RESULTS AND DISCUSSION

GICs calculations are usually separated into two parts: a “geophysical part” which encompasses the determination of the electric field occurring at the Earth’s surface due to CME interaction with the geomagnetic field, and an “engineering part” which covers the computation of GICs produced by the electric field<sup>17</sup>. In the following, only the calculation of the second part is illustrated; we assume that the electric field is already known.

Based on the physical model initially proposed by Lethinen and Pirjola<sup>18</sup> and later by Viljanen et al.<sup>19</sup>, GICs flowing in the power grid to and from the Earth at the stations of a network having  $N$  nodes are given by Eq. (1):

$$\mathbf{I}_e = (\mathbf{1} + \mathbf{Y}_n \mathbf{Z}_e)^{-1} \mathbf{J}_e \quad (1)$$

The  $N \times N$  earthing impedance matrix  $\mathbf{Z}_e$  and the  $N \times N$  network admittance matrix  $\mathbf{Y}_n$  includes the information on the system. The “perfect-earthing” current vector  $\mathbf{J}_e$  contains the information on the electric field, and  $\mathbf{1}$  is the  $N \times N$  unit identity matrix. When the earthing currents  $\mathbf{I}_e$  are known, the transmission line currents from node  $i$  to node  $j$ ,  $I_{ij}$ , can be computed.

The Finnish 400-kV power grid configuration valid in October 1978 is used as benchmark test network, as proposed by Pirjola<sup>17</sup>. The test model power grid consists of 17 stations and 19 transmission lines. Each node includes a transformer<sup>17</sup>.

As a first scoping study, the behavior of each node with respect to GIC induction as function of the E-field orientation

15 Johansson J., Hassel H. and Cedergren A., Vulnerability analysis of interdependent critical infrastructures: case study of the Swedish railway system, *International Journal of Critical Infrastructures*, 7, No.4, 2011.

16 Johansson J., Hassel H. and Zio E., Reliability and vulnerability of critical infrastructures: comparing two approaches in the context of power systems, *Reliability Engineering and System Safety*, 120, 27-38, 2013.

17 Pirjola R., Properties of matrices included in the calculation of geomagnetically induced currents (GICs) in power systems and introduction of a test model for GIC computation algorithms, *Earth Planet Space*, 61, 263-272, 2009.

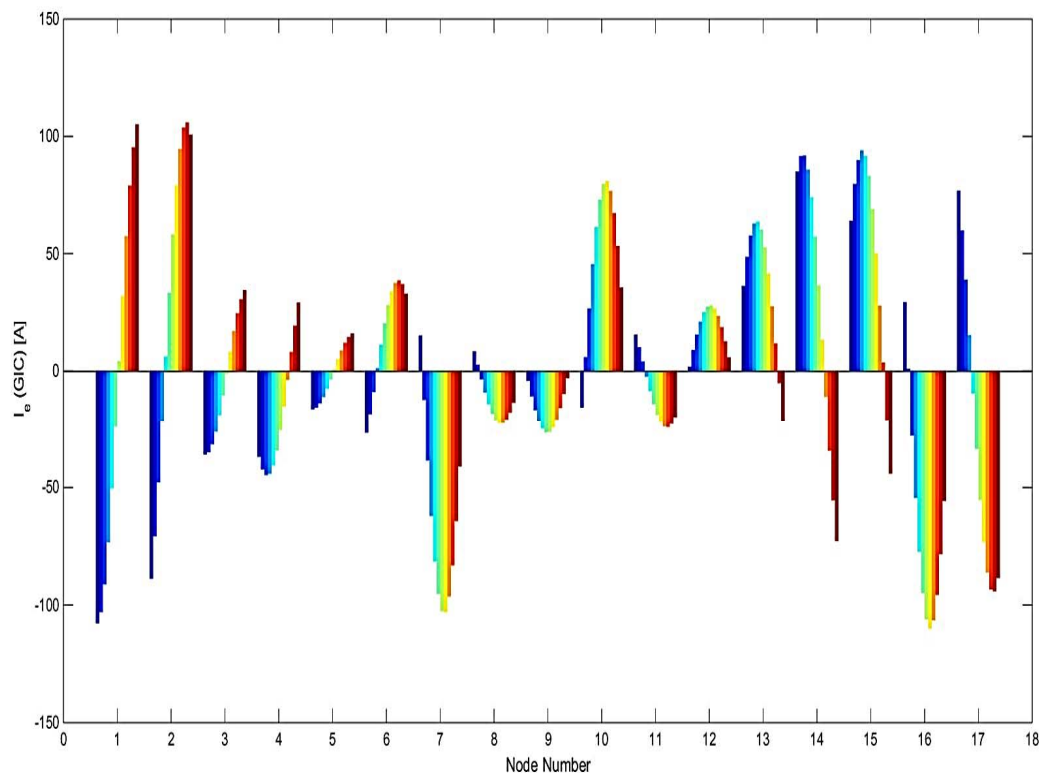
18 Lehtinen M. and Pirjola R., Currents produced in earthed conductor networks by geomagnetically-induced electric fields, *Annales Geophysicae*, 3, 4, 479-484, 1985.

19 Viljanen A., Pirjola R., Wik M., Adam A., Pracser E., Sakharov Y. and Katkalov J., Continental scale modelling of geomagnetically induced currents, *J. Space Weather Space Climate*, 2, A17, 2012.

was analysed to study directional effects. All GIC calculations on the test system were carried out considering a uniform-magnitude field scenario which assumes an electric field strength of 1V/km which varies from north (zero degrees) to 165 degrees at 15 degree increments. Electric fields of identical magnitude separated by 180 degrees have identical effects, except for a GIC sign reversal, thus it is only necessary to simulate half of the spectrum of field orientations.

Figure 1 gives an overview of the result of the calculation of the GICs flowing into the system for each node: each color represents the value of the induced currents at different angles of orientation of the electric field, starting with the direction from north to south, at 0 degree (in blue), continuing in 15 degree increments to 165 degrees (in red). The green bar represents the east-west direction, corresponding to 90 degrees. The sign of the current refers to the direction of the flow: GICs exiting a node have positive values, GICs entering a node are negative. It is found that for nodes 7 to 13 the sign of the induced currents does not depend on the orientation of the field, while in other nodes, i.e., nodes 1 or 14, GICs change sign.

Since GICs flowing into the system represent a threat, it is of the utmost importance to understand which are the features of the network that influence the diffusion of GICs throughout the grid. One of the most important measures for understanding the role played by the components of the network is betweenness centrality<sup>20</sup>. The betweenness centrality of a node  $i$  is defined as the fraction of shortest path between a pairs of nodes in the network that pass through  $i$ . When considering power networks, betweenness centrality can be regarded as a measure of the extent to which a vertex has control over the current flowing between other nodes. In power networks, however, GICs do not flow only along geodesic (shortest) paths because operational and physical rules drive the flow.

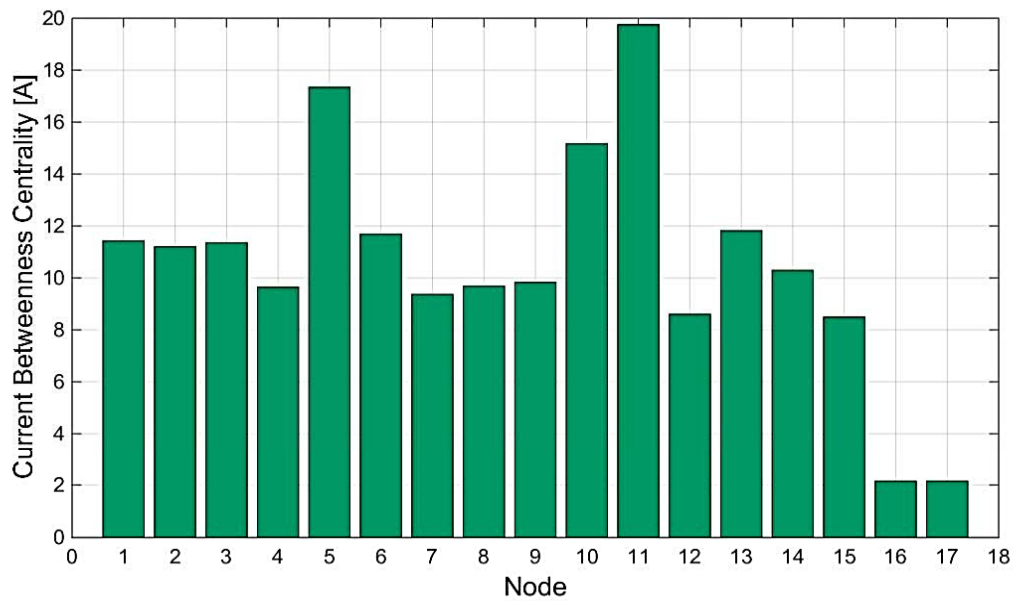


**Figure 1. Representation of GICs computed for the stations of the 400-kV Finnish power grid. For each station, the different colors represent a different orientation angle of the geoelectric field  $E$ .**

In this study, the current-flow betweenness of every node  $i$  has been computed as the amount of current that flows through  $i$  averaged over all the possible paths between source and target nodes<sup>21</sup>. The current betweenness centrality values give a ranking of the relevance of the nodes in current flow transmission in the network (Fig. 2).

20 Freeman L.C., A set of measures of centrality based upon betweenness, *Sociometry*, 40, 35-41, 1977.

21 Newman M.E.J., A measure of betweenness centrality based on random walks, *Social Networks*, 27, 39-54, 2005.



**Figure 2.** *Current betweenness centrality for the stations of the 400-kV Finnish power grid based on the topology, nodes and links, and on the characteristics of the grid, resistances and GICs.*

Except for nodes 16 and 17, which are peripheral vertices, the majority of the nodes of the network gives nearly the same contribution to the diffusion of GICs in the network. Nodes with the highest degree (nodes 5, 10 and 13 with degree  $k_5 = k_{10} = k_{13} = 3$  and node 11 with  $k_{11} = 4$ ) are also nodes with the highest betweenness centrality. These are the elements that mainly affect the spread of GICs throughout the network and should be carefully monitored in planning prevention actions of GIC diffusion during solar storms.

## OUTLOOK

Work is underway to better understand how the structure of the network influences the spreading of space weather effects into the power grid. Consequently, the centrality measures used in network theory will be adapted to embrace also the physical features of the system, for instance, the length of the lines and the location of the nodes. Moreover, the addition of load flow to the induced GIC will also be simulated to understand the resistance of the network to space-weather effects under normal operating conditions. Eventually, this work will be extended to simulate the potential space-weather vulnerability of a simplified European grid.



# Simulating Impacts of Extreme Weather Events on Urban Transport Infrastructure in the UK

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## ABSTRACT

Urban areas face many risks from future climate change and their infrastructure will be placed under more pressure due to changes in climate extremes. Using the Tyndall Centre Urban Integrated Assessment Framework, this paper describes a methodology used to assess the impacts of future climate extremes on transport infrastructure in London. Utilising high-resolution projections for future climate in the UK, alongside stochastic weather generators for downscaling, urban temperature and flooding models are used to provide information on the likelihood of future extremes. These are then coupled with spatial network models of urban transport infrastructure and, using thresholds to define the point at which systems cease to function normally, disruption to the networks can be simulated. Results are shown for both extreme heat and urban surface water flooding events and the impacts on the travelling population, in terms of both disruption time and monetary cost.

**Keywords:** Infrastructure, Extreme Weather, Urban Flooding, Transportation

## INTRODUCTION

The IPCC 5<sup>th</sup> Assessment Working Group 2 (IPCC, 2014)<sup>1</sup> report on climate impacts highlights the risks faced in urban areas by future climate change, but also that the complex nature of urban areas and their interconnected systems offer an ideal opportunity for climate change adaptation leadership. In particular, infrastructure in cities will be placed under more pressure in the future due to the changes in climate extremes (e.g. rainfall and temperature) and the concurrent increase in demand from population growth and urbanisation (Hallegatte and Corfee-Morlot, 2011)<sup>2</sup>. In order to understand where these future pressures may be spatially-concentrated, it is important to study urban infrastructure in the context of both climate change and socio-economic change. To this end, the Tyndall Centre's Urban Integrated Assessment Framework (UIAF) was developed (Hall et al, 2010)<sup>3</sup> to allow the assessment of the urban impacts of climate change coincident with other changes which may be seen in cities.

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1 IPCC (2014). *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Billir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, USA, Draft Chapter 8.

2 Hallegatte, S. & Corfee-Morlot, J. 2011. Understanding climate change impacts, vulnerability and adaptation at city scale: an introduction. *Climatic Change*, 104, 1-12.

3 Hall JW, Dawson RJ, Barr SL, Batty M, Bristow AL, Carney S, Dagoumas A, Ford A, Tight MR, Walsh CL, Watters H, Zanni AM, (2010). City-scale integrated assessment of climate impacts, adaptation and mitigation. In: Bose, R.K, ed. *Energy Efficient Cities: Assessment Tools and Benchmarking Practices*. Washington, DC, USA: World Bank, pp.43-64.

The work presented in this paper highlights a rapid assessment methodology using the UIAF for understanding potential future impacts on the users of urban transport networks from extreme weather events. This begins with climate downscaling using the UKCP Weather Generator and, in the case of extreme rainfall, simulation of surface water flooding using the CityCat model (Glenis et al, 2013)<sup>4</sup>. The spatial footprints of resulting climate hazards are then overlaid on the urban transport networks (for both public and private travel) and thresholds applied to understand where impacts will be felt. These impacts can then be assessed in terms of increased travel time for the users of the transport infrastructure and the total cost of disruption calculated. This methodology is demonstrated in this paper for both extreme heat and extreme rainfall events, on public transport and road networks in the UK.

## METHODOLOGY

This study employs the Tyndall Centre UIAF, which couples models of climate, population, transport, and land-use to allow a system-scale analysis of the inter-relationships between climate impacts, transport networks, urban residents, and the urban economy (Hall et al., 2010)<sup>3</sup>. In order to provide information on the likelihood of extreme weather events, impacts, and implications for adaptation policies, which are sometimes lacking in scenario-based city-scale climate change impact assessments, the UIAF has been extended to enable a probabilistic risk-based approach (Jenkins et al, 2012)<sup>5</sup>. This approach will be outlined for heat impacts on transport networks, whilst a more simple deterministic approach will be described for the impacts of surface water flooding.

Since the spatial and temporal resolution of climate model outputs (e.g. 25 km<sup>2</sup> for the UK Climate Projections (UKCP09)<sup>6</sup>) is often too coarse for studies of climate change impacts, downscaling techniques are often employed to produce outputs at a more suitable scale. An Urban Weather Generator (UWG) has thus been produced to supplement the UKCP09 outputs, providing hourly time series of weather variables, such as rainfall or maximum temperature) for various future climate scenarios at 5km resolution. The UWG employs a stochastic rainfall model to simulate time series of future rainfall, and thus other weather variables dependent on this initial output. Change factors can be employed to adjust the statistical measures used by the UWG based on probabilistic projections from UKCP09 (Jones et al., 2009)<sup>7</sup>. Recent advances in the UWG give an improved reproduction of extreme temperatures, spatial correlations in weather (Kilsby et al., 2011)<sup>8</sup>, and urban heat island effects (McCarthy et al., 2012)<sup>9</sup>.

The outputs from the UWG (e.g. hourly data of weather variables at 5km resolution) are used to assess the spatial and temporal variation of hazards in the urban area. In order to simplify analysis, a thresholding approach is applied where lower-order impacts are assessed when the climate inputs exceed a certain level of severity. For extreme heat events, temperature thresholds are defined above which it is expected disruption will begin to be felt on transport networks. For extreme rainfall events, a further intermediate step is needed to translate heavy rain into flood extents using CityCat, the thresholding being applied to the resultant depths of water.

## HEAT IMPACTS

Dobney et al., (2010, 2009)<sup>10,11</sup> showed that disruption to the railway network in London and the South East can

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4 Glenis V, McGough AS, Kutija V, Kilsby C, Woodman S. (2013) Flood modelling for cities using Cloud computing. *Journal of Cloud Computing: Advances, Systems and Applications*, 2(1), 7.

5 Jenkins, K., Glenis, V., Ford, A., Hall, J.(2012) "A Probabilistic Risk-Based Approach to Addressing Impacts of Climate Change on Cities: The Tyndall Centre's Urban Integrated Assessment Framework". UGEC Viewpoints, Connecting Past and Present Lessons in Urbanization and the Environment (8).

6 UKCP09 (n.d.) UKCP09 25 km grid, last updated Tuesday, 17 July 2012, <http://ukclimateprojections.metoffice.gov.uk/23233>

7 Jones, P. D., Kilsby, C. G., Harpham, C., Glenis, V. & Burton, A. (2009). UK Climate Projections science report: Projections of future daily climate for the UK from the Weather Generator. University of Newcastle, UK.

8 Kilsby, C., Jones, P., Harpham, C., Glenis, V. & Burton, A. (2011). Spatial Urban weather Generator for Future Climates. ARCADIA Task 3 Report. Available at: <http://www.arcc-cn.org.uk/wp-content/pdfs/ARCADIA-7.pdf>.

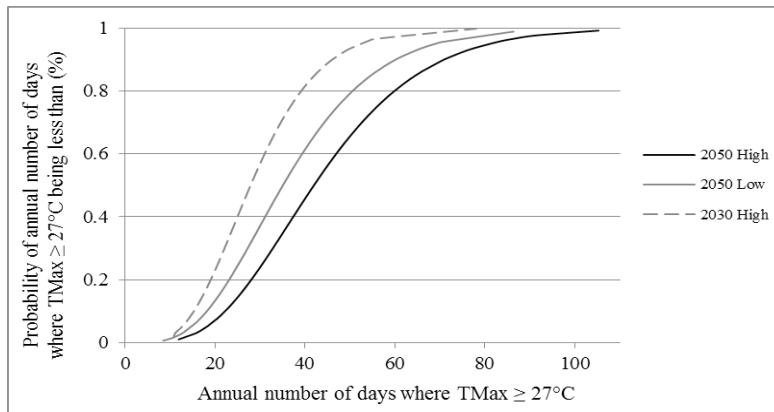
9 McCarthy, M. P., Harpham, C., Goodess, C. M. & Jones, P. D. (2012). Simulating climate change in UK cities using a regional climate model, HadRM3. *International Journal of Climatology*, 32, 1875-1888

10 Dobney, K., Baker, C. J., Quinn, A. D. & Chapman, L. (2009). Quantifying the effects of high summer temperatures due to climate change on buckling and rail related delays in south-east United Kingdom. *Meteorological Applications*, 16, 245-251.

11 Dobney, K., Baker, C. J., Chapman, L. & Quinn, A. D. (2010). The future cost to the United Kingdom's railway network of heat-related

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occur when maximum temperature exceeds 27°C, based on an analysis of the occurrence of rail buckling events reported in the Network Rail Alteration database and the corresponding observed temperature. Thus, a threshold of 27°C has been defined for initial analysis of UWG outputs. The first step of this analysis is to identify the frequency with which this threshold will be exceeded for a given climate scenario and future time period, and thus to provide hazard maps reflecting the spatial extent and severity of heat events. Analysis of UWG outputs for each climate scenario was undertaken on multiple runs with various climate model change factors for the same location, time-period, and emission scenario. Figure 1 shows the probability of the annual number of days where the maximum temperature in one or more grid cell in the study area exceeds the 27°C threshold for a range of time-periods and climate scenarios.



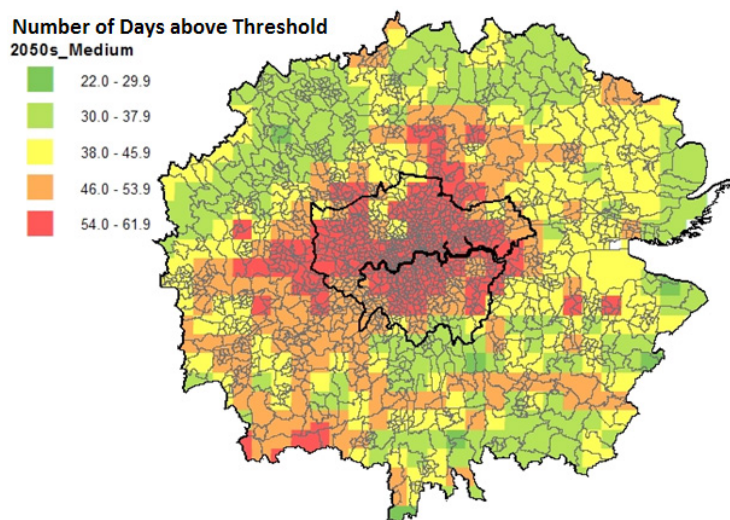
**Figure 1: Probability of the annual number of days where TMax exceeds 27°C for one or more grid cells in the study area, for the 2030s and 2050s under low and high emission scenarios**

To analyse the impact of these events on the users of the transport network, further temperature thresholds are related to speed restrictions imposed on sections of railway line (see Table 1). Single days in the UWG outputs are identified at least one grid cell exceeds one of these thresholds and then the maximum daily temperatures for each of these events can be mapped spatially across the study area on the 5km grid (Note: these are air temperatures, but methods are being developed to examine surface temperatures, which are of more relevance for impacts on railway infrastructure). Figure 2 shows the number of times each grid cell in the London study area exceeds the 27°C temperature threshold.

Threshold	Speed restriction
<27°C	None
<b>Poor</b> Rail Track ≥ 27°C < 28°C	30mph
<b>Poor</b> Rail Track ≥ 28°C	20mph
<b>Moderate</b> Rail Track ≥ 33°C <35°C	60mph
<b>Moderate</b> Rail Track ≥ 35°C	20mph
<b>Good</b> Rail Track ≥ 36°C	90mph
<b>Good</b> Rail Track ≥ 42.6°C	60mph

**Table 1: Temperature thresholds where speed restrictions are imposed. Source: Network Rail (2008)**

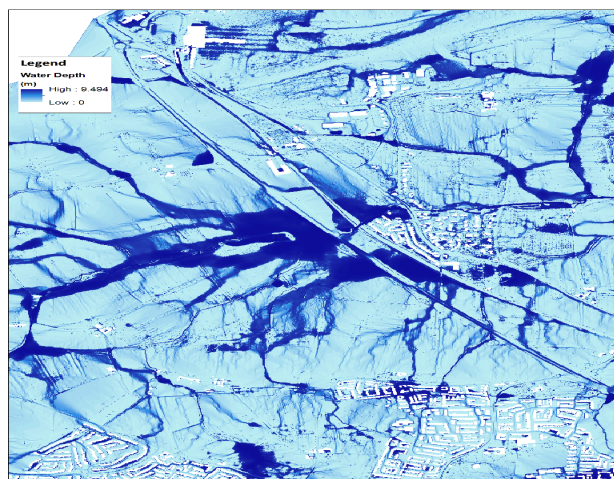




**Figure 2:** Number of days in a given 100-year simulation from the UWG for Greater London where the maximum daily temperature exceeds the 27°C threshold.

## FLOODING IMPACTS

Pluvial flooding, where intense rainfall overwhelms urban drainage systems, is sensitive to the spatio-temporal characteristics of rainfall, topography of the terrain and surface flow processes influenced by buildings and other man-made features (Glenis et al, 2013)<sup>4</sup>. Urban flood models can provide outputs of surface water depth and velocity at very high resolution, with surface water flow being modelled using two-dimensional hydrodynamic equations (ibid). Impacts on the transport network due to flooding can be analysed by examining the coincidence of these outputs with the spatial locations of urban transport infrastructure. The CityCat simulations are also driven by UKCP09 outputs, giving future estimates of rainfall across the study area. In this study, however, a particular event derived from the Flood Estimation Handbook (2 hours of duration, 200 ys return period) was analysed, producing a flood hazard map at 1m resolution depicting the resultant depths and velocities of surface water. An example output is shown in Figure 3.



**Figure 3:** an example output from CityCat showing the depth of water across an urban area during an extreme rainfall event.

For calculation of flooding disruption on transport networks a threshold is again defined, above which it is expected impacts from surface water floods will be felt. In this paper, disruption to road networks is presented. Expert guidance (e.g. Green Flag, 2014)<sup>12</sup> states that a water depth of 0.25m is the point at which driving becomes unsafe, but due

<sup>12</sup> Green Flag, (2014). Driving in floods and heavy rain (advice). <http://www.greenflag.com/advice/driving/floods.html> — retrieved 6th June, 2014



to the uncertainties in this value (e.g. type of car, type of asphalt, type of tyre, behaviour of the driver, visibility) a more conservative depth of 0.2m was defined as the threshold where speed will be reduced. A speed of 6km/h was defined as the speed at which cars can pass through water above this depth.

## NETWORK MODELLING

Whilst the climate hazards described above will obviously have wide-ranging impacts on the transport infrastructure itself, causing direct damages (e.g. through rail buckling due to extreme heat), the focus of this study is on the impacts on the users of those networks in terms of disruption to their journeys. Thus, a simple model of network trips was developed to gain an understanding of both the relative importance of network segments (in terms of their levels of use) and the number of people affected by a disruption to the network. This model used the simple Frank-Wolfe algorithm (Dafermos, 1968)<sup>13</sup> to load journey-to-work (JTW) observations from the 2001 UK census onto network models in GIS.

Two network representations were constructed in this study from a variety of data sources (e.g. Ordnance Survey ITN and Meridian data, UK NAPTAN data for public transport stops), one for private (e.g. road) transport and one for public transport. These networks were supplemented with speed and capacity information to allow the calculation of shortest routes in terms of time. These shortest routes were thus computed between origin and destination locations for the JTW observations and the observed flows assigned to the segments of the network included in these shortest routes. In this way, it is possible to build up an estimation of the number of people using links in the urban transport networks as part of their daily commute.

## SPATIAL ANALYSIS OF IMPACTS

Once spatial footprints of hazards, either from heat or flooding, have been defined they can be overlaid on spatial representations of the urban transportation networks in GIS to allow the calculation of disruption. The method for undertaking this calculation is the same for both heat and flooding impacts since a threshold approach has been applied for both. Thus, the process involves overlaying the spatial footprint of the hazard (i.e. a 5km grid cell in which the defined temperature threshold has been exceeded, or a 1m grid cell in which surface water depth has exceeded the defined flood threshold) onto the transport network and determining the portions of the transport network affected. The travel speeds on the disrupted network segments are then adjusted and new travel times between sets of origins and destinations calculated. By comparing the perturbed travel times with the original travel times before disruption, the impact on commuting journeys can be measured, and since the number of journeys using that route is known from the JTW table, the total impact in terms of Person-Minutes can be computed.

## RESULTS

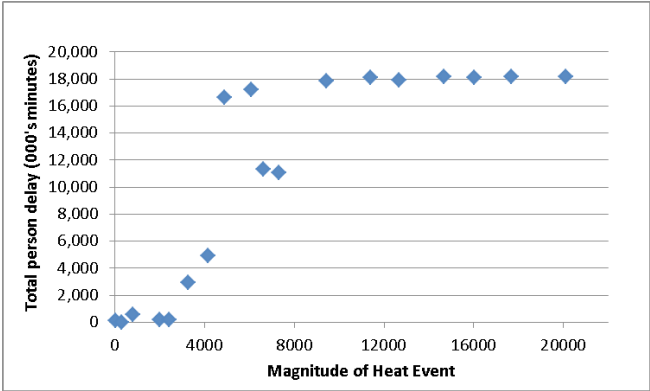
For heat disruption, 18 daily events in Greater London were produced by sampling across a range of event magnitudes sampled from 30 x 100 year weather generator simulations. The magnitude is defined as the product of the number of grid cells in the study area above the 27°C threshold and the amount by which the threshold is exceeded. For each of these events, a map of daily maximum temperature was produced and overlaid on the railway network as described above. Depending on the simulated temperature and its location, the impact on the railway network can be calculated in terms of speed restrictions and thus increased travel times.

Figure 4 shows the relationship between the magnitude of each sampled event and the total person delay in minutes which results from the disruption to the network. It can be seen that the extent of the disruption to the network very quickly reaches saturation and that there is some variation in the disruption depending on where in the network

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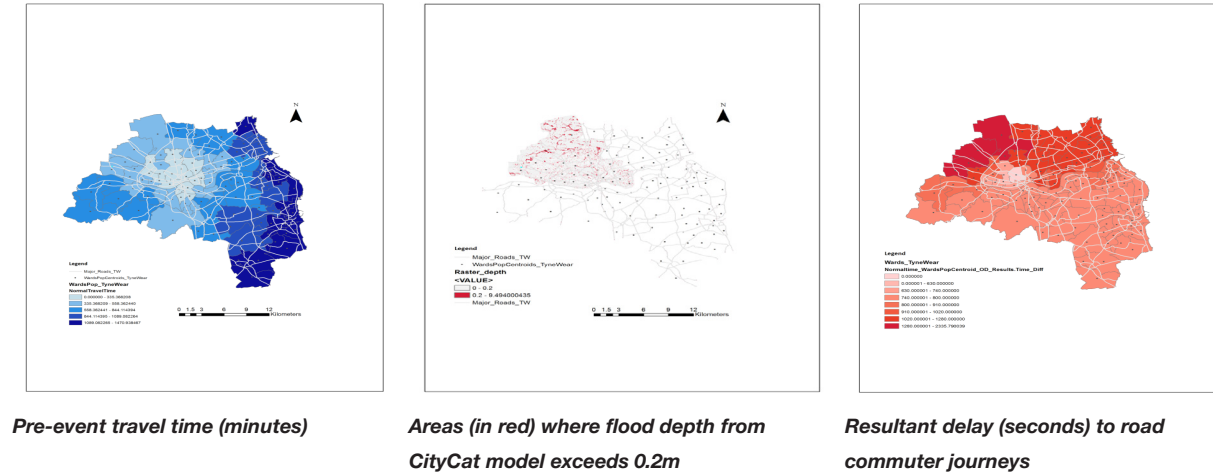
13 Dafermos, S. and Sparrow, F. (1968). The Traffic Assignment Problem for a General Network. Journal of Research of the National Bureau of Standards, 73B, pp. 91-118.

the hottest areas occur. In this example, it is assumed that all track in the simulation is of Poor quality (see Table 1). In order to represent simple adaptation to future temperature changes, similar simulations were also run with assumptions that all track was Moderate or Good.



**Figure 4: Total delays for each of the 18 events of different magnitudes**

For flooding impacts, disruption to the road network in the Tyne and Wear area of the UK was simulated as described above. Figure 5 shows the impact of a single flooding event (2 hours of duration, 1 in 200 years return period) in terms of delays to car journeys using the simple thresholding approach. It can be seen that the modelling flooding area is relatively small (due to the computational overheads of the CityCat model) but that the resultant disruption is wide-ranging. The resulting disruption is in terms of time delays for each origin-destination pair.



**Figure 5: Modelling of disruption to urban road network from flooding**

## CONCLUSION

This paper has presented an approach to examine the impacts of extreme weather events on urban transport infrastructure by combining climate simulations with spatial representations of networks. It has been demonstrated that a thresholding approach allows spatial hazard footprints to be extracted and overlaid onto network models in GIS to produce measures of disruption to commuting journeys on road and public transport networks. Whilst only current day population, from census JTW tables, has been examined in this paper, this approach can also be applied to future populations using land-use transport interaction models, allowing the examination the impacts of future socio-economic changes alongside changes to the climate.

## ACKNOWLEDGEMENTS

Part of the research in this paper was funded by the UK Engineering and Physical Sciences Research Council grant EP/G061254/2 to the ARCADIA project, for which the authors would like to express their appreciation.

# A GeoSocial Intelligence Framework for Studying & Promoting Resilience to Seasonal Flooding in Jakarta, Indonesia

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## PAPER ABSTRACT / BRIEF

**PetaJakarta.org** is a web-based platform developed to harness the power of social media to gather, sort, and display information about flooding for Jakarta residents in real time. The platform runs on the open source software **CogniCity**—an OSS platform developed by the SMART Infrastructure Facility, University of Wollongong—which allows data to be collected and disseminated by community members through their location-enabled mobile devices. The project uses a **GeoSocial Intelligence Framework** to approach the complexity of Jakarta's entangled hydraulic, hydrological and meteorological systems and thereby converts the noise of social media into knowledge about urban infrastructure and situational conditions related to flooding and inundation.

In this paper, **PetaJakarta.org** co-directors Dr Tomas Holderness, Geomatics Research Fellow at the SMART Infrastructure Facility, Dr Etienne Turpin, Vice-Chancellor's Postdoctoral Research Fellow at the SMART Infrastructure Facility, and Dr Rohan Wickramasuriyam, GIS Research Fellow at the SMART Infrastructure Facility, will discuss their GeoSocial Intelligence Framework as it applies to their current research in Jakarta. They will also present their preliminary findings from their 2014 Twitter #DataGrant, which has allowed them to develop a correlative analysis between historic social media information, the Jakarta government's flood maps, and the infrastructure used to manage critical flood emergencies. Finally, they will speculate on several future applications of the **CogniCity** OSS and suggest how it might be developed to further promote an integrated civic co-management platform with the support of business, industry, government and community organizations.

**Keywords:** Urban Resilience, Crowdsourcing, Social Media, Big Data, Flood Management, Open Source Software, Complex Urban Systems, Climate Change

## PAPER ABSTRACT / COMPLETE

As part of the SMART Infrastructure Facility's 'GeoSocial Intelligence for Urban Livability & Resilience' Research Group, Drs Dr. Etienne Turpin, Dr. Tomas Holderness, and Dr. Rohan Wickramasuriya, with the support of SMART IT architect Dr. Matthew Berryman and designer Sara Dean (M.Arch, MSc. Design), have developed the crowd-sourcing data collection project **PetaJakarta.org** (Map Jakarta). The overall aim of the project is to advance our capacity to understand and promote the resilience of cities to both extreme weather events as a result of climate change and to long-term infrastructure transformation as a process of climate adaptation. **PetaJakarta.org** is a pioneering web-based platform that harnesses the power of social media to gather, sort, and display information about flooding for Jakarta residents and governmental agencies in real time. The platform runs on the open source software (OSS) known as **CogniCity**—an OSS platform developed by the SMART Infrastructure Facility, University of Wollongong—which allows situational information to be collected and disseminated by community members through their location

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enabled mobile devices, and optimizes infrastructure surveys and asset management for governmental actors. Equipped with scalable mapping technology for mobile devices and a critical alert service, this software enables the communication of two-way time-critical information to and from individuals and government agencies.

As the pilot study for our long term SMART research project on urban resilience and adaptation to climate change in developing nations, **PetaJakarta.org** radically changes real-time data collection and feedback for flood monitoring in one of most precarious delta cities of Southeast Asia. However, **PetaJakarta.org** is powered by the highly transferable software **CogniCity**, which can be deployed in other megacities, in alternate languages, and for other critical urban problems pressurized by climate change. The presentation will outline our GeoSocial Intelligence Framework, which allows us to optimize citizen participation in Next Generation Decision-Support Systems that aid in the civic co-management of complex urban systems.

**PetaJakarta.org** works by collecting critical data about flooding and water infrastructure from existing social media networks and then inviting users to repost their messages with geo-location data to a web-based community map. Powered by our open source software, this pilot study harnesses the power of existing social media networks to provide critical, real time information about civic infrastructure and flooding. Importantly, **CogniCity** is not an app; it is the software component within our **GeoSocial Intelligence Framework** which allows data to be collected and disseminated by community members through their location-enabled mobile devices without additional plugins or programs. Within the context of the **PetaJakarta.org** pilot study, our **GeoSocial Intelligence Framework** allows us to capture critical data about environmental variables, infrastructure functionality, and individual and government responses to seasonal weather extremes, including prolonged periods of sustained precipitation, intensifying storm systems, and increasing coastal inundation due to high tides, sea level rise, and extreme land subsidence in coastal areas of the city. As this information is made available in real time to the public on our website, it is also stored for further data analysis by our SMART Research Group.

Driven by the current trend of communication interconnectivity through social media, **CogniCity** taps into the existing cultural fascination with social media in Jakarta, Indonesia, while also connecting to community initiatives which often occur offline. By deploying the project from both directions at once—through the software for social media filtering and feedback, and through grassroots organizations and networks—we can harness the real potential of social media by enabling critical information to be gathered and connected to the efforts of both citizen-led and government initiatives.

While the influence of social media on urban residents is well known, our development of a **GeoSocial Intelligence** framework that sorts, selects, and prioritizes existing social media data to enable precise, real time analysis is both unique and innovative. Other existing platforms for community mapping, such as Ushahidi, have already made possible extensive, citizen-lead data collection; **CogniCity** extends this logic by soliciting individuals to act as sensors in the city via existing social media networks. Within our **GeoSocial Intelligence Framework**, citizens as sensors provide, for the first time, comprehensive, real time coverage of infrastructure resilience throughout the city. Through our pilot study in Jakarta, this framework will allow us to study patterns of urban resilience to flooding and inundation with unprecedented detail. However, as our data analysis, public reports, and scientific findings are completed, we can also begin the design of integrated, decision-support tools for individual users, community organizations, and governmental agencies.

Our key objectives for the **PetaJakarta.org** Joint Pilot Study, conducted with the Jakarta Emergency Management Agency (BPBD DKI), with the support of the United Nations Pulse Lab and the Twitter #Data Grant, can be summarized as follows:

- 1. Develop our understanding of urban resilience in the context of rapid urbanization and changing infrastructure demands;
- 2. Capture the interactions between society and urban infrastructure as a function of resilience to change;
- 3. Quantify probabilistic risks to urban systems as a result of environmental changes;
- 4. Understand the response of communities to a range of pressures on civic infrastructure;
- 5. Employ new data sources (i.e. crowd-sourced, social media information) to analyze

## RESILIENCE PATTERNS IN SOUTHEAST AND SOUTH ASIAN MEGACITIES.

The **PetaJakarta.org** pilot study develops novel techniques and methods to better understand the response of the complex urban system to change, to promote new open source technological solutions to emergent problems within complex urban systems, and to theorize and disseminate these innovative findings through scholarly publications and conference presentations. A critical component of this research is understanding the interactions between society and infrastructure in order to quantify the response of cities to a range of scenarios in a probabilistic manner. This understanding will be derived from our analysis of data collected through our **GeoSocial Intelligence Framework**, which uses a public, web-based interface to display crowd-sourced geo-located information.

This open framework is currently being piloted in Jakarta, Indonesia, where our main objective is studying local communities and government officials as they develop co-management strategies to promote and sustain urban resilience. By integrating a network model of the flood management infrastructure, crowd-sourced information about on-the-ground situations, and government data from flood monitoring sites throughout the city, **PetaJakarta.org** will operate as a public information service, a site for the dissemination of time-critical information, and a data repository that will facilitate our integrated, ongoing analysis of urban resilience. In this respect, our project reduces the redundancy in our analysis by using the same framework for data collection and for the future development of more comprehensive decision-support systems that will compliment our real time mapping and data visualization.

As cities evolve to become increasingly complex systems of people and interconnected infrastructure, the impacts of both extreme and long-term climate change are significantly heightened. Understanding the resilience of urban systems and communities in an integrated manner is key to ensure the adaptability of cities to climate change, and the sustainability of urban populations and social welfare, both of which face considerable challenges in the 21<sup>st</sup> century. As Southeast Asia's most populous and most dense metropolitan conurbation, and the second largest urban footprint in the world, Jakarta's residents are highly exposed to rapid transformations of urban structures and systems. Recent trends in weather intensification, sea level rise, extreme pollution, severe land subsidence, and river and coastal inundation make Jakarta a key site for researching and responding to the 21<sup>st</sup> century challenges of urban resilience and climate adaptation. Moreover, the combination of Jakarta's progressive municipal government, civil society organizations, and foreign capital investment suggest a unique potential for both transforming and improving the social life of residents through the technologically-sophisticated, scientifically-innovative, and publicly accessible networked **GeoSocial Intelligence Framework**.

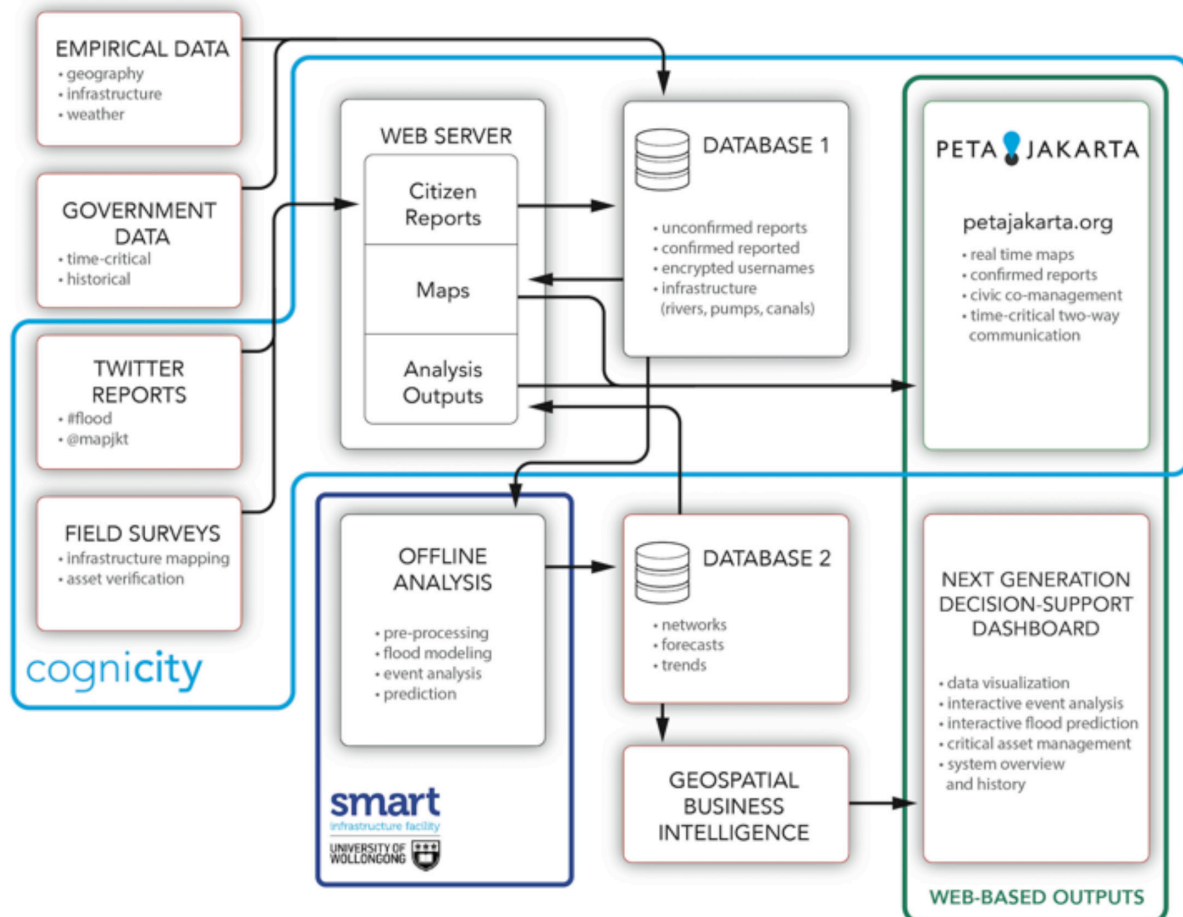
Importantly, while Jakarta's rate of urbanization, rate of subsidence, and infrastructure systems are geographically specific, it is not the only delta city to face tremendous hardship because of climate change. Chief among the difficulties for Jakarta—as well as for Southeast Asian cities like Bangkok, Ho Chi Minh City, Manila, and Phnom Penh, as well as Dhaka in Bangladesh's Bengal Delta, and Colombo, Sri Lanka, in South Asia—is the problem of flooding. Globally, flooding causes approximately half of all human deaths due to natural disasters and accounts for nearly 40% of all natural disasters worldwide. In the developing nations of the global south, these statistics become even more dire because of failing and poorly maintained infrastructure, municipal corruption, poor intergovernmental coordination, and a lack of funds for comprehensive infrastructure improvement. In the major delta cities of South and Southeast Asia, we can add poor hydrological and hydraulic planning, frequent mismanagement of waste and sewage, difficulty in transport due to traffic extreme congestion, and extreme pollution to the list of problems exacerbating the difficulty of solving the problem of flooding. And, while the costs to insurance companies and civic governments who must bear the growing burden of post-flood reconstruction and clean up efforts continues to skyrocket, we are only beginning to understand the equally severe impact of recurrent flooding on physical and mental human health and high-risk mass migration. Combined, these factors make effective flood management the top priority for investment in South and Southeast Asian infrastructure.

However, such urgent investments are often too costly, too politically-sensitive, or simply too difficult within the existing conditions on the ground to be achieved in a timely, effective manner. Our research has demonstrated clearly that what is lacking—and what is most urgently needed—is a decision-support system that can provide accurate, real time information to municipal agencies and government actors, allowing them to make evidence-based, politically-transparent, safe and effective choices in response to extreme weather events. These cities do not need more infrastructure; they need smarter systems that can manage existing civic assets, locate weaknesses, prioritize improvements, and coordinate intergovernmental efforts to relieve our cities of costly flooding due to climate change. Until **CogniCity**, and our **Next Generation Decision-Support System**, even when they could be imagined, such

powerful tools for infrastructure co-management were not yet available or were too cost prohibitive to be useful in a developing nations context.

Our project asks how innovative techniques for data collection can utilize the existing public enthusiasm for social media and extensive mobile communication networks to improve urban resilience in relation to flood management, weather-related emergencies, and emergency response. While addressing the problem of flooding in Jakarta is urgent, the significance of this research problem extends well beyond both Jakarta's geography and the specificity of flooding and inundation. In fact, how to better utilize the extensive network of personal mobile communication devices and social media platforms to improve urban resilience is a critical area of research for future climate adaptation and planning.

While the proliferation of social media might first appear as so much noise for civil and information system engineers, with the proper technologies for gathering, sorting, and analyzing data, this noise can be transformed into critical information for both understanding and promoting resilience. By connecting network models of urban infrastructure to crowd-sourced and social media-based data collection, and then making this information and analysis available through a web-based platform, our project links innovative areas of infrastructure research and multiplies the potential of each by producing a novel, open framework for citizen-participation in the co-monitoring and co-management of urban systems.



**Figure 1: PetaJakarta.org System Diagram showing relation between CogniCity, SMART Infrastructure Facility offline analysis, and public and government web-based platforms.**



# Synthetic Mudscapes: Human Interventions in Deltaic Land Building

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## ABSTRACT

In order to defend infrastructure, economy, and settlement in Southeast Louisiana, we must construct new land to mitigate increasing risk. Links between urban environments and economic drivers have constrained the dynamic delta landscape for generations, now threatening to undermine the ecological fitness of the entire region. Static methods of measuring, controlling, and valuing land fail in an environment that is constantly in flux; change and indeterminacy are denied by traditional inhabitation.

Multiple land building practices reintroduce deltaic fluctuation and strategic deposition of fertile material to form the foundations of a multi-layered defence strategy. Manufactured marshlands reduce exposure to storm surge further inland. Virtual monitoring and communication networks inform design decisions and land use becomes determined by its ecological health. Mudscapes at the threshold of land and water place new value on former wastelands. The social, economic, and ecological evolution of the region are defended by an expanded web of growing land.

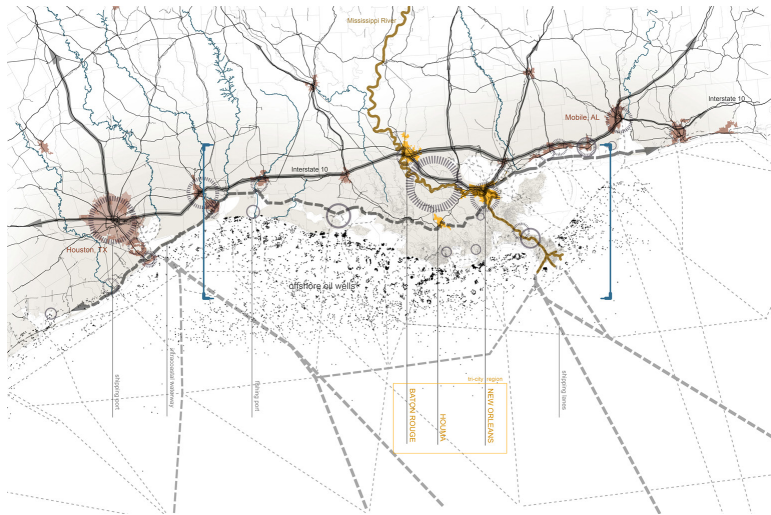
**Keywords:** Risk, Coastal, Adaptive, Mudscapes

## SUBHEAD REQUIRED

The Coastal Sustainability Studio is a transdisciplinary research and design operation at Louisiana State University. Including architects, landscape architects, urban planners, civil engineers, and coastal scientists, the workshop is a collaborative effort incorporating the College of Art+Design, the College of Engineering, and the School of the Coast & Environment. The studio addresses issues stemming from coastal erosion and wetland disintegration, incorporating the needs of specific design projects and their relationships with ecological, institutional, industrial, and socioeconomic systems amongst the built environment. The works of CSS aim to reduce economic losses and protect assets, promote a sustainable coastal system by incorporating natural and constructed processes, provide sustainable habitats to support an array of commercial and recreational heritage, and sustain the unique coastal heritage of the state of Louisiana.

Along with increased storm frequencies and intensities, coastal environments around the world are facing growing challenges of subsidence, land loss, saltwater intrusion, and sea level rise. These zones at the thresholds of land and water are often densely inhabited, both by spectrums of urban settings and the industries and infrastructures that sustain them. Incorporating gradients of population, trade, investment, and regulation, the stretch of shore between Houston, Texas and Mobile, Alabama presents one of the most vulnerable megaregions throughout the entirety of the United States. Annual land loss exposes urban cores and embedded industries to increased risk as the wetland fabric that formerly sheltered the region subsides. Amongst the silts of the Mississippi River Delta, contradictions between human and geologic time become visible; static methods to quantify, control, and value land fail in an

environment that is constantly in flux. Links between urban environments and economic drivers have constrained the dynamic delta landscape for generations, now threatening to undermine the ecological fitness of the entire region. In order to defend settlement and economy across the Gulf Coast States, the integration of infrastructures must be reconsidered and agile forms of implementation should arise in place of stagnant control systems. In these complex territories, land is a resource for mitigating risk; multiscale megaregional strategies, structural as well as nonstructural design projects, and flexible systems of implementation provide support systems that consider and assimilate environmental fluctuations in an efficient manner.



**Ecological Valuation :  
Risk Mitigation Land  
Benefits**

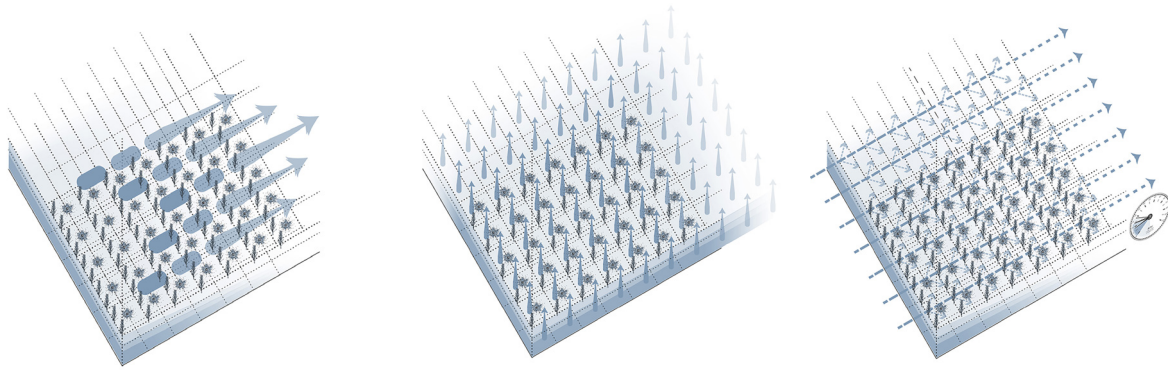
#### **Infrastructures of the Gulf Coast Megaregion**

Correlations between municipalities at neighbourhood, city, state, and regional scales evolve through and alongside environmental, economic, and industrial systems. The infrastructures that sustain these geographic expanses cross jurisdictions and boundaries, complicating the already interwoven fabrics of human settlement; however, the borders between urban, suburban, and rural environments are increasingly difficult to define, gradually eroding into density spectrums of continually populated landscapes. Along the federally funded and managed Interstate-10 [I-10] corridor, the southeast portion of the U.S. has emerged as an economically significant and industrially valuable territory. The geographic section between east Texas and south Alabama renders an increasingly intertwined urban ecology of shipping, petrochemical, and transportation infrastructures. South of this federal highway, local roads, ports, and railways are increasingly vulnerable; communities, industries, and their support structures are at risk of frequent or permanent inundation due to subsidence and coastal erosion. A 6 meter storm surge would flood 100% of the roads south of the I-10 passage. In order to defend infrastructure, economy, and settlement within the region, this project proposes that we must re-establish a rapidly disappearing landscape by constructing new land to alleviate increasing risk.

Coastal vegetation has been shown to significantly affect wave attenuation as measured by reductions in wave height per unit distance across a wetland.

Deteriorating wetland environments can impact the storm intensity that reaches inland environments. Across a geographic area, the physical functions provided by wetland environments may be similar; however, valuable services to populations vary according to density of those urban conditions and the value those communities ascribe to them. Through ecosystem services valuation methods, natural capital is ascribed to the conditions and processes of natural ecosystems and species that sustain and fulfill human life. These measurable benefits are especially considerable in terms of saltwater inundation and risk reduction. Capable of reducing the overall height of storm surge, physically slowing the forward momentum of the storm, and preventing hurricanes from pulling up more water, wetland environments are capable of providing direct and indirect value to gradients of urban conditions and the surroundings that perpetuate them.



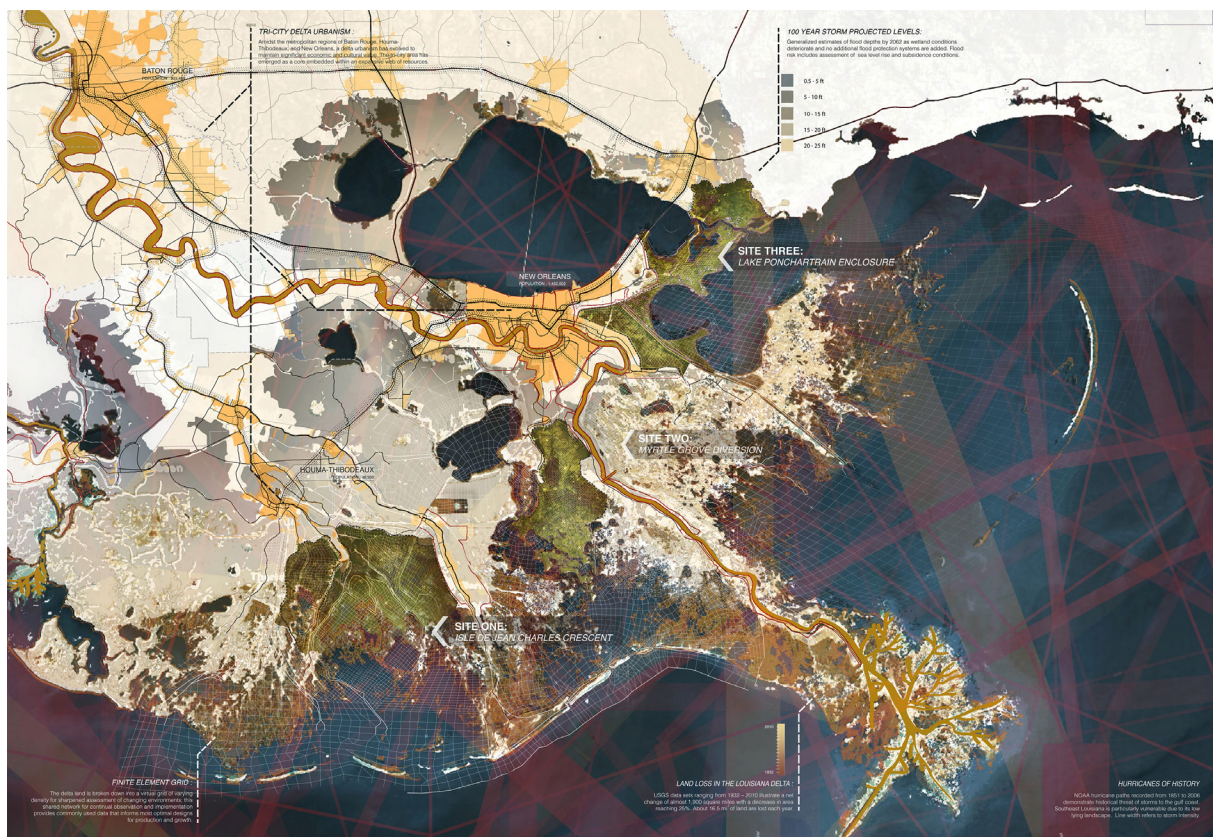


-- + **Prevent Accumulation: deprive ability of storm to pull up more water**

-- + **Decrease Velocity: slow movement forward allowing for dissipation**

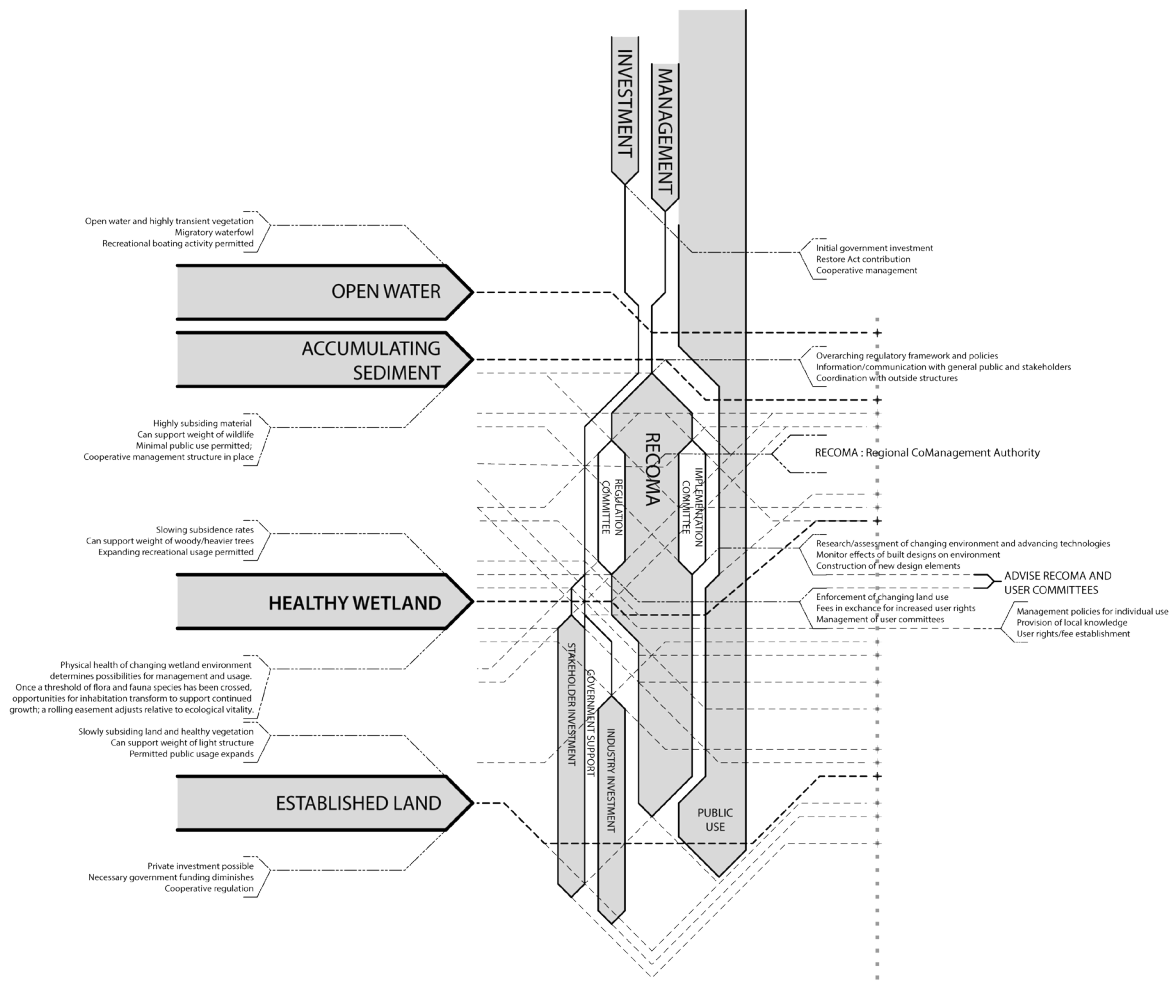
-- + **Height Reduction : reduce volume with drag of vegetation**

With the incorporation of structural and nonstructural protection systems, discrepancies in rates of deterioration, change, growth, and loss are continually present. In order to better understand the conditions as they change, continually updated datasets are required. Populations and the risks in which they are submerged continue to shift; however, regularly measuring those variables and designing their relationships, infrastructure design strategies can better understand how those varied forces overlay and interact. Population density surveys allow for an understanding of risk where sizeable communities influence reduction and response practices. Structural and nonstructural protection system diagrams illustrate design projects as they pass through stages of planning, construction, implementation, and evolution. The ability for wetland vegetation to influence risk can be partially determined by species and habitat structure; the ecosystem strength, durability, and change must be continually monitored in order to determine the value they presently provide to the surrounding areas as well as influencing future points of action. Through the Coastal Reference Monitoring System, wetland loss and restoration efforts are observed in order to understand the cumulative effectiveness of projects. This existing infrastructure assists in observation and recording of these changing conditions; however, the spatial distribution of these sites could be densified in order to better assess and quantify the transient landscape.



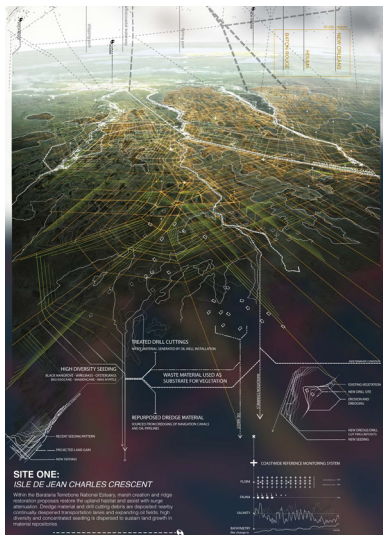
**Risk Mitigation for the Urban Ecology; Depicting gradients of exposure to the Tri-City Delta urban core, storm surge probability, historic hurricane tracks, and land loss over the better part of the last century are overlayed to illustrate the project sites within the larger Southeast Louisiana context.**

Within the urban-economic expanse of the Gulf Coast Megaregion, the tri-city delta landscape between New Orleans, Baton Rouge, and Houma-Thibodeaux has evolved to maintain significant cultural and industrial value; the central wetland of Louisiana is embedded within this expansive web of resources. Land loss and storm surge datasets continue to assist in determining optimal locations for structural and nonstructural infrastructure implementation across southeast Louisiana. In order to found a resilient, layered mitigation strategy, Synthetic Mudscapes envisions three distinct land building practices; this set of strategies provides an arc of transforming systems to fortify aforementioned spectrums of inhabitation. Within the Isle de Jean Charles Crescent, dredge material and drill cutting debris are deposited nearby continually deepened transportation lanes and expanding oil fields; high diversity and concentrated seeding is dispersed to sustain land in material repositories. Expanding from an outlet in the Mississippi River Levee System, the Myrtle Grove Diversion releases sediment and shifted landfill medium transported from the river basin is deposited to accelerate natural land building processes. Combining treated sewage for wetland fertilization as well as wave attenuation arrays in nearby open waters, the Lake Ponchartrain Enclosure evolves as a constructed topography incorporating strategic infill of repurposed waste from nearby urban areas. Each of these strategies reintroduces fluctuation and adaptive management in order to form the foundations of protective, fertile fabrics.

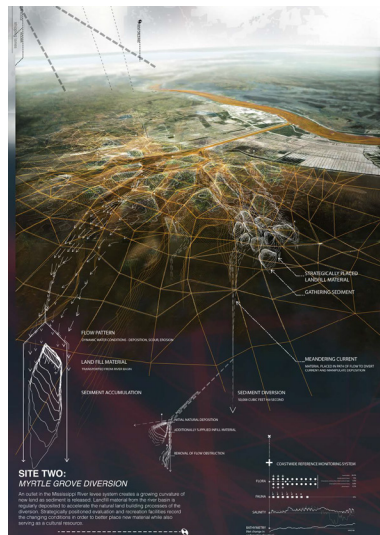


### Ecosystem Service Dependent Landscape Use Strategy

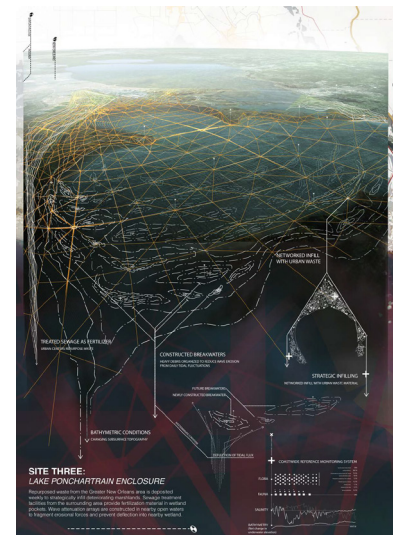




*Land Building Site 1: Isle de Jean Charles Crescent; Within the Barataria Terrebonne National Estuary, marsh creation and ridge restoration proposals restore the upland habitat and assist with surge attenuation. Dredge material and drill cutting debris are deposited nearby continually deepened transportation lanes and expanding oil fields; high diversity and concentrated seeding is dispersed to sustain land growth in material repositories.*



*Land Building Site 2: Myrtle Grove Diversion; An outlet in the Mississippi River levee system creates a growing curvature of new land as sediment is released. Landfill material from the river basin is regularly deposited to accelerate natural land building processes as strategically placed evaluation and recreation facilities record the changing conditions in order to better place new material while also serving as a cultural resource.*



***Land Building Site 3: Lake Ponchartrain Enclosure; Repurposed waste from the Greater New Orleans area is deposited weekly to strategically infill deteriorating marshlands. Sewage treatment facilities from the surrounding area provide fertilization material in wetland pockets while wave attenuation arrays are constructed in nearby open waters to fragment erosional forces and prevent deflection into fragile, nearby marshes.***

The possibility for considering such methods of transformative infrastructures lies in the capacity to understand environments as they transform; through a latticed network of spatial nodes, a finite element grid establishes a framework for constant methods of measurement in a continually shifting environment. Changes and developments in urban ecosystems are registered and the system projects viability estimations and success rates of reconstructive design processes; the density of the mesh communicates situational variances in graphically illustrated detail. Data acquisitions and incorporations allow for interplays between distant information and related design decisions; deposition and integration strategies are based on continually monitored ecosystem vitality at the scale of inhabitation. Information acquired through satellite locations provides the capacity for virtual cartographies to become embedded with layers of relevant information; data collection becomes a tactic for understanding relationships between scales in time and the landscape. Considerate assimilation of these datasets promotes the integration of design and implementation practices across the varied delta landscape; a resilient, urban, coastal ecosystem arises from understandings of interwoven industrial, ecological, economic, and regulatory relationships.

While effectiveness of infrastructure projects is continually measured, an investment and management strategy is implemented to respond to the dynamism of the urban ecology. As the surface area of land changes, varied methods of financing and occupation are put in practice to fund transforming infrastructures. Initial investments of federal, state, and local government are followed by possibilities of shared occupation and rights to the land as a resource; multiple users contribute relative to function for maintenance and growth. As variations in wetland environments shift between open water and established land, the quality and physical condition of the ecosystem determines its usage; public and industrial utilization is accepted at stronger, healthier stages of ecosystem development. However, as territories remain within a delicate stage of accumulating sediment, the overarching regulatory framework and policies reflect the significance of future risk reducing interests via stakeholders and the general public. Changing use and increased user rights accompanies management policies with newly established or re-established land. Questions of utilization and occupation are addressed through an adjustable support structure.

From the cores of urban areas to the surroundings that sustain them, continually changing environments require infrastructures that can consider and assimilate environmental fluctuations efficiently. Reflexive practices that integrate

transdisciplinary proposals with a monitored understanding of conditions as they change, flexible investment and management practice, and adaptive implementation strategies can be deployed across scales in a considerate and particular manner. Multiscalar processes require agile infrastructures to respond to increased risk and a variety of design practices can be introduced within those landscapes. Additionally, including land growth in contrast to the construction of a floodwall, variations in time frames for actualization must be considered throughout project development and deployment. Structural and nonstructural projects can be assimilated in dialogue through data acquisition and continual communication between design and planning bodies. Relationships between populations and the environments they inhabit are in constant flux; being so, it is necessary that the tactics we use to invest in, construct, and manage these processes reflect this continual change. Rising seas, subsidence, and coastal erosion are reorganizations that are constantly evolving and often relatively unpredictable; linear methods of working are incapable of functioning in these complex territories and are ill equipped to respond to these recurring transformations. Megaregional infrastructural systems traverse borders and boundaries, industries, economies, cultures and populated jurisdictions; understanding how infrastructures affect and are affected by the geographies they support is necessary to advance our interwoven, urban ecologies. In order to satisfy the requirements of the diverse demographically and industrially inhabited megaregion, the complex natural environments in which they are embedded must be continually addressed.

# **Multi-Level and Transnational Governance Issues**



# Emergence of District-Heating Networks; Barriers and Enablers in the Development Process

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<http://discovery.ucl.ac.uk/1469407/>

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## ABSTRACT

Infrastructure provision business models that promise resource efficiencies and additional benefits, such as job creation, community cohesion and crime reduction exist at sub-national scales. These local business models, however, exist only as isolated cases of good practice and their expansion and wider adoption has been limited in the context of many centralised systems that are currently the norm. In this contribution, we present a conceptual agent based model for analysing the potential for different actors to implement local infrastructure provision business models. The model is based on agents' ability to overcome barriers that occur throughout the development (i.e. feasibility, business case, procurement, and construction), and operation and maintenance of alternative business models. This presents a novel approach insofar as previous models have concentrated on the acceptance of alternative value provision models rather than the emergence of underlying business models. We implement the model for the case study of district heating networks in the UK, which have the potential to significantly contribute to carbon emission reductions, but remain under-developed compared with other European countries.

**Keywords:** District Heating, Agent Based Model, Infrastructure Business Models

## INTRODUCTION

Infrastructure systems are vital to enable modern, sustainable societies to prosper. The infrastructure systems that have been developed since the industrial revolution are largely unfit for this purpose. Utility provision infrastructure (i.e. energy, water, transport and waste removal), in particular, is characterised by carbon intensive generation and supply for unconstrained and unsustainable levels of demand<sup>1</sup>. The transition to environmental, social and economically sustainable infrastructure systems requires a fundamental transformation of both the physical infrastructure and the business models operating it, in the context of enabling governance regimes<sup>2</sup>.

Alternative business models exist that operate more resource efficient physical infrastructure and are capable of creating and capturing wider forms of social and environmental value. These, however, exist only as isolated 'niche' examples of good practice and are far from becoming mainstream. In this contribution, we present a modelling framework to study the barriers facing the mainstreaming of these types of business models and the attributes of actors and policy interventions that can enable them. Our model framework concentrates on the actors involved in an infrastructure business model throughout project development and operation, both embedded in the broader socio-

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1 Roelich, K. *et al.* Towards resource-efficient and service-oriented integrated infrastructure operation. (*submitted*).

2 Geels, F. W. The dynamics of transitions in socio-technical systems: A multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860–1930). *Technol. Anal. Strateg. Manag.* **17**, 445–476 (2005).

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technical context. This builds on previous work that studied the barriers to MUSCOs (Multi-utility service company business models)<sup>1,3</sup> and local authority energy planning<sup>4,5</sup>.

A socio-technical modelling approach brings a number of advantages and insights. First, it forces the clarification of an interdisciplinary system representation that includes physical infrastructure, actor behaviour and their interactions, and the relevant policy environment. Second, it goes beyond standard economic assumptions of rational choice and a demand-driven market to capture complex behaviours and interactions between agents across both the demand side and the system of provision. Finally, a socio-technical model allows us to explore the emergence of different systemic patterns of behaviour under varying policy regimes. Agent-based modelling (ABM) is able to capture such complex interactions between policy interventions, social and technical structure, and individual behaviour<sup>6,7</sup>. While agent-based models of social systems abound, only recently, work has emerged to simulate the long-term development of infrastructure and other socio-technical systems<sup>8,9,10,11</sup>. In this contribution we describe the insights gained from developing an agent-based socio-technical model specification for analysing the emergence of alternative infrastructure operation business models, exemplified by the roll-out of district heating networks in the UK.

## DISTRICT HEATING IN THE UK

District heating networks have the potential to significantly improve the energy efficiency and carbon intensity of heat and hot water supply to domestic and commercial buildings<sup>12</sup>, particularly where heat can be sourced from combined heat and power (CHP) generators. Although this potential is recognised by the UK government, progress in achieving this potential is still very slow. The UK has very low penetration of heat networks with only around 1% of the population getting heat from a district heat network<sup>13</sup>. This is much lower than most European countries where some, including Denmark, Poland and Estonia, have more than 60% of the populations heat supply provided by district heating<sup>13</sup>.

The barriers to a larger roll-out of district heating networks in the UK have already been identified in a number of studies<sup>4,14,15,16</sup>. In some of these studies, the barriers are also linked to the type of actors and where in the development process they occur. A full listing of the barriers we have collated is beyond the scope of this paper, but they generally fall into one of five categories:

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- 3 Knoeri, C., Steinberger, J. K. & Roelich, K. End-user centred infrastructure operation: Towards integrated infrastructure service delivery. (*submitted*)
  - 4 Bale, C. S. E., Foxon, T. J., Hannon, M. J. & Gale, W. F. Strategic energy planning within local authorities in the UK: A study of the city of Leeds. *Energy Policy* **48**, 242–251 (2012).
  - 5 Knoeri, C., Goetz, A. & Binder, C. R. Generic bottom-up building-energy models for developing regional energy transition scenarios. in *9th Conf. Eur. Soc. Simul. Assoc.* (2014).
  - 6 Grimm, V. & Railsback, S. F. *Individual-based Modeling and Ecology*. (Princeton University Press, 2005).
  - 7 Janssen, M. A. & Ostrom, E. Governing socio-ecological systems in *Handbook of Computational Economics II: agent-based computational Economics* (eds. Tesfatsion, L. & Judd, K. L.) (Elsevier, 2005).
  - 8 Van Dam, K. H., Nikolic, I. & Lukszo, Z. *Agent-Based Modelling of Socio-Technical Systems*. (Springer, 2013).
  - 9 Bergman, N. *et al.* Modelling Socio-Technical Transition Patterns and Pathways. *J. Artif. Soc. Soc. Simul.* **11**, (2008).
  - 10 Kempener, R., Beck, J. & Petrie, J. Design and Analysis of Bioenergy Networks. *J. Ind. Ecol.* **13**, 284–305 (2009).
  - 11 Knoeri, C., Nikoli, I., Althaus, H.-J. & Binder, C. R. Enhancing Recycling of Construction Materials; an Agent Based Model with Empirically Based Decision Parameters. (*submitted*)
  - 12 Department of Energy & Climate Change. *The Future of Heating: Meeting the challenge*. (2013).
  - 13 Euroheat. *District Heating and Cooling Statistics*. (2009).
  - 14 Department of Energy & Climate change. Research into barriers to deployment of district heating networks. (2013).
  - 15 Hawkey, D., Webb, J. & Winskel, M. Organisation and governance of urban energy systems: district heating and cooling in the UK. *J. Clean. Prod.* **50**, 22–31 (2013).
  - 16 Poyry & Faber Maunsell. The Potential and Costs of District Heating Networks: A report to the Department of Energy and Climate Change. (2009).
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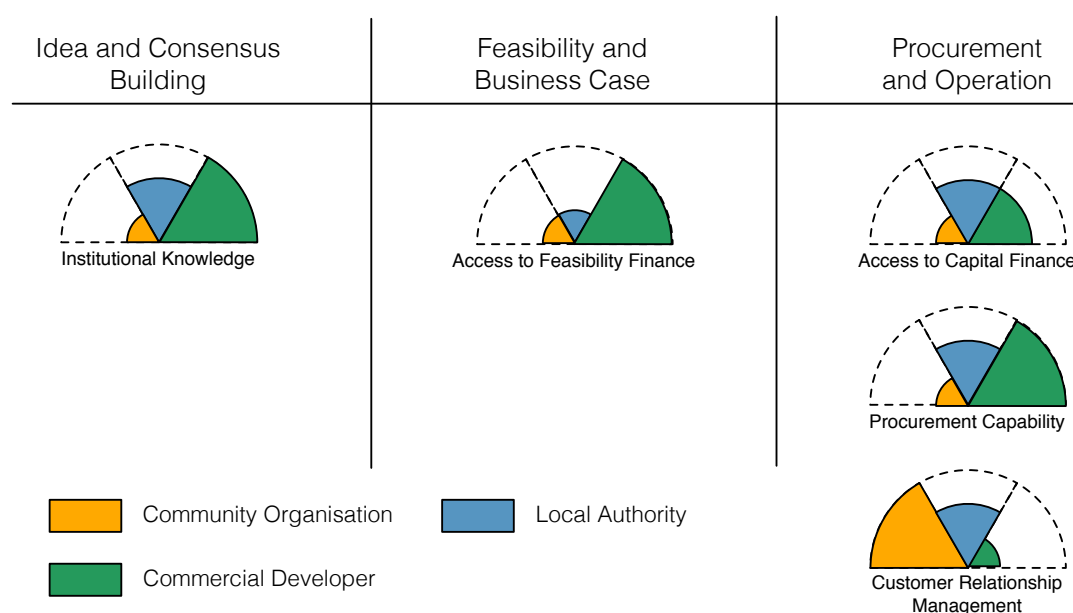


<b>financing and risk</b>	e.g. access to development finance and willingness to hold debt
<b>knowledge and data</b>	e.g. a motivated and knowledgeable individual within the instigating organisation
<b>relationships</b>	e.g. access to an appropriate network of partners
<b>legal capabilities</b>	e.g. drawing up contracts and meeting requirements of a supply licence
<b>market and regulation</b>	e.g. access to a guaranteed heat demand over the lifespan of the scheme

The growth of district heating in the UK can happen either through the development of entirely new networks, or the expansion of already existing ones. The development of new networks is often linked to the development of new housing or commercial buildings, but can also be part of a retrofitting process for old housing stock. In either case, the process of developing a district heating network depends on both the agents decision making and housing stock dynamics. Drawing on policy and guidance documents<sup>14,17,18</sup> we separate the process into three broad phases: feasibility study and business case development, procurement and construction, and operation and maintenance. We use these phases and the barriers described above as the basis of an agent based model specification, which is described in the following section.

### AGENT-BASED SOCIO-TECHNICAL MODEL

According to DECC statistics<sup>12</sup>, there are around 2,000 individual district heating networks in the UK supplying 210,000 dwellings and 1,700 commercial and public buildings. Heat networks can be categorised into three types: large campus based schemes serving universities or hospitals; private sector developments including commercial and housing schemes; and 'public' schemes that serve social housing and may include connections to public buildings such as schools or swimming pools. In some cases, for example the Byker estate<sup>19</sup>, social housing heat networks are taken over by community organisations. We hence include three types of instigators and operators of district heating networks: community organisations, local authorities and commercial developers.



**Figure 1: A subset of barriers faced in the three phases of the development and operation of district heating networks with a preliminary estimate of the severity of each for the three different types of actors indicated by the size of the coloured wedge (small = low severity, large = high severity).**

17 King, M. & Shaw, R. Community Energy: Planning, Development and Delivery. (2010).

18 Ove Arup & Partners Ltd. *Decentralised Energy Masterplanning A manual for local authorities*. (2011).

19 Byker Community Trust. *CORPORATE PLAN 2012-2015*. (2012).

Figure 1 shows a small subset of relevant barriers faced by these actors in the phase of the process they are encountered and a preliminary estimate of the severity of the barrier for the different type of actor. The severity estimates are based on the study into barriers to district heating commissioned by DECC<sup>14</sup>, with some additional assumptions for community organisations. Future work will carry out a comprehensive analysis of all the identified barriers with severity estimates derived from case study interviews. At this stage already, however, it is clear that there are significant differences in the barriers faced by communities and local authorities on the one hand and commercial developers on the other.

Based on the above description of actors, barriers and processes we have developed a conceptual socio-technical model. The purpose of this model is to analyse the most significant barriers preventing the emergence of district heating networks in the UK, and where policy interventions can have an impact in removing these barriers.

*Modelled entities:* The model includes three basic types of agents: instigators who seek to develop a heat network; heat demand agents; and heat source agents. The instigators are the community organisations, local authorities and commercial developers discussed in the previous section. Heat demand agents are further classified into private housing (including owner-occupied and private rented), social housing (both local authority owned and other social housing providers), public (for example swimming pools, schools, hospitals and council offices) and commercial. Heat source agents represent existing sources of waste heat that can be integrated with a district heating network, in practice the only relevant heat sources likely to be integrated are large incinerators.

*Key processes:* The model procedure runs on the back of a bottom-up building stock model, which includes demolitions, construction and refurbishment processes<sup>11</sup>. Two drivers can start the process for developing a district heat network: the initiation of a new housing or commercial development, or the decision by a housing operator to refurbish housing and install a district heating network. In either case, if a heat network already exists in close proximity, expansion will be considered. Once started, the development and operation process proceeds through the actions of the relevant instigator and interactions with other agents. The instigator actors possess a set of attributes that determines their likelihood of successfully completing the actions they must take throughout the development process. These attributes are derived from the barriers they face where a high severity barrier translates into an attribute having a high chance of falling short. In the initial implementation of the model we include only a small number of attributes, namely those shown in Figure 1, as these were previously identified as the most common and severe<sup>14</sup>.

*Model development:* Starting with a very simple model will allow us to test the explanatory power of the variables we have chosen to include and then incrementally add further variables to determine their impact. Policy interventions are included in the model through the ability to change key variables used in conjunction with attributes: for example the availability of development finance and capital finance and the availability of guidance and support to ease development planning. Development will be informed through both case study interviews and workshops to elicit stakeholder validation of the model structure and outputs.

## CONCLUSIONS AND FURTHER WORK

The development of the model specification described above has brought useful insights into the relationship between the barriers to district heating network development and the attributes of different types of actors involved in this process. The approach of developing a socio-technical model of district heating has highlighted that the key drivers are intimately related to both the dynamics of the built environment stock and the motivations of a number of key actors that include local authorities, commercial developers and potentially community organisations (although these are still rare cases).

A further important methodological improvement is in the separation of barriers and actor attributes. By assigning attributes to different actors to represent their ability to overcome the barriers they face in the development process, it becomes clear that the relevance of barriers is likely to vary widely between different types of organisations, scale and scope of the projects. This observation leads to an issue that we intend to investigate with an extended model – how different forms of value creation and capture can be enabled by policy intervention. Different organisation, by virtue of their purpose, motivations and geographical extent are capable of generating different kinds of social and environmental value, as well as economic value at different scales. Local authorities are motivated by fuel poverty reduction, community groups may seek to create community cohesion and both may create jobs locally more than a national scale commercial developer. Policy interventions that enable one type of actor more than others will consequently favour the creation of a different set of values.

The model development we have presented here is based on a highly interdisciplinary research approach that integrates technical infrastructure and building stock models with agents that make decisions based not only on economic considerations but also based on their capabilities. This interdisciplinary approach is crucial in studying infrastructure systems, which, due to their scale and key role in providing societies needs, are tightly regulated, difficult to finance and capable of causing enormous environmental damage. The agent-based modelling approach also allows us to connect the micro-level analysis of barriers and actions to the wider governance regime. Barriers at the micro-scale are often a manifestation of a meso- and macro-scale policy regime and landscape that favours the incumbents. A socio-technical model can connect changes to the policy regimes back to the micro-level of actors implementing alternative infrastructure business models.



# Improving Engineering Governance for Large Infrastructure Projects

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<http://discovery.ucl.ac.uk/1469408/>

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## ABSTRACT

The increased complexity of modern infrastructure projects together with the desire of governments to provide improved services to their citizens gives rise to the need for much better engineering governance capability and the ability to model system and user behaviour to ensure the desired increased level of service. Modelling all aspects of planned systems through the use of standardised architecture framework models that can be developed to provide the necessary insight across all aspects and levels of concern for the system(s) is an excellent approach for achieving this.

This paper describes the initial phase of development of such a toolset for the Asset Standards Authority (ASA) of Transport for New South Wales (TfNSW) that will be used to ensure coordinated development activities between all divisions in the department, as well as with Planning NSW and the private sector providers for system design, implementation, maintenance and operation. The initial development described here particularly focuses on existing, current and future heavy rail projects, but continuing work is under way to extend and generalise the model so that it applies to all rail transport modes (rapid transit metro and light rail) and eventually to include all other TfNSW transport modes — buses, walkways, ferries, cycle ways, and roads. Furthermore, this paper details how the use of a metamodel for the architecture framework provides the rigour and abstraction necessary to allow this generalisation within the same model structure.

**Keywords:** Enterprise Modelling, TRAK Meta-Model, SysML Modelling Language

## BACKGROUND

The Australian State of New South Wales (NSW) has recently reorganised the way in which it will deliver new transportation assets (including infrastructure and vehicles). Existing capability has either been retained within the new Transport for NSW (TfNSW) organisation, or outsourced to the private sector. Six new divisions have been created within TfNSW with well-defined responsibilities for the delivery of an ambitious program of new transport assets for the state. At the same time it was recognised that this structure would need strong asset management governance to ensure that the new structure did not become siloed, thereby leading to asset planning and delivery mis-matches. In addition there is also the need to coordinate effectively with private sector providers as Authorised Engineering Organisations (AEOs). The means of achieving this has been to create the Assets Standards Authority (ASA).

“The Asset Standards Authority (ASA) is an independent unit established within Transport for NSW, and is the network design and standards authority for NSW transport assets. The ASA is responsible for developing engineering governance and frameworks to support industry delivery in assurance of design, safety, integrity, construction, commissioning, maintenance and disposal of transport assets for the whole asset life cycle. The ASA is also responsible for providing the standards for NSW rail assets, which industry organisations can use to deliver projects

and manage assets in a more innovative, safe and efficient manner.” ([www.transport.nsw.gov.au/asa](http://www.transport.nsw.gov.au/asa))

This presentation and paper describes architecture framework modelling that is being carried out by the ASA and the SMART Infrastructure facility at the University of Wollongong to provide the intellectual rigor and tools to accomplish these goals in a manner that is auditable, efficient and engages the stakeholders.

## APPROACH

Delivering modern infrastructure is a complex enterprise involving many stakeholders namely; Politicians, government planning, Authorised Engineering Organisations (AEOs), design and acquisition agencies, finance organisations, private contractors, system operators and perhaps most important, the customers of TfNSW. The top level goal of TfNSW is the delivery of cost effective, reliable, sustainable, efficient, convenient and most importantly safe heavy rail and other services to the state's population to satisfy the expectations of the customers' experience.

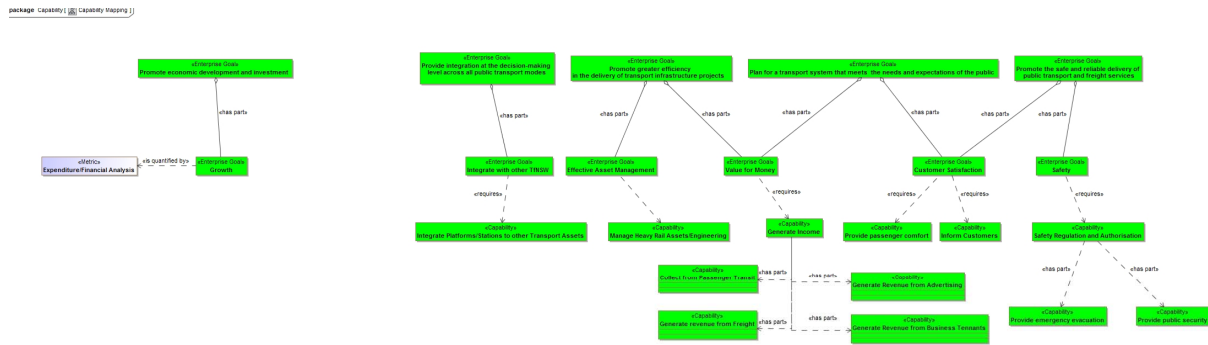
The approach being considered and developed by ASA to deliver the structure to accomplish management of this Transport System of Systems (SOS) is the development of an architecture framework based toolset capable of describing and linking all key transport enterprise stakeholder concerns and involvements in the delivery process. The initial work described here has been the development of the toolset for the Heavy Rail sector of transportation, with the ultimate goal being to generalise the model that is the basis of the toolset to eventually include all transport modes in the framework, including multi-modal operations.

The top level concepts included in the toolset model development are being built using the TRAK metamodel and architecture framework ([trak.sourceforge.net](http://trak.sourceforge.net)). The original TRAK metamodel and architecture framework was developed in the UK for application to railway projects, and was derived from the Ministry of Defence Architecture Framework (MODAF). The TRAK metamodel is now a general purpose and enterprise architecture framework which provides 5 key viewpoints into the enterprise, which in this case is taken as the provision of heavy commuter rail assets and services. These viewpoints are – Enterprise, Concept, Solution (Inclusive of solution resource), Procurement, and Management. The TRAK metamodel, being based on the Unified Modelling Language (UML) does not specify how these viewpoints are to be expressed as requirements and performance parameters. Therefore, in this work we have chosen to use SysML ([www.sysml.org](http://www.sysml.org)) because TfNSW requires understanding (and therefore representation) of low level functional behaviour of passengers, trains and elements of the railway system such as energy supply and train control, and SysML has the capacity to do this better than UML. Another need that TfNSW has is to be able to validate the requirements of its high level enterprise goals and capabilities in terms of traceability to the lower level functional and physical requirements that arise from them and SysML is able to support this through the use of its parametric diagram view. In addition to the modelling of the physical asset performance of the new heavy rail systems, this work is also developing the structure for modelling passenger behaviour throughout the use profile of passengers, and also specific scenarios such as the effects of passenger numbers on platform dwell times, and the effect these can have on the provision of high frequency train services.

## MODEL DEVELOPMENT TO MID 2014

In this section we illustrate with a few of the model elements the manner in which an Architecture framework model can depict and link all levels of an enterprise, so that knowledge about the system at all stages can be accessed in the context of the system as a whole. While this can be seen as a lot of work – and it certainly is – all evidence is that the ROI can be huge in the avoided cost of later scope and performance errors and shortfalls being discovered at a stage in the project where correcting them is hugely expensive and usually leads to significant delays.

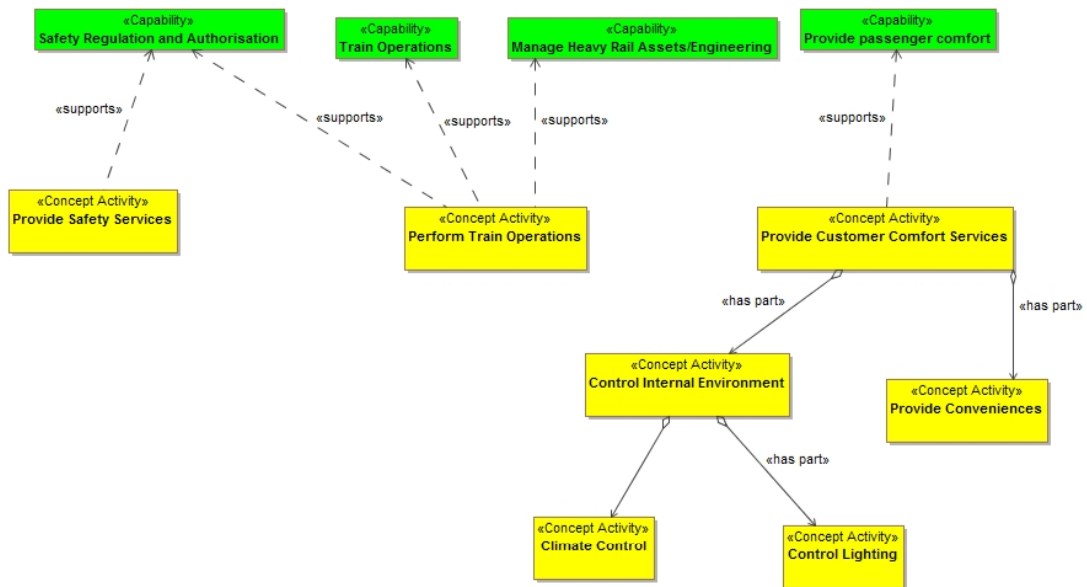
At the enterprise level the enterprise goals (as stated in the NSW Long Term Transport Master Plan) required a set of supporting capabilities as shown in Figure 1. The Concept Activities that support these capabilities were then identified as shown in Figure 2. This diagram captures the traceability of which concept activities directly support the required capabilities. In this way the diagram both provides justification for these needed activities and provides the structure and location in the model where evidence that all capabilities have been addressed can be either confirmed, or if absent, cause early corrective action to be taken.



**Figure 1: Capability mapping based on enterprises goals**

Although some of these diagrams (such as Figures 1 and 6) are often impossible to read on the page of a document this is not an issue in using the model as they are designed as entry points into the model and its database rather than only being guides to enterprise structure. The model is designed and expected to only be used on a capable computer system where such diagrams can always be expanded so that the diagrams can be read.

**bdd [Package] Capability [ CVP-04 Concept Activity to Capability Mapping - Rolling Stock ]**

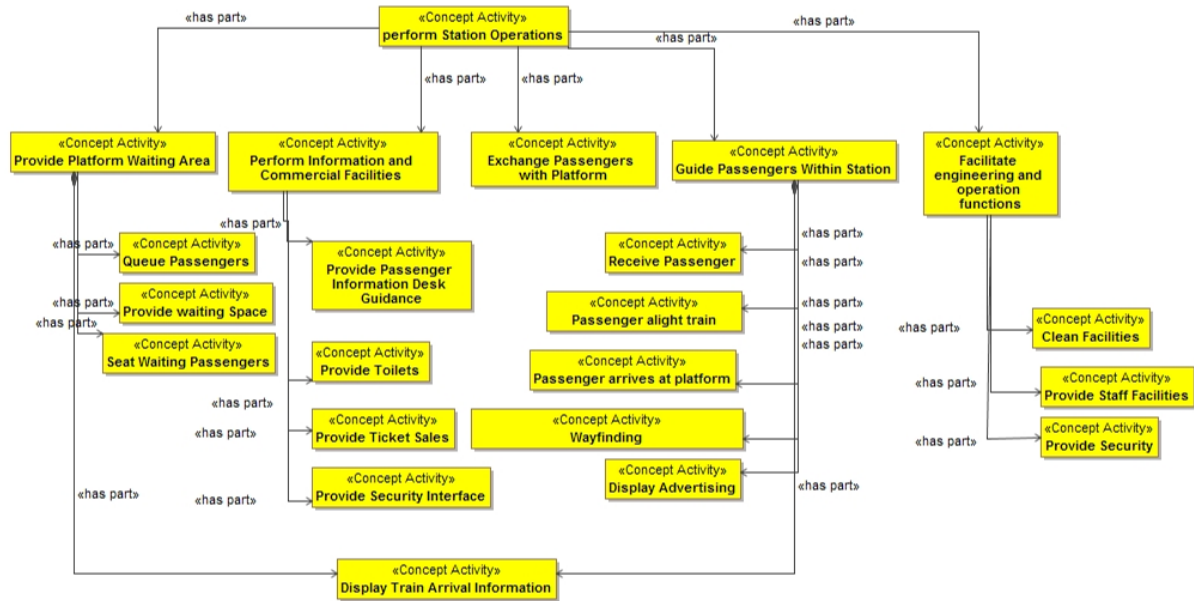


**Figure 2: Capabilities mapped onto concept activities**

The initial model developed by ASA using TRAK, on which this SysML model is based, defines the major system elements as rolling stock, stations and buildings, telecommunications, electrical supply, signals, rail network and management. Development so far has focused on the rolling stock, telecommunications and stations and buildings, though aspects of the other elements have been defined where they touch upon the model behaviour. Here we describe the development of the stations and buildings component to illustrate the development process at a lower level.

The station operations conceptual hierarchy model is shown in Figure 3.



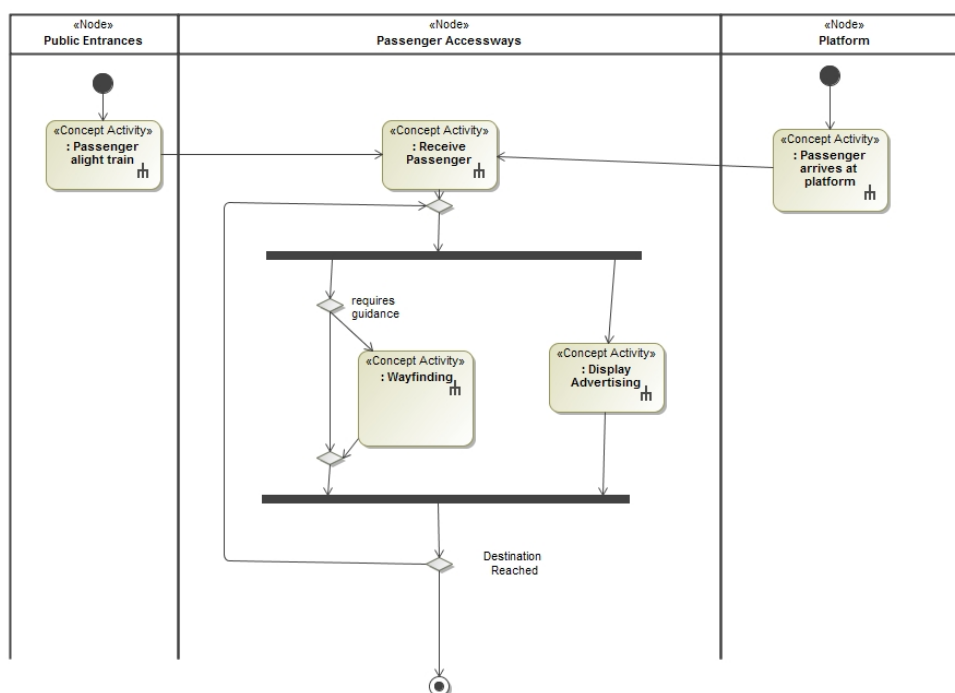


**Figure 3: Station operations conceptual activity hierarchy**

The diagram shows a representative sample collection of concept activities that are needed to perform the necessary station operations of the rail system, and the dependencies between them. Each of the nodes (logical operational entities) in the diagram can then be further developed with more detail, including the standards that apply and eventually the design documents and validation activities.

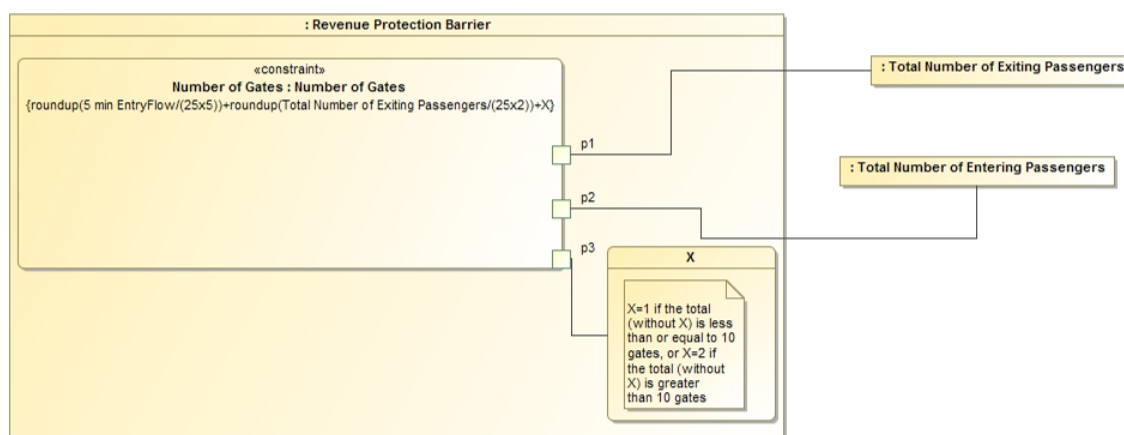
Figure 4 shows an example of the concept activities that are needed to guide passenger within a station. Note that this is still done at an abstract level, so that the diagram has general applicability. Here it applies to a railway station, but a very similar diagram would also apply to passengers using a ferry service – where the platform becomes a wharf, but otherwise activities are similar or the same at the abstract level, and then can be instantiated with the particular details for each application.

At a lower level still, Figure 5 is a parametric diagram showing the model structure into which the behaviour models – in this case either a simple queuing model or possibly an agent based model capable of modelling passengers with individual attributes – can be executed to validate the capability of optional numbers of gates to meet the expected passenger use rates.



**Figure 4: Interaction between concept activities.**

**par** [Class] Revenue Protection Barrier [ Revenue Protection Barrier ]

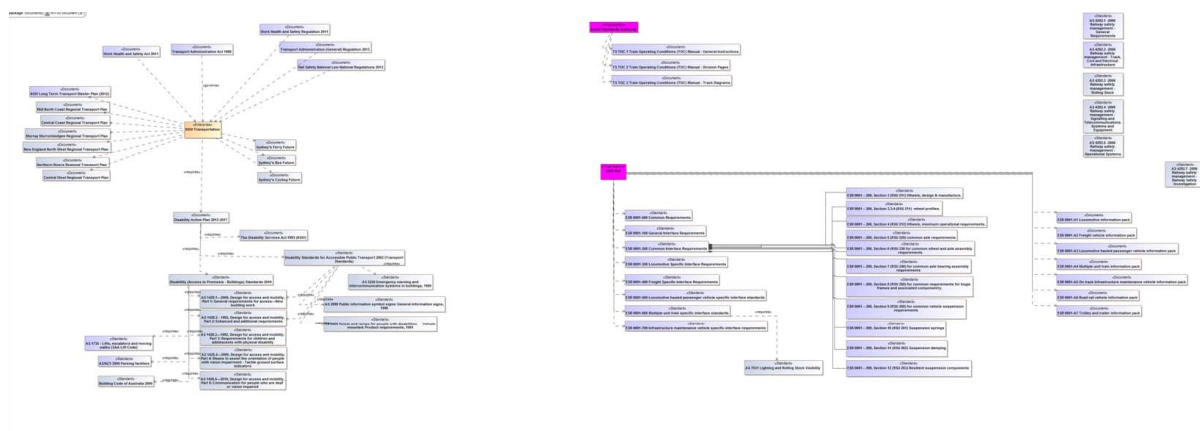


**Figure 5: Parametric diagram to determine the number of gates needed in a revenue protection barrier**

As embodied in its title, the ASA is particularly concerned with improving the ability of TfNSW to manage the impact of standards on the development of future assets. To date it has identified over 1,000 standards that potentially apply to its current heavy rail assets – which includes a new high frequency line to the North West suburbs of Sydney and upgrades to a higher level of service on the main western line from the CBD through to North Sydney. In addition to this large body of documents, which contains figures and diagrams as well as text, any asset type also has the specific documents developed for its design and realisation, and sitting above all this are the various acts and other high level legal instruments under which TfNSW must function. One of the goals that TfNSW and ASA have is to move the existing approach based on specify type standards to functional and performance based standards, with the expectation that this will allow more scope for innovations by the supply chain in procuring future transportation assets. In carrying out this objective, the ability to understand how the multitudes of standards are linked to all the asset design elements is of extreme importance.

The tools available in the model also provide the opportunity for linking documents directly to the database. Stakeholders need to specify applicable documents and standards that have to be met, or guidance that influences

the design of the systems. These documents can often specify further documentation to cause a traceability chain that, if unmanaged, can cause difficulties in maintaining adequate knowledge of the system as a whole. Standards and legislation can change, so that the new standard needs to be re-examined to determine the implications of these changes. There have also been cases where cyclic references have been generated by standards produced in isolation. The way in which the model has been developed to address the need for document traceability is shown in Figure 6.



**Figure 6: Document library**

The documents shown in the library diagram can be linked either to copies found either on the same machine as the model or via a URL. This helps maintain the connectivity of the model information as the “single source of truth” with relevant documentation and makes document navigation easier. The application of the SysML model to the management of standards can be illustrated by the following example of the standards that apply to detailed physical design level for a carriage bogie. Figure 7 shows the way in which the nodes in a bogie design can be traced through the requirements back to the applicable standards.

## CONCLUSION

As illustrated by the set of diagrams presented here, the use of an architecture framework type model expressed in SysML provides a powerful toolset for managing the engineering and behavioural aspects of large complex transport systems. At the top level many stakeholders and their expectations are modelled so that the interdependencies can be managed in a timely manner. At the lowest level the hundreds of thousands of standards, design documents, requirements specifications can all be placed in a common data base and linked to the applicable nodes and viewpoints in the model. As the complexity of modern transport projects continues to increase through the need for provision for greater efficiency, improved safety and greater user satisfaction, the need for such a model based systems engineering approach and toolset is becoming more and more urgent. A major issue in developing such tools is the dearth of trained people with the ability to do so effectively.

What has been described here is a work in progress. In addition to continuing the present development to support more detailed toolset capability, it is planned to extend the model to a generalised version that can be used for all transport modes in NSW, and to ensure that the requirements diagrams in the model are structured to support the automatic generation and export of text requirements in the nearly ubiquitous requirements tool DOORS that is used elsewhere in TfNSW. Research will also be conducted into the feasibility of machine reading of the requirements arising from the standards as an aid to coping with the huge load involved in applying them to new work as well as the transforming them to a performance based form.

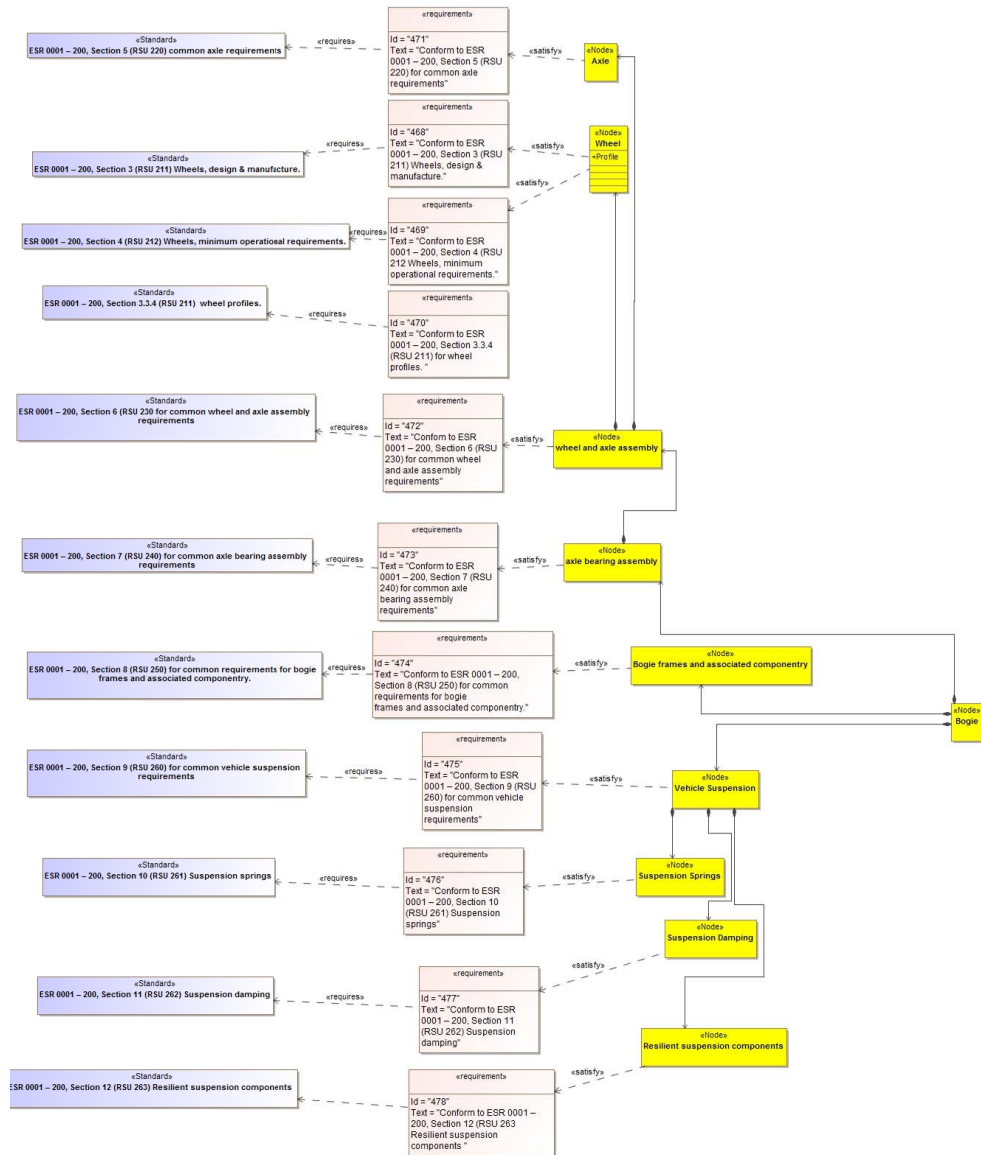


Figure 7: Traceability from nodes through requirements to stand



# An Interdisciplinary Approach for the Assessment and Implementation of Resilient and Flexible Water Supply Infrastructure under Changing or Instable Conditions

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<http://discovery.ucl.ac.uk/1469409/>

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## ABSTRACT

In case of demographic changes or emergencies pipeline bound infrastructure like gas or water is specifically challenged. Then, the advantages of decentralized infrastructure should be considered: Minimization of asset bound funds; flexibility; resilience; response capacity. A research project at the Federal Armed Forces University together with the Brazilian utility company COPASA, the process engineering company Grünbeck and the ICT company Phönix focused on: A procedure for successful decentralized water infrastructure implementation; a new operation scheme; related pilot tests. To describe the local situation the Open System of Boundaries is created comprising 13 interdisciplinary groups and 68 subgroups. To describe water supply systems the Open System of Attributes is created comprising 15 groups and 64 subgroups. An Attributes Profile which fits into the Boundaries Profile makes a resilient decentralized application more likely. For Minas Gerais, Brazil, i.e. for instable conditions the Boundaries Profile and the Attributes Profile of a decentralized SCADA equipped water treatment plant are compiled. Results of on-site tests are discussed. Recommendations for decentralized water supply under instable conditions are given. The application of standardized SCADA equipped treatment plants is suggested with remote supervision from one control centre.

**Keywords:** Resilience, Decentralised Water Supply, Open System, SCADA

## INTRODUCTION

Today, hard infrastructure and especially grid and pipeline bound infrastructure like electricity, gas, water, wastewater and also traffic are facing numerous challenges on many different levels globally. With regard to water supply three cases can be identified where classical centralized pipeline bound infrastructure systems are specifically challenged:

- Urban or rural connection deprived regions in an instable environment,
- Situations when existing infrastructure has to adapt to upwards or downwards demographic changes,
- The case of emergencies.

Amongst others these cases are commonly characterized by fast or sudden changes in the overall physical and intangible environment, by a future which is hard to predict, by the need for a fast response and resilience or by many interfaces with other infrastructure systems – i.e. by situations unsuitable for inflexible centralized pipeline bound infrastructure systems.

The water transportation and distribution network of centralized systems often accounts for more than 50% of the hardware costs with an average service life of up to 50 years. These are long-time bound funds which on the one hand make adaptations in the system difficult and which on the other could be saved by decentralized systems. The advantages of the latter are:

- Minimization of asset bound funds,
- Cost effectiveness,
- Flexibility in management,
- Reliability under varying conditions,
- Resilience and response capacity to sudden changes in the environment,
- Possibility of accelerated implementation,
- According to necessity simple as well as complex technologies possible,
- Because of usually short transport distances, water is delivered in adequate quality to the consumer.

Therefore, in the three cases mentioned above the application of more decentralized infrastructure systems seems promising. This goes especially for connection deprived rural regions in Newly Industrialized Countries NICs.

### **MACRO-LEVEL SITUATION IN NEWLY INDUSTRIALIZED COUNTRIES NICs**

There exists no universal definition of NICs which was the reason to follow Goldman Sachs papers in selecting BRICS, i.e. Brazil, Russia, India, China and South Africa and Next-Eleven countries, i.e. Bangladesh, Egypt, Indonesia, Iran, Mexico, Nigeria, Pakistan, Philippines, South Korea, Turkey and Vietnam for the assessments.

The analysis of the contribution of their agricultural, industrial and service sector to their national GDP and their water withdrawal distribution between the agricultural, industrial and municipal sector shows that the two are reverse. There is a trend of an increase of the third GDP sector at the cost of the first one. However, by far the largest water withdrawal is dedicated to the first sector which contributes to the GDP little or least.

The urban and rural population distributions do not show a common pattern. BRICS and N-11 countries with a large third sector have a higher urbanization rate in general. Most analyzed countries' annual urbanization rate is superior to the respective population growth rate. The coverage ratios of improved water sources and improved sanitation facilities following WHO definitions are higher in urban areas than they are in rural ones. In rural areas they might even deteriorate which leads to drawbacks like the practice of open defecation in some countries.



## RESEARCH PROJECT

When an existing central infrastructure system needs to be assessed regarding e.g. its capacity of adaptability or when a hard infrastructure system is to be implemented for the first time two procedures are of utmost importance in order to define the most appropriate and suitable decentralized configuration:

- The precise and multidisciplinary description of the local situation and of the overall boundaries,
- The precise and multidisciplinary assessment of the existing infrastructure system / of the system which is about to be implemented with regard to the local situation.

Both procedures reflect the interactions between hard and soft aspects of infrastructure. However, until now no comprehensive instruments existed in order to carry out the two steps. Deficits in the knowledge about the local situation and about the attributes of infrastructure systems induced numerous infrastructure implementation failures, especially under instable or changing conditions.

A research project at the Universität der Bundeswehr München / University of the Federal Armed Forces of Germany at Munich together with the Brazilian utility company COPASA, the process engineering company Grünbeck and the ICT company Phönix Contact focused on these open questions mainly via the following central research assumptions<sup>1</sup>:

1. The key to a successful application of decentralized water supply is the selection of appropriate systems. Crucial is the knowledge about the local situation and the precise system description.
2. Decentralized water treatment incorporating advanced technology can be applied under instable conditions when the technological aspects are embedded into the socio-economical-cultural ones.

Following the three stage approach of description, systematization and experimentation<sup>2</sup> studies were carried out in several NICs and DCs. The research region for the exemplary assessment of a modular, SCADA equipped membrane-based decentralized water treatment plant, short pilot plant, was the Brazilian state of Minas Gerais (look figure 1). Qualitative and quantitative methods were applied for the analysis of the empirical data material.



**Figure 1: Decentralized water treatment pilot plant in Minas Gerais, Brazil**

Picture: Wolfgang K. Walter

Stemming from the project experience the “Open System of Boundaries for Decentralized Water Supply” is created in order to describe the local situation (look figure 2). It comprises 13 groups of boundaries, e.g. geographical factors, state of local sanitary engineering, macro- and microeconomics, social and cultural factors, etc., including 68 sub-boundaries.

To describe the properties of water treatment and supply systems the “Open System of Attributes of Decentralized

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<sup>1</sup> Walter, W.K. *Recommendations for Small Water Supply Systems in Newly Industrialized Countries on the Example of Assessments in the State of Minas Gerais, Brazil*. Aachen: Shaker (2013).

<sup>2</sup> Windelband, W. *Präludien – Aufsätze und Reden zur Philosophie und ihrer Geschichte*, 2. Band. Tübingen: J.C.B. Mohr, Paul Siebeck (1915).

Water Supply Systems” is created (look figure 3). It comprises 15 groups of attributes, e.g. system type, process engineering, transportability, social aspects, macro- and microeconomics, etc., including 64 sub-attributes.

For a specific case the “Open System of Boundaries for Decentralized Water Supply” can be employed to describe the local situation. As a result, the local situation is labelled by a distinctive “Boundaries Profile”. The “Open System of Attributes of Decentralized Water Supply Systems” is employed to describe water treatment technology in the planning stage or infrastructure which has already been implemented. In both cases, water supply systems get a distinctive “Attributes Profile”. An “Attributes Profile” which fits into the “Boundaries Profile” makes a successful, sustainable, resilient and flexible decentralized system application more likely.

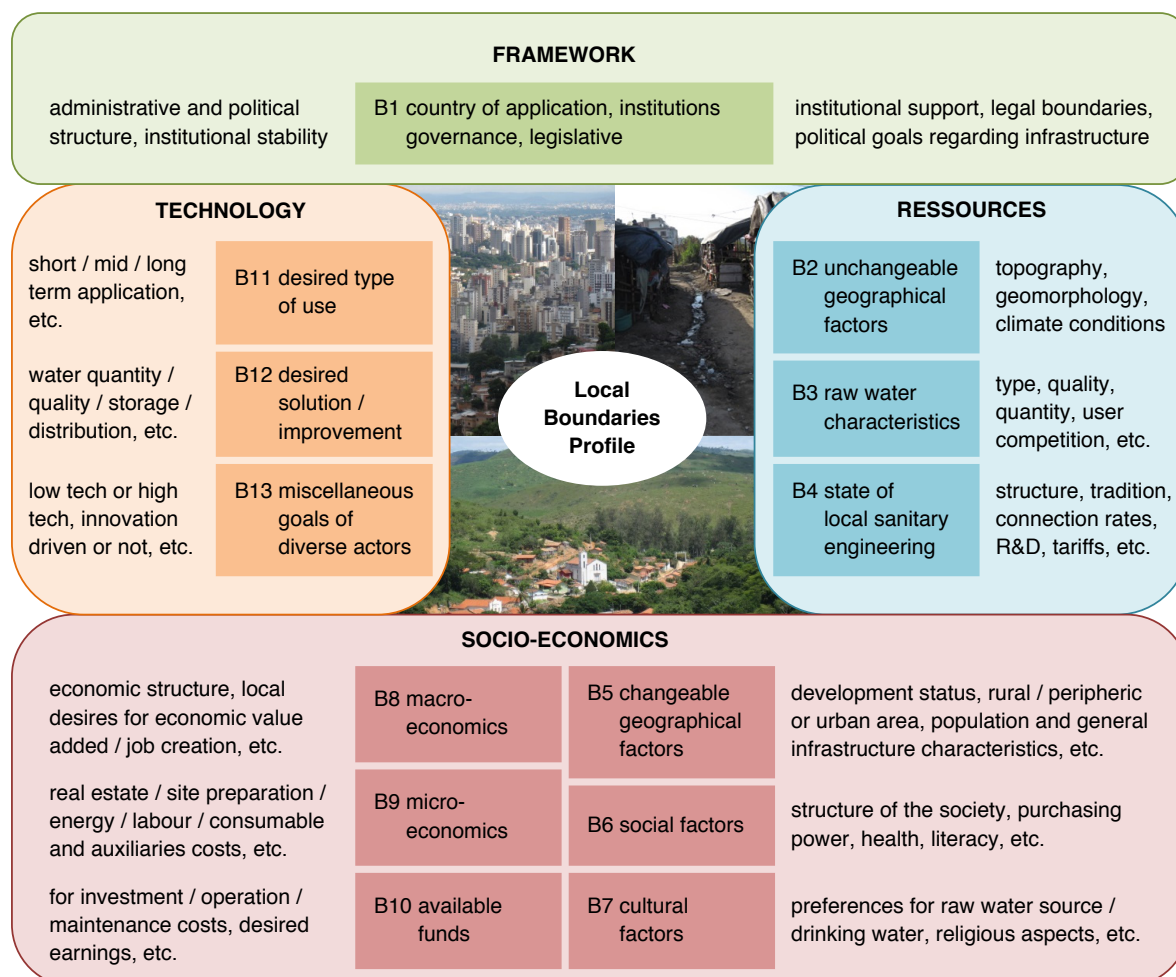


Figure 2: Open system of boundaries for decentralized water supply applications with examples of the 68 sub-boundary-groups

FRAMEWORK	TECHNOLOGY	OPERATIONAL BEHAVIOUR	SOCIO-ECONOMICS
A1 system type, general plant description	A4 process engineering	A8 transportability	A12 social aspects
A2 tasks covered by the system	A5 electrical engineering, energy supply	A9 operation set-up	A13 macroeconomics
A3 plant operation strategy	A6 assembly	A10 movable character	A14 microeconomics
	A7 adaptability	A11 plant behaviour under continuing operation	A15 cost assessment

**Figure 3: Structure and content units of the open system of attributes of decentralized water supply systems; further on divided into 64 sub-groups**

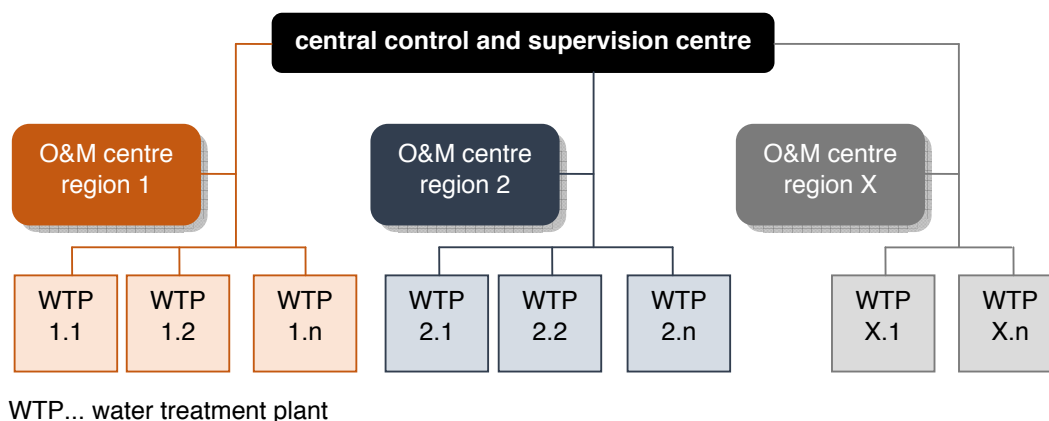
### CONCEPT FOR RESILIENT AND FLEXIBLE DECENTRALIZED WATER INFRASTRUCTURE

Decentralized water supply infrastructure incorporate many advantages compared to conventional centralized infrastructure systems, especially when it comes to resilience and flexibility. Nevertheless, the literature mentions associated disadvantages:

- Often a wide range of different systems is in use in a certain area,
- Difficulties with operation, maintenance and monitoring,
- Therefore, water quality and public health concerns.

To overcome these disadvantages the application of standardized, automated, SCADA equipped decentralized water treatment plants is suggested. Automation, quality measurement equipment and SCADA could improve quality transparency of decentralized water treatment plants. For the case that several similar plants are implemented, remote supervision from one control centre would be possible (look figure 4). This would allow centralized online control of the local plant status and of quality parameters. Water safety would be improved for the water customers. Supervision and O&M would be facilitated for the water supplier. Regional O&M centres could be responsible for regular O&M. Irregular maintenance upon instruction from the central control centre could be executed from these regional O&M centres as well. This concept is of special interest for

- rural regions where up to hundreds of decentralized water treatment plants need to be implemented and operated in small communities, i.e. e.g. for large surface states like Brazil.



**Figure 4: Decentralized water supply supervision, operation and maintenance concept**

## PILOT PLANT TEST RESULTS AND OUTLOOK

The backbone of the concept presented in figure 4 are the stand-alone water treatment plants. After compiling the local “Boundaries Profile” a related pilot plant was tested in the Brazilian State of Minas Gerais within the research project described in section three. The pilot plant was a Small Water System (look figure 1). All the equipment was fixed in two ten feet high cube containers which were electrically and hydraulically connected on site. A modular built up incorporated potential for future adaptability. The pilot plant’s treatment steps were:

Hydrocyclone (alternatively) - Flocculation/coagulation and pH-value correction (alternatively) - Pre-oxidation (alternatively) - Drum filter or a plate separator - Aerator (alternatively) – Ultrafiltration - Reverse osmosis unit (alternatively) - Final chlorination and adding of fluorine (both alternatively).

Automation, equipment with online quality measurement devices and SCADA were the core features of pilot plant configuration and of its operation strategy. Personnel extensive, remote telecontrolled membrane water treatment was the desired goal. Results of in-depth on-site tests showed that both, the integrity of the treatment system under difficult raw water conditions as well as the compliance with the local drinking water quality provisions were guaranteed. However, regarding the supervision and O&M concept the findings revealed general challenges under instable and extreme conditions:

- Telecommunication availability,
- Reliability of digital quality measurement equipment,
- Local supply chain management of hardware and consumables.
- Local understanding for the necessity of capacity building,
- The local personnel’s education and knowledge level regarding advanced technology,
- Unclear expectations about what an automated membrane water treatment plant can and what it cannot.

# **Special Session:**

**Past and future energy  
infrastructures in the global  
south — Perspectives  
for decentralization**



# **Legacies of a Past Modernism Discourses of Development and the Shaping of Centralized Electricity Infrastructures in Late- and Postcolonial Tanzania**

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<http://discovery.ucl.ac.uk/1469410/>

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## **ABSTRACT**

As the UN has declared the years 2014-2024 the “Decade of Sustainable Energy for All”, countries in Sub-Saharan Africa struggle with the transition towards more sustainable and more inclusive energy infrastructures. In many rural areas, electrification rates remain as low as 1-2%. For many countries, one of the main barriers for rural electrification is the legacy of a model of top-down planning, large-scale power generation and a centralized topology of the electricity infrastructure. Nonetheless, historiography on electricity infrastructures in Africa is nearly non-existent. At the example of Tanzania this paper shows, that the centralized power models which dominate the continent today were shaped by modernization and development discourses during the late colonial and post-independence period. Because of its particular characteristics, electricity lent itself perfectly to the goal of making development measurable — a goal which was essential to a “high modernist” vision of development, advocated by new nation states as well as international funders. The paper illustrates how large hydropower projects proved successful in expanding generation capacities and urban electrification rates, but failed in providing electricity to rural areas and created path-dependencies which have led to dead ends in the last 20 years.

**Keywords:** Legacy Infrastructure, Sub-Saharan Africa, Centralized Power Systems, Development Discourses, High Modernism

## **SUBHEAD REQUIRED**

While Europe and other post-industrial economies are struggling with the transition to more flexible and adaptable low-carbon electricity infrastructure, much of the developing world faces challenges on a much more basic level. In Sub-Saharan Africa (excluding South Africa) for example, only 14 percent of rural households have access to any electricity at all, according to a widely cited estimate.<sup>1</sup> As in Europe however, the legacy of inadequate past electricity infrastructure remains one of the main barriers for the transition towards a more sustainable, more flexible and especially in the case of Sub-Saharan Africa, a more inclusive energy system. Most African countries have inherited a model of top-down planning, large-scale generation (mostly through hydropower plants) and centralized transmission, which “focuses on large-scale energy consumers whose activity influences macro-economic indicators like GNP, and labels a broad range of domestic and rural electricity benefits and beneficiaries as ‘uneconomic’ or expensive social welfare” (Showers 2011).<sup>2</sup> The long-term neglect of participatory, bottom-up and decentralized approaches is not

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1 IEA (International Energy Agency), Energy for All. Financing Access for the Poor. Special early excerpt of the World Energy Outlook 2011, Paris 2012. (online). <http://www.worldenergyoutlook.org/resources/energydevelopment/accesstoelectricity/>.

2 Kate B. Showers, Electrifying Africa: an environmental, history with policy implications', in: Geografiska Annaler: Series B, Human

only due to the legacy of existing physical infrastructure, but also due to the interests of national policy institutions, international donor relations and a governing paradigm of centralized power systems. It has only been recently acknowledged by some African governments that there is a centralized power model crisis<sup>3</sup>, leading them to integrate a “decentralized track”<sup>4</sup> into their national electrification strategies, promoting small power producers and mini-grids in rural areas.

At the same time, it seems that big and mega-engineering projects for electricity generation and transmission continue to dominate the political agenda throughout Sub-Saharan Africa. Posing as an alleged single technological fix for a country’s unreliable and insufficient electricity infrastructure, these projects prevail in the debate on how to prioritize needs for investment in the competition for scarce capital. The absence of historians and of historical perspective in this debate is particularly noteworthy. Except for a few laudable exceptions<sup>5</sup>, works that treat the history of electricity in Sub-Saharan Africa (except for South Africa) are rare and studies with a focus on infrastructure history are non-existent. It shall be argued in this paper, that the detailed knowledge of how the centralized electricity infrastructures, which dominate on the continent today, have historically emerged is not only a valuable but essential aspect of this debate, as a glance to the industrialized West shows.

Historiography of electricity in Europe and the United States has contributed much to widening the traditional “engineering perspective” and enabling a much deeper understanding of the social complexity which underlies electricity infrastructure. For example, Gilson has shown that in Germany in the first half of the 20th century a pressure group made up from political institutions, large-scale electro-industry and financial capital played an essential role in establishing a “dogma of the economic superiority” of the centralized power model in academia.<sup>6</sup> This inherent superiority has been convincingly questioned by Stier.<sup>7</sup> The concept of decentralized cogeneration of heat and electricity was discussed at an early stage of German electrification as an option with a higher overall efficiency than single-purpose electricity generation. It was only dismissed because economists and engineers of the time had a narrow focus on electricity generation. Models of “decentralized and customer-oriented, cost-effective and democratically controlled power supply” existed in some regions but fell victim to the drastic centralization policy of National Socialism. Some authors have gone as far as to radically deconstruct structuralist approaches. In his study on Switzerland, Gugerli has argued that its electrification was essentially a result of societal communication about the potentials and consequences of electricity.<sup>8</sup> One doesn’t have to follow the radical nature of his thesis to acknowledge the importance of historical discourses in shaping electricity infrastructures.

Using the example of Tanzania, this paper therefore looks at the historical discourses associated with the emergence of centralized power models in Sub-Saharan Africa in the late colonial and early post-independence era. It is firstly argued that it was not only due to advances in long-distance electricity transmission or an inherent technical or economical superiority that was the main driver for the emergence of the centralized power model. Instead the centralized power models were the result of a particularly sweeping vision of development, using benefits of technical and scientific progress and measuring progress in technical and economic indicators. This vision was derived from the historical industrialization in the West, inspired by large-scale river basin development projects like the Tennessee Valley Authority (TVA) and advocated by the newly emerging interventionist development states as well as international organizations. Secondly, it will be shown that because of its particular characteristics, electricity perfectly lends itself to this vision of development. Thirdly, the role of the different decision makers in establishing the centralized power model will be discussed. It will be argued that hydropower development in postcolonial Africa was not primarily an attempt of authoritarian national states to engineer their environments as described in James C. Scott’s widely acknowledged

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Geography 93,3 (2011), 193–221.

3 Stephen Karekezi, Renewables in Africa – meeting the energy needs of the poor, in: *Energy Policy* 30, 11–12 (2002), 1059–1069; C. M. Haanyika, Rural electrification in Zambia: a policy institutional analysis, in: *Energy Policy* 36, 3 (2008), 1044–1058.

4 Bernard William Tenenbaum, Chris Greacen, Tilak Siyambalapitiya, James Knuckles, *From the bottom up: how small power producers and mini-grids can deliver electrification and renewable energy in Africa*. Washington, D.C. 2014.

5 Catherine Coquery-Vidrovitch, *Electricity Networks in Africa: A Comparative Study, or How to Write Social History from Economic Sources*, in: Toyin Falola/ Christian Jennings (eds.), *Sources and Methods in African History*, 2003, 346–360; Ghanadan, Rebecca, *Public Service or Commodity Goods? Electricity Reforms, Access, and the Politics of Development in Tanzania*. Unv. Diss., University of California, Berkeley, USA 2008; Shower, *Electrifying Africa*.

6 Norbert Gilson, *Konzepte von Elektrizitätsversorgung und Elektrizitätswirtschaft: Zur Entstehung eines neuen Fachgebietes der Technikwissenschaften zwischen 1880 und 1945*. Stuttgart 1994.

7 Bernhard Stier, *Staat und Strom: die politische Steuerung des Elektrizitätssystems in Deutschland 1890 – 1950*. Ubstadt-Weiher 1999.

8 Gugerli, David, *Redeströme: Zur Elektrifizierung der Schweiz 1880–1914*. Zürich 1996.



book “Seeing like a state”, but was largely driven by interests of foreign industry, development aid organizations and international funding agencies such as the World Bank.<sup>9</sup> It will finally be shown that this legacy of a centralized electricity infrastructure, which almost exclusively relied on hydropower until 2002, left the Tanzanian energy sector badly positioned to deal with the challenges of the late 20<sup>th</sup> and early 21<sup>st</sup> century: The need for flexibility, adaptability to changing demand and the urgent need to attract private capital for modernization and expansion.

The paper is based on preliminary results of an ongoing research project on the history of electrification in Tanzania. The project makes use of written sources from the British mandated Tanganyika Territory and post-independence Tanzania, planning documents and reports from the state utility, international consultants and organizations associated with early development funding and assistance as well as contemporary academic literature. Archival work will be supplemented by expert interviews and has been carried out in the national archives of Tanzania and the UK, and at the Tanzanian national electricity utility Tanesco. At the methodological level the project seeks to explore ways of writing a history of electrification in Sub-Saharan Africa, given that written sources are scarce and dispersed amongst the archives of a multitude of national and international actors– a research challenge that Tanzania generally shares with many other former colonies in Africa.

From the turn of the 20<sup>th</sup> century, when a private German company installed the first wood-fired steam turbines for power generation Dar es Salaam until the early 1930ies, electricity in Tanganyika was supplied by a few isolated small-scale generators and hydro-power plants.<sup>10</sup> In Dar es Salaam and a few cities along the railroads they supplied power to the colonial administration, European and some Asian city-dwellers, providing them with the amenities of domestic and street lighting. Africans were not considered eligible as customers nor thought to be able to pay for electricity. Nevertheless, the British administration was aware of the potential of electric power to increase productivity and profitability of the colonial extractive industries. A report from 1928 described electricity as the most effective form of power for machinery at the plantations for sisal, the colony’s major export commodity.<sup>11</sup> Consequently, Tanzania’s first medium-sized hydroelectric plant, which started operation in 1936 at Pangani Falls, supplied the local sisal industry through a 400 km transmission system. Still, in 1955 the country’s total installed capacity was at 29 MW only.<sup>12</sup>

In the first two decades of British colonial administration, the economic policy of Tanganyika was mainly focused on extractive industries. This changed after World War II, when colonial administrations shifted to a concept of integrated social-economic development. The 1946 Colonial Development and Welfare Act emphasized “native development” and “social welfare” as a part of broader economic considerations. This program was accompanied by the rise of the interventionist development state and a “particularly sweeping vision of how the benefits of technical and scientific progress might be applied-usually through the state in every field of human activity”, which James Scott has called “high modernism”. It implies the administrative ordering of nature and society to make them “legible” to central authorities, manipulating complex circumstances into simplified and aggregated data. When this ideology results into attempts authoritarian states to engineer their social environments it can become lethal – especially when a “prostrate civil society” lacks the ability to resist the governments plans.<sup>13</sup>

Under the British mandate, Tanganyika proved to be one of the most fertile grounds for the high modernist ideology. During World War II the British Colonial Regime began planning large-scale agricultural development projects and mobilizing the necessary labour. The most ambitious was the gigantic groundnut scheme, which failed due to its narrow agronomic and abstract design, and the planners “blind faith in machinery and large-scale operation”.<sup>14</sup> After independence Julius Nyerere adopted the colonialist view that successful economic development requires a strong state. Consequently, Tanzania’s natural, industrial, and communications resources were nationalized in the Arusha Declaration in 1967. Tanzanias “ujamaa” villagization program in the early 1970s sets a classical and well-documented example of state-initiated social engineering. In the course of the campaign more than 5 million Tanzanians were resettled in villages where the layouts, housing designs, and local economies were planned, partly or wholly, by officials of the central government. Nyerere’s argument for the ujamaa villages was the following:

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9 James C. Scott, *Seeing like a State – How Certain Schemes to Improve the Human Conditions Have Failed*. New Haven/London 1998.

10 H. A. Byatt, From H. A. Byatt, Administrator, Dar-Es-Salaam to Principal Secretary of State for the Colonies, London, 9th June 1920, Tanganyika Territory No. 224. Public Record Office, Kew. PRO T 161-1049. Tanzania was a German colony before World War I.

11 SPARKS&PARTNERS, Report by Messrs. SPARKS&PARTNERS 1928, Colonial Office, Kew. CO 691-98-3.

12 John Frederick Rowland Hill, *Tanganyika: A Review of Its Resources and Their Development*. Dar es Salaam 1955.

13 Scott, *Seeing like a State*.

14 Scott, *Seeing like a State*, 229.

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*“And if you ask me why the government wants us to live in villages, the answer is just as simple: unless we do we shall not be able to provide ourselves with the things we need to develop our land and to raise our standard of living. We shall not be able to use tractors; (...) it will be quite impossible to start small village industries, and instead we shall have to go on depending on the towns for all our requirements; and if we had a plentiful supply of electric power we should never be able to connect it up to each isolated homestead.”<sup>15</sup>*

The pursuit of electricity as a modernizing and developmental force for state-led development coincided with the global rise of an ideology of multipurpose river basin planning.<sup>16</sup> This was the idea of managing an entire river for human benefit, for hydroelectric power production, navigation, irrigation and flood control. The success of the TVA, “the granddaddy of all regional development projects”<sup>17</sup>, following its formation in 1933, inspired visions of river basin planning as a global tool for development in the 1950s.<sup>18</sup> In addition, technological advances in long-distance transmission made centralized generation more economically viable and opened up prospects for mineral exploitation using cheap electricity from hydropower. Colonial governments all over the African continent commissioned hydropower surveys and started large dam projects, which were readily continued by the new states after independence. The exported model of river basin planning, however, was more focused on industrial and agricultural growth rather than on regional needs for social development. Rural Electrification, job creation and the provision of infrastructure services was given low priority.<sup>19</sup>

Despite its African socialists’ rhetoric of local small-scale development, the model of river basin development was as attractive to Tanzania’s post-independence government and to international funders. Encouraged by the World Bank the Swedish Institute for Development Assistance (SIDA) began working on the Great Ruaha river basin during the 1960s. Kidatu, where constructions began in 1969 and were completed in 1980, became the first large-scale hydropower project in Tanzania, paving the way for the beginning of the big dam era. The debates associated with the project firstly exemplify the rationale underlying the planning and construction of big dams for hydropower generation and in turn the emergence of centralized power infrastructures in many African countries, which could be rightfully called “high modernist”.<sup>20</sup> Secondly, they show that it was less the authoritarian state, as suggested by Scott, but international development organizations that advocated and enforced the mega-engineering of natural environments for the single purpose of hydropower generation for industry and urban areas and to the detriment of rural development. This was partly made possible by the change of power relations between local actors and different international actors in the context of the postwar shift from bilateral colonial relationships to the multilateralism of development assistance. On a formal level, sovereignty turned these relations into one among equals; but, as Cooper has lately suggested, “independence turned entitlement into supplication”.<sup>21</sup> This became apparent when interests conflicted in regard to the purpose of large dams. The Tanzanian government, the water authority and President Nyerere were in favour of a multipurpose project. Drawing on the British colonial plans for agricultural development, they had made irrigation an important part of the five-year plan of 1964. In contrast, the World Bank changed from supporting large-scale irrigation to supporting large-scale power production during the 1960s. Comparative studies, giving no space to irrigation benefits provided the necessary arguments for Tanzania’s government to change its opinion. Consequently, plans for a multipurpose project at Wami River were given up in favour of the single-purpose Great Ruaha Project.

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15 Julius K. Nyerere, “President’s Inaugural Address” (December 10, 1962), quoted from Scott 1998, 230

16 Patrick McCully, *Silenced Rivers: The Ecology and Politics of Large Dams*. London 1996.

17 Scott, *Seeing like a State*, 6.

18 In 1956, the UN Secretary General declared that “River basin development is now recognized as an essential feature of economic development (UN EcoSoc Council Office Record 21st Session, 1956, quoted in: Heather J. Hoag, *Transplanting the TVA? International Contributions to Postwar River Development in Tanzania*, in: *Comparative Technology Transfer and Society* 4, 3, (2006), 247–267, 253.

19 The Volta River Project in Ghana for example, one of the first and most prominent examples for river basin planning in Africa, was mainly built to produce power for processing Ghana’s bauxite deposits into aluminum. Its centerpiece, the 80-meter Akosombo Dam was heralded as “a solid symbol in the dream of prosperity” upon commissioning in 1966 (Nkrumah switches on Volta River power” (1966, January 24). *The Nationalist*; quoted from Hoag, *Transplanting the TVA*, 249).

20 The debates have been well documented in: May-Britt Öhman, *Taming Exotic Beauties: Swedish Hydropower Constructions in Tanzania in the Era of Development Assistance, 1960s – 1990s*. Unpubl. Diss, Royal Institute of Technology, Stockholm, Sweden 2007.

21 Frederick Cooper, *Writing the History of Development*, in: Corinna R. Unger, Stephan Malinowski and Andreas Eckert (eds.), *Modernizing Missions: Approaches to ‘Developing’ the Non-Western World after 1945* special issue, *Journal of Modern European History*, 8, 1 (2010), 5–23.

Hydroelectricity generation perfectly lent itself to the high modernist goal of making development “legible”, giving it the decisive advantage over other development goals like irrigation. For Great Ruaha, one contemporary consultant pointedly stated that only power generation could provide the fixed values that the World Bank needed for their calculations:

*“Money should be made to talk: each one of the parties should be made to weigh the money value of their wishes against the costs to be covered. – In this respect power seems to be superior. Opinions are divided as to the relative benefits in the future, but one thing is absolutely certain: plans for power are much more definite and much more accessible to assessments of costs and benefits, in a word much more tangible, than plans for flood control and irrigation; however important the latter may be in the future, they are at present, to say the least of it, slightly vague. The important thing is that money should be permitted to talk and to dictate decisions, and so it does: it talks to Tanesco the way it always talks to power enterprises.”<sup>22</sup>*

The Kidatu and Mtera plants in the Great Ruaha river basin were the largest of about half a dozen hydropower projects which substantially transformed the Tanzanian electricity infrastructure. At the time of independence it consisted of a few isolated grids in larger cities and a low-voltage grid supplying hydropower from Pangani Falls to the sisal plantations in the north. In 1990 high voltage transmission lines connected the key hydropower sites at Pangani and Greater Ruaha rivers with the coastal grid system around Dar es Salaam and most of the bigger cities in the northern part of the country.<sup>23</sup> Hydropower development dramatically increased the country’s total installed capacity, which had been below 50 MW in 1960 – a low figure even for a developing country.<sup>24</sup> Between 1960 and 1990, 380 MW of hydropower were added to the grid, about 200 MW of which from Great Ruaha, and by 1990 hydropower contributed 95% of the country’s total electricity generation.<sup>25</sup>

The effects of this increase of this transition of the generation and transmission system on service provision show an ambivalent picture. On the one hand, it allowed for an increase of the number of connections from 11,000 in 1950 to 156,000 in 1990, further rising to about half a million in 2000.<sup>26</sup> It is one of the major accomplishments of state-led development, to deepen access to electricity in the urban areas beyond colonial service provision. Being a privilege a nearly exclusive privilege for the European and Asian population in colonial times, it became available to a base of urban African electricity users. By 2000, coverage had expanded to 59% of Dar es Salaam residents and around 30% in other urban areas. On the other hand, benefits of electricity access remained comparatively low on national scale and were unevenly distributed between urban and rural areas.<sup>27</sup> In 2000 still only 10% of households in Tanzania had access to grid electricity and a mere 1% of households in rural areas.<sup>28</sup> In regard to electricity provision, African socialists’ promise of rural development was not fulfilled. At Kidatu, for example, electricity leaves the hydropower site on 220 kV high-voltage transmission line, passing numerous unelectrified villages and going directly 300 km to Dar es Salaam and the Ubungu control center for further distribution into the national grid. This picture seems to illustrate, what Showers has conceptualized as an “urban exploitation of distant (invisible) ecosystems that accompanied expanded transmission capabilities”, connecting “widely separated islands of Neo-European technological modernity over the heads of excluded African majorities”.<sup>29</sup>

Its patterns of physical infrastructure was not the only feature of centralized power model, which made an extension of service provision to rural areas a particularly challenging undertaking, but also the associated monopolistic structures, tariff systems and planning processes. During colonial times, tariffs were sectorally and regionally highly differentiated and reflected local loads and generation costs. Two years after its nationalization in 1964, Tanesco

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22 World Bank consultant John Fletcher, quoted from Öhman, *Taming Exotic Beauties*, 186. As a closer look on the appraisal furthermore shows that it was the only World Bank’s methods of economic calculation, the “discounted cash flow” method and credits at a low rate of interest through which SIDA and the World Bank which made the Great Ruaha power project a better alternative from a cost aspect compared to a diesel plant (Öhman, *Taming Exotic Beauties*)

23 Still, some cities especially in the western and southern parts of the country are not connected to the national grid and are supplied by isolated grids.

24 Hans Amann, *Energy Supply and Economic Development in East Africa*, London 1969.

25 Ghanadan, *Public Service or Commodity Goods*, 59.

26 Ghanadan, *Public Service or Commodity Goods*.

27 Björn Kjellström, Maneno Katyega, Henry Kadete, Dolf Noppen, Abu Mvungi, *Rural electrification in Tanzania. Past experiences – New Approaches*. Stockholm 1992.

28 Ghanadan 2008.

29 Showers, *Electrifying Africa*, 215, 207.

adopted a model of four standardized national tariffs. It was praised by contemporary experts for its simplicity, equal treatment of sectors and regions and increase of revenues but rendered isolated systems and rural electrification projects highly uneconomic. Except for a few projects, which were highly subsidized by the government, “RE (rural electrification - author’s note), remaine[d] in a very early stage of development which must be characterized as being just a wish or hope, formulated as a consequence of a rural-production-oriented development policy of “self-reliance”.<sup>30</sup> In reality, electricity policy and -planning was largely centrally administered, expert driven and emphasized macro-level objectives. The Power System Master Plan focused on generation and transmission up to the level of substations and was more or less detached from local distribution planning, which was done on branch level.<sup>31</sup>

Besides the structural imbalance, giving advantage to urban areas, the transition to a centralized power infrastructure also lead to some inherent problems related to its high dependence on large hydropower plants. These problems became apparent when in 1992 a combination of factors, including of shortcomings of the Great Ruaha projects’ design, mismanagement and a natural drought led to a dramatically decrease in generation which affected the whole centralized national grid. For two years electricity had to be rationed in Dar es Salaam. With the first free elections shortly ahead in 1993, this supply crisis put the ruling *Party of the Revolution* under enormous pressure to act. In the hectic attempt to expand power supply, the monopoly of Tanesco in electricity generation was lifted to invite private investors to build new power plants. Two Independent Power Producers were hastily contracted and started to build a new “emergency” power plant each, one was run with diesel, the other with gas. When the diesel plant was finally connected to the grid in 2002, it was among the most expensive projects of its kind on the continent.<sup>32</sup> It is not without a certain irony that the construction of a large hydropower plant which was not least motivated by the prospect of getting independent from diesel imports, finally lead to a chronic contractual dependency on an expensive diesel-powered plant. Whenever water levels are low at Mtera, Tanesco enters into a “financial limbo”, buying electricity at rates between 34-50 US cents from the independent power producers and selling it at around 12 US cents.<sup>33</sup> It has only been recently that efforts to escape this dead end – through tariff increases, a number of new generation and transmission projects which are financed either by the state or by public-private-partnerships, and a progressive regulatory framework for Small Power Producers – have delivered first successes.

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30 Amann, *Energy Supply and Economic Development*, 126, 164.

31 It is only at present, that efforts are being made to merge both plans, as the former director of Tanesco’s research department stated in an interview.

32 Rebecca Ghanadan, *Connected geographies and struggles over access: Electricity commercialisation in Tanzania*, in: David A. McDonald (eds.), *Electric Capitalism: Recolonising Africa on the Power Grid*. Kapstadt 2009, 400-436; Michael Degani, *Emergency Power: Time, Ethics, and Electricity in Postsocialist Tanzania*, in: Sarah Strauss/ Stephanie Rupp/ Thomas Love (eds.), *Cultures of Energy*. Walnut Creek (2013), 177-193; Martin Walsh, *The not-so-Great Ruaha and hidden histories of an environmental panic in Tanzania*, in: *Journal of Eastern African Studies* 6, 2 (2012), 303-335.

33 Quoted from a keynote of the Tanzanian Minister of Energy and Mines 2014 at the Powering Africa, Tanzania conference from in January 2014 in Dar es Salaam.

# **Off-Grid Electrification and its Impacts on the Waste Management System – the Case of Bangladesh**

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## **ABSTRACT**

By the end of 2010 more than 1.6 billion people lacked access to modern energy services. To overcome this situation the United Nations started the “sustainable energy for all initiative” with the objective to provide access to modern energy services for all until 2030. Especially for off-grid areas in the least developed countries decentralized systems based on renewable energies and in particular solar energy are seen as the most promising solution for electrification. Lack of access to modern energy services goes in general along with a lack of a proper waste management system for the expected future waste electrical and electronic equipment (WEEE). The main lessons learned from a waste management perspective, is that prequalification of the suppliers can change industry standards. Local battery producers and recyclers and a working collection system are needed to guarantee that lead acid batteries are recycled properly.

**Keywords:** Rural Electrification, Waste Management, Solar Home System, Battery Recycling, Microenergy System, Bangladesh, Least Developed Countries

## **INTRODUCTION**

By the end of 2010 more than 1.6 billion people lacked access to modern energy services. To overcome this situation the United Nations started the “sustainable energy for all initiative” with the objective to provide access to modern energy services for all until 2030. Especially for off-grid areas in the least developed countries decentralized systems based on renewable energies and in particular solar energy are seen as the most promising solution to electrify regions<sup>1</sup>. Lack of access to modern energy services goes in general along with a lack of proper waste management systems for the expected future waste electrical and electronic equipment (WEEE). The “Rural Electrification and Renewable Energy Development Project (REREDP)” in Bangladesh is one of the most successful rural electrification programs in world. The REREDP can and will draw important lessons for upcoming off-grid electrification projects in other regions of the world.

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<sup>1</sup> IRENA (2014). International Renewable Energy Agency. RETHinking Energy 2014 – Towards a new power system. <http://www.irena.org/rethinking/> [Last accessed 10th of September 2014]

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## REGIONAL BACKGROUND AND THE CASE OF THE RENEWABLE ENERGY DEVELOPMENT PROJECT

The REREDP I of Bangladesh started back in 2002. The second round of the REREDP was launched in 2012. In 2002 microfinance organizations had already spread throughout Bangladesh and Solar Home Systems (SHS) for the electrification of rural households were distributed in combination with microfinance. The SHS are sold to the end users by so called Partner Organizations (PO), which provide microcredits as well as the maintenance of the SHS. The POs receive financial support from the Infrastructure and Development Company Limited (IDCOL) while IDCOL receives financial support for the REREDP from the Worldbank, KfW and the Asian Development Bank among others<sup>2</sup>.

The standard configuration nowadays for a SHS in rural areas is a 35W<sub>p</sub> solar panel, a charge controller and a lead-acid battery with a capacity of 50Ah. A SHS supplies enough energy to the household to use a television, six LED-lights, a fan and mobile phone charging. The yearly installation rate of Solar Home Systems under the REREDP was at the beginning comparatively low. In 2008 the program started to grow rapidly with a total yearly installation of about 100.000. Within four years the yearly installations grew to 600.000 SHS in 2012<sup>3</sup>. In total more than 2.7 Million SHS were installed under the REREDP by the end of 2013 and SHS are close to become economical viable without subsidies. With an average household size of 5 persons almost 14 million Bangladeshi already directly benefit from the REREDP electrifying about 10% of the total population. To fulfill the goal of 6 Million SHS by the end of 2016 yearly installation rates have to exceed one million SHS. In Addition to the SHS goals until 2016 a total number of 50 solar minigrids and 1550 solar irrigation pumps will be installed according to IDCOL<sup>4</sup>.

According to the Blacksmith Institute which published in cooperation with the Green Cross a report, lead pollution is among the six worst pollution a problems of the world<sup>5</sup>. In low- and middle-income countries car battery recycling is one of the main sources of lead pollution<sup>6</sup>. About three quarter of all lead is used for batteries<sup>7</sup>. In Bangladesh Solar-Batteries already have a market share of about 25% (Total market size around 2.5 million lead-acid batteries) and the share is rapidly growing. Photovoltaic energy systems are already identified to contribute significantly to lead pollution in China and India among other countries<sup>8</sup>. Depending on the recycling facilities and technologies the lead losses over the life time vary between 5% in countries with advanced infrastructure and 50% only in the recycling phase in the informal sector<sup>9</sup>.

Based on historical installation rates of SHS between 800.000 and 1.2 million lead-acid solar batteries equaling an total amount of approximately 6.000 to 8.000 metric tons of lead will enter the waste management system of Bangladesh in 2016<sup>10</sup>. A research conducted by Waste Concern in 2006 showed that the recycling capacity for lead of the formal sector was only 3.000 metric tons per year<sup>11</sup> and reached nowadays almost 15.000 metric tons per year<sup>12</sup>. Therefore the impact of the REREDP on the battery industry and especially on the waste management system can already be observed. According to that, the question has to be raised how future infrastructure programs for rural electrification in developing countries can address environmental impacts due to improper recycling and recycling facilities in advance and how it should be integrated into the project design. Since Bangladesh has a very successful

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2 Sadeque, Z., Rysankova, D., Elahi, R., Soni, R., 2014. Scaling Up Access to Electricity: The Case of Bangladesh, Live Wire: A knowledge note series for the energy practice. World Bank Group.

3 World Bank (2013a). Implementation Completion and Results Report. Rural Electrification and Renewable Energy Development Project. The World Bank. <http://www-wds.worldbank.org/>. [Last accessed 20th of January 2014].

4 IDCOL (2014a). Renewable Energy Projects. <http://idcol.org/energyProject.php>. [Last accessed 20th of January 2014].

5 Blacksmith Institute (2010). World's Worst Pollution Problems Report 2010. Blacksmith Institute, [www.worstpolluted.org/files/FileUpload/files/2010/WWPP-2010-Report-Web.pdf](http://www.worstpolluted.org/files/FileUpload/files/2010/WWPP-2010-Report-Web.pdf). [Last accessed 08th of January 2014].

6 Blacksmith Institute (2010), World's Worst Pollution Problems.

7 Roberts, H. (2003). Changing Patterns in Global Lead Supply and Demand. *Journal of Power Sources* 116 (1–2): 23–31. doi:10.1016/S0378-7753(02)00701-2.

8 Gottesfeld, P. and Cherry, C. (2011). Lead Emissions from Solar Photovoltaic Energy Systems in China and India. *Energy Policy* 39 (9): 4939–46. doi:10.1016/j.enpol.2011.06.021.

9 Hoffmann, U. and B Wilson. (2000). Requirements For, and Benefits Of, Environmentally Sound and Economically Viable Management of Battery Recycling in the Philippines in the Wake of Basel Convention Trade Restrictions. *Journal of Power Sources* 88 (1): 115–23. doi:10.1016/S0378-7753(99)00519-4.

10 Batteiger, A. (2014). Towards a waste management System, Innovating Energy Access for Remote Areas: Discovering untapped resources, University of California: Symposium 10.-12.04.2014 (forthcoming).

11 Waste Concern (2006). Lead Acid Battery Recycling in Bangladesh. <http://www.wasteconcern.org/Publication/BatteryRecyclingBroFinal.pdf>. [Last accessed 14th of January 2014].

12 IDCOL (2014b). ISO 14001:2004 and OHSAS 18001:2007 Compliance Status Report of Battery Suppliers and Recyclers of IDCOL SHS Program, <http://www.idcol.org/download/5d86a0e52ea14328b0e421c1c9504594.pdf> [Last accessed 18th of June 2014]



rural electrification program, the case and lessons learned out of a waste management perspective of Bangladesh are presented. The main objective of this research is how energy access for all can go along with a proper treatment of the resulting WEEE, especially for lead-acid batteries and how the REREDP influenced the battery industry in Bangladesh.

## METHODOLOGY

An intensive literature review on recycling of SHS, lead-acid batteries and the recycling sector in developing countries and with a special focus on Bangladesh and the REREDP I and II was conducted. Out of the literature review a waste estimation model was developed and described<sup>13</sup>. In a field research in Bangladesh semi-structured interviews with representatives of the four biggest lead-acid battery producers and recyclers representing over 80% of the market and 100% of the exports were conducted. Two lead-acid battery factories with recycling facilities of the formal sector as well as two facilities of the informal sector were visited.

## RESULTS

In the beginning of the first round of the REREDP in 2002 no environmental impacts other than CO<sub>2</sub>-Mitigation were assessed by the involved institutions<sup>14</sup>. The REREDP was in 2002 planned to be a 50 Million USD project. Due to its success, international support for the program soon began to rise and environmental impacts became visible. In 2005 IDCOL developed a policy guideline on the disposal of warranty expired batteries. Costumers should be notified three months before the warranty of five years expires to change their batteries<sup>15</sup>. In 2006 the Department of Environment of Bangladesh added an amendment to the Environmental Protection Act of 1995, which regulated the battery recycling and collection<sup>16</sup>. In 2006 the recycling of solar batteries had no basically no impact on the regulation. Nevertheless, in the national 3R Strategy (Reduce, Reuse, Recycle) in 2010 it was stated that the Solar Home System Program has a growing impact on the recycling of lead-acid batteries<sup>17</sup>. In the final report of the World Bank of the first round of the REREDP it was stated that the project helped to increase standards in battery recycling. In 2012 the second round of the project was launched, since than regular assessments of environmental impacts have to be reported<sup>18</sup>. In the first environmental and social impact report of IDCOL, two major environmental impacts related to the SHS-Project were reported: Improper disposal of lead-acid batteries (LABs) and solar panels<sup>19</sup>. By the end of 2013 all battery producers of Bangladesh were ISO 14001 (Environmental Management Standard) and OHSAS 18001:2007 (Occupational Health Safety Standard) certified<sup>20</sup>. IDCOL has forced its suppliers to establish standards due to the pressure of the developing organizations.

The results of the interviews with the four biggest battery producers of Bangladesh show, that they follow the ISO standard because of the REREDP. All the battery producers expect future sales of solar batteries in Bangladesh to grow and hope to export more. The biggest of the four producers already started to export solar batteries to more than 50 countries in the world. The strategy of the lead recycling and lead usage differs between the battery producers. There is one producer using 100% recycled local lead out of the company owned recycling facility, while two producers answered that they do not use recycled lead. The fourth answered, that they use a bit less than 20% of recycled lead, but the prize of the scrap-lead in the market is too high to recycle with proper and environmental sound technology. According to the two visited battery recyclers of the informal sector the market is still growing. Even though that due to the regulations by IDCOL none of the solar-batteries should be recycled in the informal

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13 Batteiger (2014), Towards a Waste Management System for SHS in Bangladesh.

14 World Bank (2013a), Implementation Completion and Results Report.

15,19 IDCOL (2013). Environmental and social management framework. Infrastructure Development Company Limited, Dhaka. <http://www.idcol.org/Download/Harmonised%20ESMF%202013.pdf>. [Last accessed 14th of January 2014].

16,17 DOE (2010). National 3R Strategy for Waste Management. Department of Environment. Ministry of Environment and Forests. Government of the People's Republic of Bangladesh. Dhaka.

18 WB (2013b). Project Appraisal Document: Rural Electrification and Renewable Energy Development II (REREDII) Project. World Bank. <http://www-wds.worldbank.org/>. [Last accessed 18th of January 2014].

20 IDCOL 2014b, ISO 14001:2004 and OHSAS 18001:2007.

sector<sup>21</sup>. Especially in rural areas lead-acid batteries are mostly recycled in the informal sector. The reason for that seems to be, that costumers trust the local recyclers more than the collection framework of the Partner Organizations (PO) and after the warranty time of 5 years the POs lose their interest in maintaining the contact with the costumers<sup>22</sup>.

All the battery producers stated that the collection system of used lead-acid batteries needs to be improved, since not enough used lead-acid batteries enter the system. In the “Environmental and Social Management Framework” of IDCOL it is stated that none of the battery recyclers is collecting the batteries with the acids. This mainly happens because of cost savings due to lower weight of the batteries. According to the report “the electrolyte is poured here and there”<sup>23</sup>. The visited battery recycling plants of the battery producers had a high standard. In both factories air treatment and waste water treatment facilities were in use. The complete recycling process was done indoors and nearly all of the workers were wearing breathing protection.

## DISCUSSION

The case of SHS program under the REREDP shows how rural electrification influence supplying industries. As all international organizations started to ask for environmental impact reports, IDCOL was forced to change the prequalification of the battery suppliers<sup>24</sup>. Solar batteries have a market share of only 25% in the Bangladeshi battery market, but changed the complete industry due to the implementation of international standards. Therefore one of the lessons learned is, that prequalification in rural electrification projects can force an industry to change towards more ecological sound producing and recycling. Another important factor of the battery recycling is the existence of local battery factories and therefore formal local lead recyclers, since this is the only way to guaranty that high quantities of the used lead-acid batteries enter the formal recycling sector. For minimizing the environmental impacts of rural electrification programs based on solar energies it is key to think about working waste collection systems, since lead losses in the informal sector can be as high as 50% only in the recycling phase. Especially for the collection of the uses lead-acid batteries with the acids or a local acid treatment of the acid, new concepts need to be developed.

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21,24 IDCOL (2014a), Renewable Energy Projects.

22 Brossmann, M. (2013). Off-Grid Rural Electrification and Fighting Poverty. Master Thesis, University of Tübingen.

23 IDCOL (2013), Environmental and Social Management Framework.



# **A System Complexity Approach to Swarm Electrification**

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## **ABSTRACT**

The study investigates a bottom-up concept for microgrids. Financial analysis is performed through a business model approach to test for viability when replacing a researched energy expenditure baseline in Bangladesh. A literature review compares the approach to current trends in microgrids. A case study of Bangladesh illustrates the potential for building on the existing infrastructure base of solar home systems. Opportunities are identified to improve access to reliable energy through a microgrid approach that aims at community-driven economic and infrastructure development by building on network effects generated through the inclusion of localized economies with strong producer-consumer linkages embedded within larger systems of trade and exchange. The analysed approach involves the linking together of individual stand-alone energy systems to form a microgrid that can eventually interconnect with present legacy infrastructure consisting of national or regional grids. The approach is likened to the concept of swarm intelligence, where each individual node brings independent input to create a conglomerate of value greater than the sum of its parts.

**Keywords:** Electricity Access, Bottom-up Microgrid, Microfinance, Bangladesh, Developing Country

## **INTRODUCTION**

Across the Global South, infrastructure development, such as on the national electricity grid, scores high on the agenda in terms of national income invested.<sup>1</sup> At the same time, the UN Sustainable Energy for All (SE4A) target of universal energy access by 2030 is looming large<sup>2</sup>, pointing to a greater part to decentralized options.<sup>3</sup> This leaves the question at hand what kind of infrastructure systems ought to be developed given past, present and future investments in micro and larger scale legacy infrastructure, ranging from small stand-alone solar home systems (SHS) to the national grid in order to reach the set target. Because without “the ability to avail energy that is adequate, available when needed, reliable, of good quality, affordable, legal, convenient, healthy & safe, for all required energy services across household, productive and community uses”<sup>4</sup> the affected people’s economic development is inhibited -or at least- delayed. The exact<sup>5</sup> number of people lacking of these electricity services

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1 Dobbs R, Pohl H, Lin D et al. (2013) Infrastructure productivity: How to save \$1trillion a year. McKinsey Global Institute.

2 Ki-moon B (2011) Sustainable Energy for All: A Vision Statement. United Nations Organization. New York.

3 OECD/ IEA (2011) Technology Roadmap Smart Grids. Paris: OECD/IEA.

4 Bhatia M and Angelou N (2014) Capturing the Multi-Dimensionality of Energy Access. LiveWire. The World Bank. Washington.

5 Groh S (2014) The role of energy in development processes - The Energy Poverty Penalty: Case study of Arequipa (Peru). Energy for Sustainable Development. 18. pp. 83–99.

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so far remains unknown. What is known, however, is that despite increasing rhetoric on the need to change the situation of 1.3 billion lacking access to the national grid,<sup>6</sup> and another billion people with a severely intermittent supply number of electricity connection,<sup>7</sup> are outstripped by population growth in large parts of the Global South.<sup>8</sup> Discussions on this are usually centered around two key players of development: the government and the private sector. This approach fails, however, to take into account “the crucial third agent, in whose name development is carried out: people organized as communities and collectives, people seen not as ‘beneficiaries’ of the state or ‘consumers’ of private services but as drivers of their own destiny, empowered to self-provision basic needs and to govern from below”.<sup>9</sup> Putting it into the language of complex systems, it is the “prosumer” who is the critical agent in the system, performing critical actions.<sup>10</sup> A prosumer in an energy system is “an economically motivated entity that: 1. Consumes, produces, and stores electricity, 2. Operates or owns a power grid small or large, and hence transports electricity, and 3. Optimizes the economic decisions regarding its energy utilization.”<sup>11</sup> The complexity lies here in both the physical/technical and the social/economic dimension.<sup>12</sup> Weijnen et al., therefore, speak of infra-systems or infrastructural systems instead of infrastructures. They further argue that it is the socio-technical connection that crucially affects how the system performs. It is, therefore, precisely not dependent on initial system design or engineering from central entities who, once failing, can limit system performance, (e.g. mis-management or bad design affects livelihood aspects of households and businesses). User centered- models usually draw on the particularities of the complexity of energy systems rather than trying to avoid them, e.g. through using patterns of self-organization and emergence to grow the system by allowing for new business opportunities with a widening space of possibilities (e.g. prosumers). Only recently, the discussions on rural electrification have changed their dichotomous approach characterized by either centralized (e.g. national grid extension) or decentralized solutions (e.g. stand-alone SHS or isolated microgrids) towards the question of having access or the level of access.<sup>13</sup> This may be due to historic developments in the developed economies which made way for mental lock-ins. As a result, the economic calculus is based on the (non-) viability of grid extension, which is measured by the distance-based cost of extension. Villages too remote and with too low a load factor demand need to be electrified with a “second class” solution through a decentralized approach.<sup>14</sup> This paper joins the effort to distance itself from a binary category of energy access towards a multi-tier framework in order to be able to measure a continuum of improvement.<sup>15</sup> The service quality of electricity supply through the main grid varies substantially (e.g. in terms of black- & brown-outs, voltage fluctuation, among others) in different countries, regions of a country and even parts of the same city. The quality of decentralized energy systems varies even more in terms of possible loads to connect, time and duration of usage. Thus, a mere measurement in overall supply (Wh) per household counteracts a strive for more energy efficient appliances that run with those systems, thus neglecting the importance of the load attached (W). These multiple access solutions, partly designed as transitional solutions or even running in parallel, need to be assessed reflecting these differences in service supply. Therefore, reference is taken here to the multi-tier approach to measuring energy access, distinguishing five tiers based on six attributes of electricity supply. Nonetheless, the technology options presently discussed under the tier framework are all “engineered” in a certain size, with certain assumptions, for certain purposes. Space to act for the end-user remains very limited. The future notion should thus

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6 IEA (2012) World Energy Outlook 2012. Paris: OECD/IEA.

7 AGECC (2010) Energy for a Sustainable Future. Secretary-General's Advisory Group on Energy and Climate. Summary Report and Recommendations. New York.

8 Pachauri S, Ruijven BJ, Nagai Y, Riahi K, van Vuuren BJ, Brew-Hammond A and Nakicenovic N (2013) Pathways to achieve universal household access to modern energy by 2030. *Environ. Res. Lett.* 8. pp. 7ff.

9 Kothari A and Shrivastava A (2013) Economists on the Wrong Foot. *Economic and Political Weekly*. Vol. - XLVIII No. 33, August 17, 2013.

10 Ritzer G, Dean P, Jurgenson N (2012) The Coming of Age of the Prosumer. *American Behavioral Scientist*. 56(4). pp.379-398.

11 Grijalva S and Tariq MU (2011) Prosumer-Based Smart Grid Architecture Enables a Flat, Sustainable Electricity Industry. *IEEE*.

12 Weijnen MPC, Herder PM and Bouwmans I (2008) Designing complex systems: A contradiction in terms. In Eekhout, M., R. Visser and T. Tomiyama, Delft Science in Design. A Congress on Interdisciplinary Design. Vol. 3. pp. 235-254.

13 Tenenbaum B, Greacen C, Siyambalapitiya T et al. (2014) From the Bottom Up - How Small Power Producers and Microgrids Can Deliver Electrification and Renewable Energy in Africa. The World Bank. Washington.

14 Mandelli S and Mereu R (2013) Distributed Generation for Access to Electricity: “Off-Main-Grid” Systems from Home-Based to Microgrid. Book section. In: Renewable Energy for Unleashing Sustainable Development. Springer Press. pp. 75-97.

15 Energy Sector Management Assistance Program (2014) A New Multi-tier Approach to Measuring Energy Access. Available under [http://www.esmap.org/sites/esmap.org/files/DocumentLibrary/Multi-tier%20BBL\\_Feb19\\_Final\\_no%20annex.pdf](http://www.esmap.org/sites/esmap.org/files/DocumentLibrary/Multi-tier%20BBL_Feb19_Final_no%20annex.pdf). Last accessed: August 21, 2014.

not be centralized versus decentralized (nor access versus no-access) systems designed to cope with complexity but on robust, adaptable, fast changing (self-organizing) infra-systems that use complexity for their advantage. The latter are characterized by the co-evolution of supply capacity and respective (economically feasible) demand that fits the overall system size. These systems achieve their robustness through usage of information and communication technology (ICT) -convergence- in order to communicate power, information and monetary flows that keep the physical system stable (e.g. by intervening when the system moves far from equilibrium (demand >> supply or demand << supply), constraining actions such as using devices with too high demand) while signaling actors when new spaces of opportunities open up (e.g. by integrating new storage or generation capacity that creates income for the actors; or use cheap and abundant electricity for productive purposes, respectively).<sup>16</sup>

The authors assume that in certain scenarios a paradigm shift away from exogenously engineered approach to user-centric emergence schemes may lead to a better system performance. Furthermore, the authors hypothesize that such a paradigm shift could improve on existing decentralized methods for rural energy, including stand-alone one-off SHS and baseline energy fuels such as kerosene. This research seeks to further look into this hypothesis through the analysis of a newly developed bottom-up concept, referred to as swarm electrification (SE), a sharing-based energy infra-system, based on decentralization and resource efficiency.<sup>17</sup> SE is based on nodes in a swarm intelligence network where information and electricity flows are shared among neighbors “to achieve a compounding network effect, in that they are linked together to form a microgrid – to achieve a networked grid effect.”<sup>18</sup> The concept follows the principle of a bottom-up initiative, often referred to grassroots innovations, in the sense of that it is a decentralized track which is generally carried out through non-governmental entities such as cooperatives, community user groups, or private entrepreneurs and households. Smith et al describe grassroots innovations as “movements seek innovation processes that are socially inclusive towards local communities in terms of the knowledge, processes and outcomes involved.”<sup>19</sup> The SE concept further envisions a readiness toward the actors and infrastructure of the centralized track, being the utilities and the national electricity grid. The objective of this paper is therefore to investigate the feasibility of an approach where the people themselves start building upon their present resources in order to form a balancing network and prepare themselves for an eventual grid connection. Given the unpredictability of system emergence, the underlying research question raised here is whether such a grid can be built from the bottom-up avoiding path dependencies and leading to more resilient and ultimately sustainable infra-systems. Sustainability is here not understood as a condition of stasis but “a process of continuous adaptation, of perpetually addressing new or on-going problems and securing the resources to do so.”<sup>20</sup>

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16 Weijnen MPC and Bouwmans I (2006) Innovation in networked infrastructures: coping with complexity. *Int. Journal of Critical Infrastructures*. Vol 2(2). pp. 121-132.

17 Groh S, Philipp D, Edlefsen B, Kirchhoff H. (2014a) Swarm Electrification - suggesting a paradigm shift through building up microgrids bottom-up. *Proc. of the Int. Conf. Innovating Energy Access for Remote Areas: Discovering untapped resources*. Microenergy Systems and Berkeley Rural Energy Group. Berkeley, USA. 2014; ISBN: 978-3-7983-2694-1.

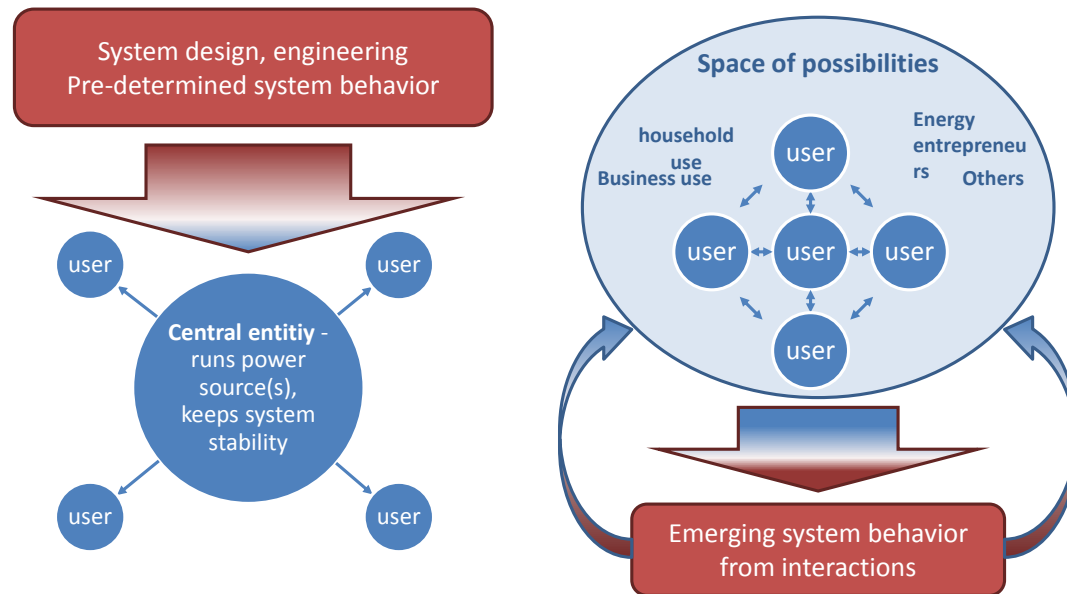
18 Groh S, Philipp D, Edlefsen B, Kirchhoff H. (2014) Swarm Electrification - suggesting a paradigm shift through building up microgrids bottom-up. *Proc. of the Int. Conf. Innovating Energy Access for Remote Areas: Discovering untapped resources*. Microenergy Systems and Berkeley Rural Energy Group. Berkeley, USA. 2014; ISBN: 978-3-7983-2694-1.

19 Smith A, Fressoli M, Hernán T (2014) Grassroots innovation movements: challenges and contributions. *Journal of Cleaner Production*. 63. pp. 114-124.

20 Tainter JA (2011) Energy, complexity, and sustainability: A historical perspective. *Environmental Innovation and Societal Transitions*. 1.pp. 89-95.

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## METHODOLOGY AND CONCEPTUALIZATION OF SWARM ELECTRIFICATION



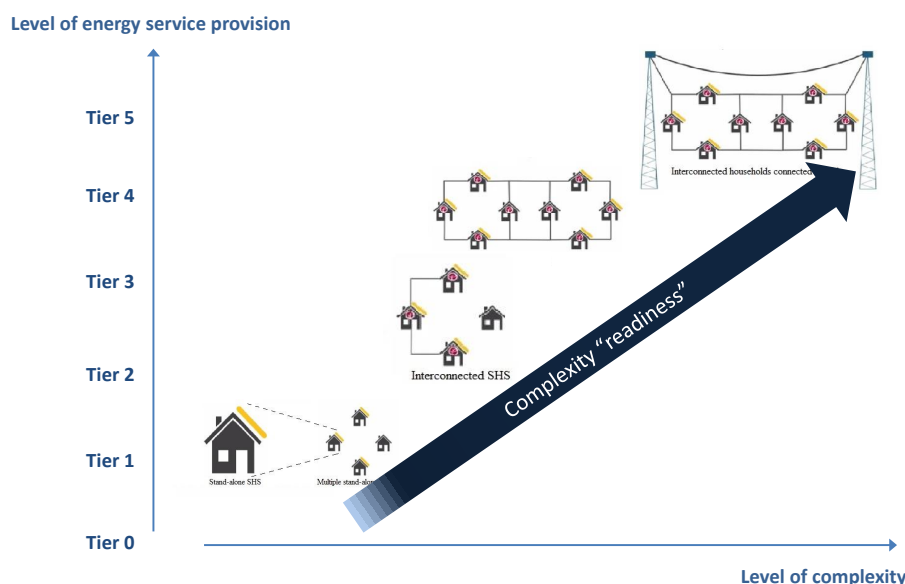
**Figure 1: The (mis-) understanding of electricity infra-systems vs. the bottom-up swarm approach**

From the perspective of complex system theory, the authors analyze a bottom-up concept drawn from an approach that follows the basic principles of swarm intelligence in distributed information and communications technologies networks.<sup>21</sup> In the swarm electrification scheme, each individual node brings independent input to create a conglomerate of value even greater than the sum of its parts. In the way that each node in a swarm intelligence network shares information with its neighbors to achieve a compounding effect, individual stand-alone household energy systems could share electrical power. Hence, each node/agent acts independently while her action influences other agents and her own future way of acting (connected and interdependent entities in a dynamic environment), thereby opening possibilities for non-intended actions (non-predictable emergence) benefitting the system (or community, but finally feeds back to electricity system as well). Finally, a stable (and self-stabilizing) system component is attractive for the larger system to connect to, in order to create more overall stability and robustness. In our understanding, a bottom-up approach is mainly characterized through its user-centricity. Figure 1 shows the main difference to a centralized-planned approach.

Whereas the latter is designed for a specific purpose and thus rigid and dependent on a single central entity to manage it, the bottom-up system ought to be

- non-pre-engineered, meaning it can adapt and re-configure (through built-in ICT solutions), leading to path-independency and the avoidance of legacy infrastructure problems,
- user-centered, meaning it does not depend on one single entity or agent to run the system, thus leading to higher robustness (comparable to the built-in-robustness of electricity systems under the so called “n-1 criterion”, meaning the user and clusters of users and their interaction will lead to a site-specific emergence of overall system behavior which in turn opens up new possibilities for the users both as consumers and producers of energy while constraining other actions.

21 Groh S, Philipp D, Edlefsen B, Kirchhoff H. (2014a) Swarm Electrification - suggesting a paradigm shift through building up microgrids bottom-up. Proc. of the Int. Conf. Innovating Energy Access for Remote Areas: Discovering untapped resources. Microenergy Systems and Berkeley Rural Energy Group. Berkeley, USA. 2014; ISBN: 978-3-7983-2694-1.



**Figure 2: Swarm electrification steps in the context of tier based service provisions and added complexity**

## DRAWING FROM THE BANGLADESH EXPERIENCE: IMPLICATIONS FOR A COMPLEXITY-EMBRACING APPROACH

Applying the concept of SE and interlinking these clustered SHS to form a microgrid, end-users could act as “prosumers”, as agents of a newly formed local energy system. These agents are then empowered to consume electricity from the microgrid as well as feed electricity into the microgrid and thus generate direct income. The interconnection has the potential to create synergy effects. The emergence of macro-patterns through the connection of people and technology triggers the conversion of the SHS from a mere energy source to a business-enabling vehicle. But at the same time the process increases interdependence which may lead to catastrophe. These aspects need to be taken into consideration at the device layer where smart devices can provide mechanisms for local control and beyond that are dynamic.<sup>22</sup> This control unit can be referred to as the system communication controller, robustness controller, energy flow manager, or monetary flow manager. The key aspect here is that it can be easily (re-)programed in order to account for unpredictable behavior. With recent advances in smart grid technologies as a consequence of the convergence of energy and ICT, such a bottom-up interconnected electrification approach can become feasible.<sup>23</sup> Unlike traditional microgrid approaches, there is a dynamic participatory inclusion of community members based on their existing equipment assets. A new system is built based on a myriad of existing sub-systems. As each agent can also act independently, varying degrees of the quality/ health of the systems do not interfere. Utilizing systems that are already existent in a particular household or business helps to minimize challenges associated with generation and storage sizing basically taking it from a complicated task to a complex system, while allowing the agents in the infra-system to share power and thereby balance out mismatches over time. By forming a village-scale microgrid connection through the network of electricity-sharing homes, the agents make use of their differentiated energy generation, storage capacities and consumption patterns to allow for a more efficient and consistent electricity service for all involved: both for SHS-equipped as well as non-equipped households and businesses. This again adds complexity but also a significant amount of benefits in terms of energy inclusion. Figure 2 illustrates the step-wise approach of SE in the context of tier based service provisions and added complexity. Step one shows individual households equipped with DC SHS as well as houses with neither solar nor grid electricity supply. Step 2 shows the interconnection of households with SHS, whereas in Step 3 the remaining houses are included in the growing DC microgrid. In step 4 different clusters can be interconnected. As a final step, the microgrid can be connected to a national or regional grid with minimal points of AC/DC conversion interfaces. The resulting

<sup>22</sup> Grijalva S and Tariq MU (2011) Prosumer-Based Smart Grid Architecture Enables a Flat, Sustainable Electricity Industry. IEEE.

<sup>23</sup> OECD/ IEA (2011) Technology Roadmap Smart Grids. Paris: OECD/IEA.

network is a DC grid that can facilitate trade and increase usage flexibility and reliability beyond the status quo of one-off systems. The advantages such as better system performance due to better battery charging cycles, more flexible usage of electricity, better system integration and opportunities for increased income generation through acquisition of bigger panel (and battery) sizes are reflected in the evolutionary development across the different tier levels. In terms of the ability to cope with the characteristics of complexity as described above, there is an important pattern to observe. While the increase in complexity per se is rising progressively, the demand for the ability to deal with socio-technical system complexity is more dualistic. While single, stand-alone systems do not need to have it, connected systems with multiple agents need them. Thus, the ex-ante incorporation of complexity-handling ICT not only enables systems with swarm controllers to connect to the grid but actually attracts the grid to connect to them once they reach critical size. Village-level micro-grids that were built from the bottom up can generally be able to serve high-power appliances for productive use. However, they face the problem of legacy infrastructure (electrical wiring) due to the assumable concentration on low-invest equipment in the first development stages of the system. As such, unlike traditional microgrids, the swarm model might need to tackle the challenge of limitations that occur when the technical system remains dependent on the existing SHS cabling and voltage levels, thereby retaining the instantaneous power draw limits of the SHS even if the overall energy availability and system performance increases. This represents the downside of the usage of existing resources and legacy infrastructure, even though in this case the infrastructure investment is considerably lower. The graph above reflects this issue where the jump from tier 1 to tier 2 occurs with only little increase in complexity. It must be noted, however, that the transition from tier 1 to tier 2 is critical as the technology undergoes changes from a single-device artefact (single lamp) to a more complicated technical system (SHS). This system interacts with the user layer, but the number of agents per system involved remains minimal. The first step of interconnection and consequently the upgrade to tier 3 level, however, results in a stronger increase in complexity due to the network system and interdependencies. The transition from tier 4 to 5 then has even more increase complexity when bottom-up and top-down infra-system are integrated into each other, leading to an overlay of networks with multi-role agents. Applying the 4A criteria to the concept, a central public value comes into play set out by the GoB in its Vision 2021: universal electricity access. In order to be able to assess the swarm concept against this goal, feedback loops are analyzed through graphical illustration. It is an attempt to show the logic and dynamic behind the 4As scheme. Figure 3 discusses the impact of a combined energy and financial inclusion measure, which seem to be mutually related as debated in Khandker et al. (2012), as well as in Groh and Taylor (2013), on an existing vicious cycle of a low income combined with high energy cost and limited usage capabilities from poor energy services, in short an “energy poverty penalty.”<sup>24</sup> Tier 1 and 2 provision of electricity services cover basic needs but also give the people a taste for electricity resulting in higher electricity demand patterns as shown in Figure 4 below and observed by various authors. A case study of SHS in Zambia showed that energy demand in the household increased with time, leading to over-usage of the systems.<sup>25</sup> For mini-grids the same applies: a study in India demonstrated that “people gradually started to look for more electricity.”<sup>26</sup> Another study from China showed a significant drop in service time from 12 to 3 hours per day for due to over-usage.<sup>27</sup>

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24 Groh S (2014) The role of energy in development processes - The Energy Poverty Penalty: Case study of Arequipa (Peru). *Energy for Sustainable Development*. 18. pp. 83–99.

25 Gustavsson M (2007) With Time Comes Increased loads—An Analysis of Solar Home System Use in Lundazi, Zambia. *Renewable Energy*. 32(5). pp. 796 – 813.

26 Ulsrud K, Winther T, Palit D, Rohrer H and Sandgren J (2011) The Solar Transitions Research on Solar Mini-Grids in India: Learning from Local Cases of Innovative Socio-Technical Systems. *Energy for Sustainable Development*. 15(3). pp. 293 – 303.

27 Shyu CW (2013) End-users’ experiences with electricity supply from stand-alone mini-grid solar PV power stations in rural areas of western China. *Energy for Sustainable Development*. 17(4). pp. 391-400.

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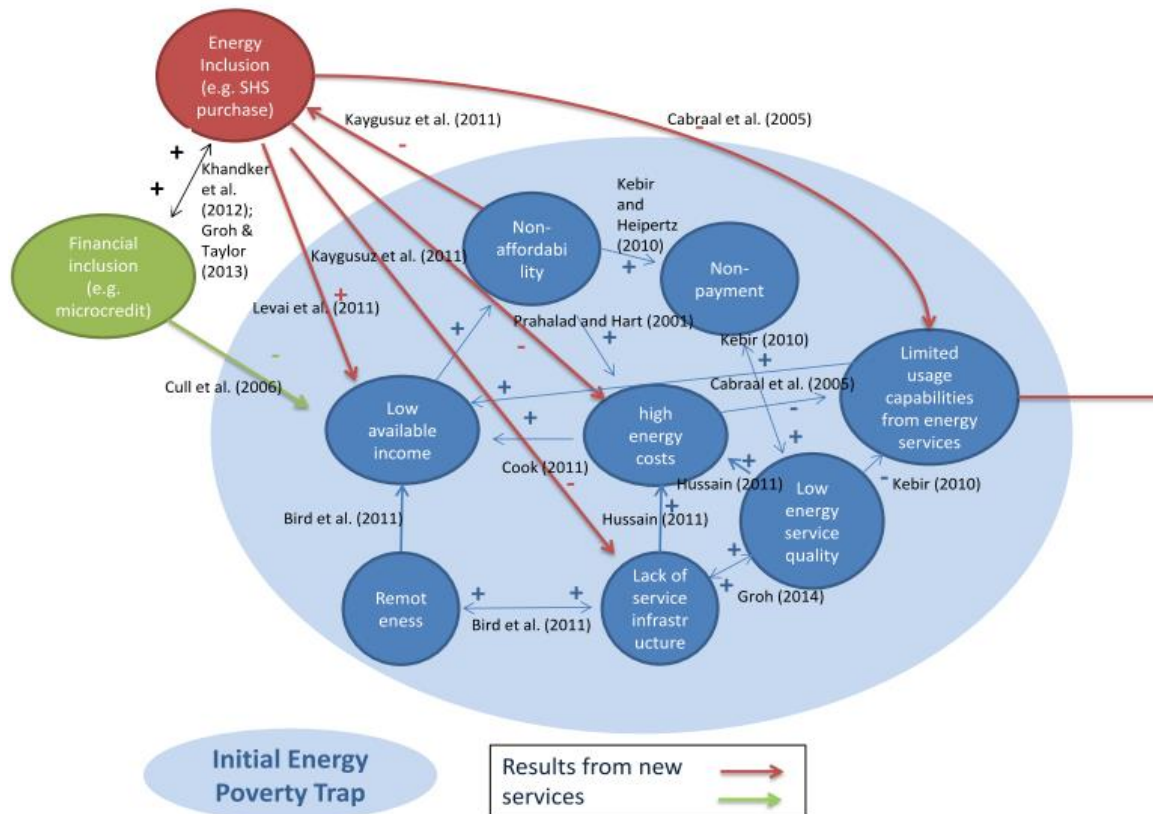


Figure 3: Household and microbusiness based feedback loops

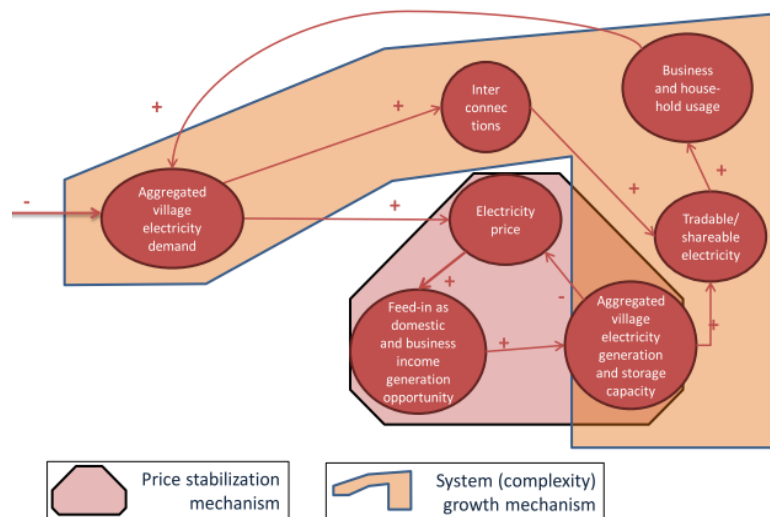


Figure 4: System feedbacks on village level

Figure 4 distinguishes between a system complexity growth mechanism which has been earlier described along the tier framework in Figure 2 and a price stabilization mechanism. In the latter one it is important to note that depending on the incentives set though dynamic pricing there are two possible dynamics: First, it can stimulate higher demand which can be realized system internally but also through extension to net consumers which translates into additional electrification. Second, it can trigger entrepreneurial behavior aiming for surplus generation capacity that can be traded.



## CONCLUSION

Although, the concept has a built-in opportunity for scalability, the issue of replication potential for other perhaps less densely populated areas and countries remains to be seen. However, generally speaking, the concept seems to be applicable in all off-grid areas where there is a certain density of social and economic activity. As SE so far remains a theoretical model, as a next step dynamic growth models testing the assumptions need to be computed as well as field tests conducted with a close monitoring. Looking at energy access efforts through the lens of system complexity can reveal strengths and weaknesses of approaches ex-ante and ex-post. In the light of many unsuccessful approaches in the past, there is a strong need to avoid similar pitfalls in the future. The authors hope that this is rather a starting point in a new discussion than a final statement. Based on our analysis, we argue that future infra-systems must be treated complex rather than complicated. The need for the incorporation of complexity with all its characteristics might thus be larger than the need for precise system layout from the beginning. Systems need, therefore, to be built bottom up avoiding “unhelpful forms of top-down intervention” [Lewis, 2011, p. 196]. This means that the electricity infra-system in the Global South has the chance use the convergence of ICT and energy, coupled with innovations in both areas, and leapfrog technology by avoiding legacy infrastructures. The tools and concepts to design adaptable, robust, decentralized, democratic and socially just electricity systems are in place.





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