A National Model for Strategic Planning of Infrastructure Systems

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ABSTRACT

Governments worldwide are paying increasing attention to the role of infrastructure systems in promoting economic growth and environmental sustainability. However, infrastructure planning and provision tends to be addressed in sector-specific silos, which overlooks the interdependencies between sectors and focusses upon the provision of projects rather than the performance of systems of systems. In this paper we report on the development of the National Infrastructure System Model (NISMOD) family of models and in particular the NISMOD-LP model, which is a national model of the long term performance of infrastructure systems. NISMOD-LP is driven by high resolution demographic projects and regional multi-sectoral economic scenarios. These provide the basis for scenarios of future demand for infrastructure services. Separate modules simulate the future capacity and performance of energy, transport, water, waste water and solid waste sectors. These different perspectives are integrated through a common architecture for sampling uncertainties, construction of cross-sectoral policy responses and visualisation of future infrastructure performance.

INFRASRUCTURE AS A PRIORITY FOR NATIONAL ECONOMIC DEVELOPMENT

Infrastructure, including energy, transportation, water, waste and digital communications, is essential for human well-being and economic productivity (OECD, 2006). Infrastructure is an often-cited key ingredient for a nation's economic competiveness (ULI and Ernst & Young, 2011). For example, the World Economic Forum lists infrastructure as the second 'pillar' in its Global Competitiveness Index (WEF, 2011). Infrastructure networks are also one of mankind's most visible impacts on the environment, and decarbonising infrastructure is key for climate change mitigation. As infrastructure is largely made up of long-lived assets (e.g. 50–100 years for many water assets) with high up-front costs, the wrong decisions during planning and design can 'lock in' unsustainable patterns of development. To steer towards more sustainable infrastructure systems requires a transformation in both thinking and methodology.

The infrastructure assets of developed countries in the west and the east are ageing and deteriorating (Davis et al., 2010), while under the pressure of ever increasing demand. Consider for example the water infrastructure in London: nearly half of the water mains are over 100 years old, yet the system is having to cope with increasing demand due to population growth. In the case of the energy sector, the UK will need to replace 25% of its electricity capacity in the next decade as it will come to the end of its life or be phased out in order to meet EU regulations for large combustion plants (SSE, 2011). Further, the need for the UK to increase the proportion of final energy consumption from renewable sources to 20% to meet binding EU targets (House of Lords, 2008, POST, 2008) implies a transformation of the electricity transmission grids.

Thus, highly developed countries are now at a critical crossroads where the pathways chosen for new and replacement capacity will both dictate future infrastructure supply security, and have critical environmental implications, such as climate change. Yet it is in rapidly industrialising countries that the most significant infrastructure commitments are now being made, which is locking in future patterns of development and carbon emissions. China for example spent approximately 6.8% of GDP (Ahya and Gupta, 2010) on transportation and water infrastructure during the 2010/2009 fiscal year – over two and a half times that of the U.S in 2007 (Congressional Budget Office, 2010, The Economist, 2011). Now more than ever, it is essential that governments and utility providers have access to new methods that enable the evaluation of the performance and impact of long-term plans and policy for infrastructure service provision that accounts for the complexity and uncertainty discussed above.

The key forces that influence demand for infrastructure services are deeply uncertain in the long term. For example, changes in population and economic growth both serve to modify demand for infrastructure services. Climate change is undermining the conventional assumptions of infrastructure designers about the environmental hazards to which infrastructure will be subjected (Milly et al., 2008). Still more uncertain is the role that technological change will have on patterns of behaviour and demand for infrastructure services. Yet while a ‘predict and provide’ approach to infrastructure planning may be out-dated, infrastructure owners still have to look far into the future and plan for a range of eventualities. Long term scenario planning is well established within infrastructure sectors, and in the UK is well developed for example in energy supply and water resources planning. At a global scale integrated assessment models are becoming increasingly refined in their representation of multi-sectoral economic activity (Janssen, 1998, Edmonds et al., 2012). However, their resolution of infrastructure is very limited, spatially and sectorally, so these broad-scale tools are not appropriate for evaluation of realistic physical portfolios of infrastructure options.

Current methods and models for infrastructure planning and design are not well suited to incorporating cross-sectoral interdependencies or to coping with the major uncertainties that lie ahead. If the process of transforming infrastructure is to take place efficiently, while minimizing the associated risks, it will need to be underpinned by a long-term, cross-sectoral approach to planning for infrastructure under a range of possible futures.

THE NISMOD-LP MODEL OF LONG TERM PERFORMANCE OF NATIONAL INFRASTRUCTURE SYSTEMS

The UK Infrastructure Transitions Research Consortium (ITRC) (Hall, 2011) is a multidisciplinary collaboration of scientists, engineers, economists and policy-makers, funded by the UK's Engineering and Physical Sciences Research Council to analyse the long-term dynamics of interdependent infrastructure systems. Composed of seven universities (i.e. Oxford, Cambridge, Newcastle, Leeds, Cardiff, Southampton, and Sussex), the consortium is creating a new generation of models and tools that assist policymakers in the evaluation of strategies for infrastructure provision.

An integrated assessment is needed to address the aforementioned challenges associated with the evolving complexity of infrastructure. However, the legacy of sector-based planning combined with uncertainty in the long-term challenge the development of such an assessment. If the process of transforming infrastructure is to take place efficiently, while minimizing the associated risks, it will need to be underpinned by a long-term, cross-sectoral approach to planning for infrastructure under a range of possible futures. We argue that such an approach needs to account for:

1. Changing patterns of demand for infrastructure services, and their associated uncertainties. In many respects, demand is shaped by the cost and availability of infrastructure services. However, it is informative to explore the effects of major drivers of infrastructure demand such as population, economic growth and climate change. As there are deep uncertainties associated with these drivers, a methodology is needed that is capable of exploring sensitivities to a wide range of uncertainties;
2. Interdependencies between sectors, in terms of cross-sectoral demands, and because many of the drivers of final demand (e.g. population) are correlated across sectors.
3. An extended timescale of assessment, given the long legacy of most physical infrastructures;
4. The current state of the infrastructure system and confirmed projects, which initialise and constrain the scope of future possibilities;
5. Multiple alternative future policies and system modifications that might be considered with respect to both infrastructure capacity and demand, and how these are combined into coherent cross-sectoral portfolios and implemented as staged and adaptive pathways through time;
6. Quantification and visualisation of performance of infrastructure systems, according to multi-attribute performance metrics. Given the multi-dimensional nature of the information generated by the analysis (including variation through time), effective visualisation is important to scrutinise and communicate the results and engage relevant stakeholders.

The proposed methodology therefore contains aspects of several existing methodologies, including robust decision making (Lempert et al., 2003), multi-sectoral economic modelling (Barker and Peterson, 1987) and decision pathways (Haasnoot et al., 2013).

Experience from previous complex systems modelling projects illustrated the importance of a quick 'first pass' through the systems modelling problem. We did this Fast Track Analysis (FTA) during the first year of the project. It is reported in Hall et al. (2012, 2013, 2014). Following on from that, we have since early 2012 been developing an integrated system of models of the energy, transport, water, waste water and solid waste sectors. Though we have not adopted the same explicit network system modelling approach for digital communications and computational infrastructure, the development of ICT is deeply embedded in all of our future scenarios.

The overall structure of the analysis is illustrated in Figure 1. The analysis is based around a common spatial database (NISMOD-DB) which contains all of the input data for the individual sector models as well as hosting the model outputs. A series of pre- and post-processing scripts generate a large sample of model inputs and visualise the results.

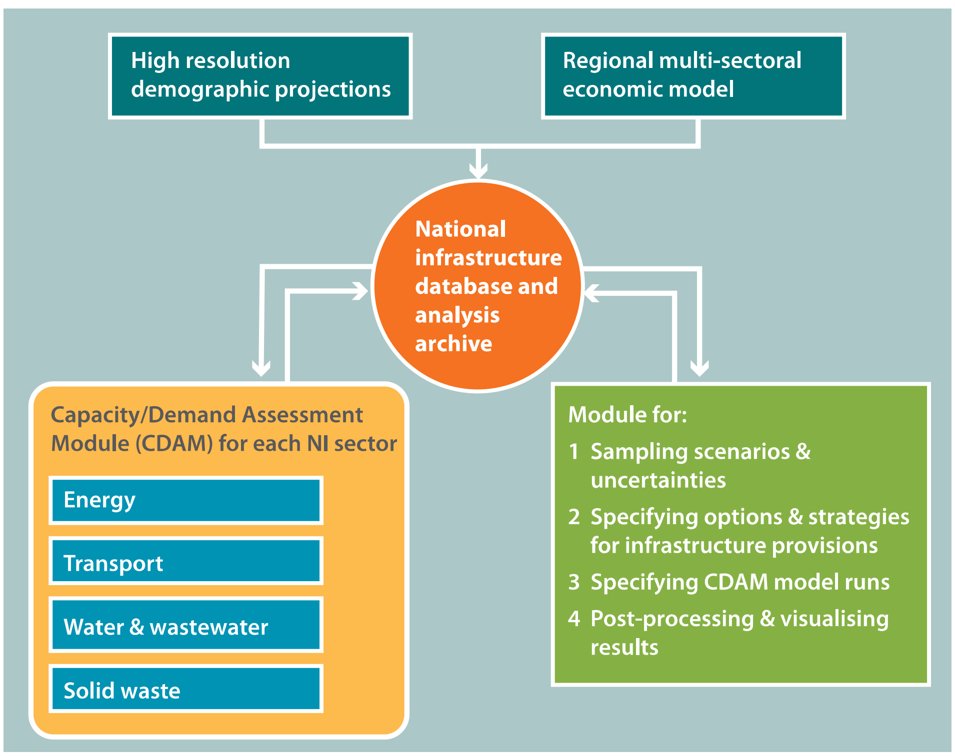

Figure 2. Overview of the NISMOD-LP system simulation architecture

The analysis is driven by long term quantified scenarios of population and economic growth. These are required in order to understand the potential range of demands for infrastructure services. The population scenarios are generated from a household-level micro-simulation model, based on census data for the UK. It generates projections of age distribution, household size and regional distribution of population.

The economic scenarios come from the Cambridge Econometrics MDM multi-sectoral regional economic model. The model outputs are conditioned on assumed average rates of economic growth, for which we test a range of scenarios. The model helps to understand the potential sectoral distribution of economic activities and implications for employment, as well as for infrastructure demand.

These projections of factors influencing demand are then input to five infrastructure sector models:

Energy: A new spatial energy demand model has been developed at the University of Oxford. The model computes average and peak demand from households and industry under a range of different scenarios for behavioural and technological change. Energy supply is analysed using the CGEN+ model, an adaptation of the CGEN model of the UK's electricity and gas networks developed at Cardiff University. CGEN+ includes all of the supply and transmission infrastructure in the UK, with the functionality to include a wide range of possible future supply scenarios, including large amounts of offshore wind, nuclear and CCS.

Transport: A new national transport model for Great Britain (GB) has been developed at the University of Southampton. The model includes road, rail, shipping and aviation transport modes. It operates at the scale of local authority districts and, in the absence of national origin-destination information, computes the passenger and freight fluxes across the boundaries of these spatial units. The model enables computation of the effects of infrastructure investments, prices and other factors that influence passenger demand.

Water: A national model of water resources has been adapted at Newcastle University. The model is driven by probabilistic scenarios of future climate and includes the main storage and transfer infrastructures. Water demand is calculated primarily in terms of per capital municipal demand and cooling water abstractions for energy (Byers et al., 2014).

Waste Water: The model of waste water infrastructure being developed at Newcastle University has assembled data on treatment plant size and location in Great Britain and is using this to understand future investment needs, given changing population.

Solid Waste: The solid waste module that has been developed at the University of Southampton computes waste arising from domestic and commercial sectors and evaluates infrastructure options for treatment, waste recovery and disposal.

Interdependencies between these sectors are analysed by identifying the cross-sectoral demands for infrastructure services. All sectors demand energy, though the transport sector is the only sector that accounts for more than a few % of energy demand. Therefore energy-transport interactions have been a particular focus of attention. The energy sector is a significant demand for water resources, so has been given explicit attention in the water resources modelling.

TESTING STRAEGIES FOR NATIONAL INFRASTRUCURE PROVISION

The ITRC has developed a national assessment of options for infrastructure provision in Great Britain, using the NISMOD-LP model. In that model-based assessment, a range of alternative strategies for national infrastructure provision are being analysed. They are composed of a portfolio of supply-side (i.e. capacity options) and demand management policies for each infrastructure sector oriented towards a specific aim. Recognising the inertia due to the legacy of existing infrastructure, each strategy starts with today's infrastructure system but the strategies transition into the future in contrasting policy directions. In summary the national infrastructure strategies currently being analysed are:

Minimum Intervention (P-MI), which reflects historical levels of investment, continued maintenance and incremental change in the performance of the current system.

Long-term Capacity Expansion (P-CE), which focuses on large scale, long-term investment into physical capacity expansion to meet increasing demand.

Increasing System Efficiency (P-SE), which focuses on deploying the full range of technological and policy interventions to increase efficiency of the current system targeting both supply and demand.

New Service Planning and Design (P-NS), which focuses on restructuring the current mode of infrastructure service provision through long-term investment in innovation and design of new service delivery models. A combination of targeted centralisation and decentralisation approaches are deployed.

Analysis of these strategies is helping to address the following high level policy questions:

Capacity provision:

- What are the trade-offs in provision of new capacity versus the associated costs?
- When will capacity constraints be critical in each sector?
- Where should additional capacity be provided? What are the regional variants/options in provision of new capacity?

Demand management:

- What level of demand restraint could be achieved compared to unrestricted demand? How?
- What are the trade-offs associated with vigorous demand management?

- o Are synergies achievable in demand management by taking a cross-sectoral approach?

Carbon reduction:

- o What is the cost of meeting carbon targets?
- o How can carbon reduction costs be most efficiently factored into capacity upgrades?

Alternative infrastructure pathways:

- o What might the potential of ICT be to transform infrastructure provision in the future? How should we be planning for or enabling that now?
- o Is a highly decentralised future of infrastructure provision a viable strategy, given current network configuration? How might we achieve it and what would be the costs and benefits?

The answers to these questions are being presented in terms of a set of key common performance metrics (Table 1).

CONCLUSIONS

There are increasing calls for evidence-based long term planning of infrastructure provision, which can help to disconnect infrastructure from some of the vagaries of the political process (Armitt, 2013). The analysis that would be required to inform a National Infrastructure Commission of type proposed by Sir John Armitt is being provided by the ITRC's NISMOD-LP model. NISMOD-LP enables the appraisal of alternative long term strategies for national infrastructure provision, based on a generic set of metrics and consistent set of scenarios of the wide range of future uncertainties.

Strategies for infrastructure provision have been developed that combine investments in new capacity with a range of measures on the demand side. The scale of action that is required on the demand side is sensitive to population projections and behavioural and economic factors.

This paper has focused upon the NISMOD-LP model, though reference has also been made to the underpinning NISMOD-DB database, which hosts all of the necessary national infrastructure daases and the outputs from the runs of NISMOD-LP. NISMOD-DB also provides a toolkit of visualization facilities to enable scrutiny of the complex results that emerge from NISMOD-LP.

The emphasis upon NISMOD-LP is upon the capacity of infrastructure systems and how this compares with average and peak demand. Policy makers and utile operators are also concerned about the risk of failure in extreme conditions, and in particular the poneial effects of interdependence between infrastructure networks. The NISMOD-RV model focusses upon the risk of infrastructure failure and system vulnerability to extreme disruptive evens.

Together the NISMOD family of models provides the evidence to inform a more rational, long term approach o national infrastructure provision.

Table 1. Summary of quantitative performance metrics

Sector	Quantitative performance metrics
Energy	Total cost of capacity installation Total electricity sector CO_2 emissions Diversity of supply
Transport	Passenger demand (road, rail, air) Passenger km (road, rail, domestic air) Train km per track km Freight tonne km (road, rail, waterway, pipeline) Delays on trunk roads CO_2 emissions Fuel/energy use
Water supply	Water available Total water consumption Capital cost
Waste water	Demand for waste water treatment Capacity of waste water treatment facilities Costs of waste water treatment facilities Waste water treatment cost per capita
Solid waste	Municipal solid waste arising Commercial and industrial solid waste arising Construction and demolition solid waste arising Destination (recycling, landfill, energy from waste) Recovery rates Capital costs
ICT	Energy consumption Data centre usage Broadband coverage Mobile data traffic

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REFERENCES

Ahya, C and Gupta, T (2010). *India and China: New Tigers of Asia, Part III: India to Outpace China's Growth by 2013-15. Special Economic Analysis*. Morgan Stanley

Armitt (2013). *The Armitt Review: An independent review of long term infrastructure planning commissioned for Labour's Policy Review*. Labour Party, London.

Barker, T and Peterson, W eds (1987) *The Cambridge Multisectoral Dynamic Model of the British Economy.* Cambridge University Press, Cambridge.

Congressional Budget Office (2010). *Public Spending on Transportation and Water Infrastructure*. Congress of the United States.

Davis, SJ, Caldeira, K and Matthews, HD (2010) Future CO2 Emissions and Climate Change from Existing Energy Infrastructure. *Science* 329(5997): 1330-1333.

Edmonds, J, Calvin, K, Clarke, L, Janetos, A, Kim, S, Wise, M and McJeon, H (2012) *Integrated Assessment Modeling. Climate Change Modeling Methodology.* Springer, New York.

Hall, JW (2011) Introducing the Infrastructure Transitions Research Consortium. *Civil Engineering* 164: 51.

Hall, JW, Henriques, JJ, Hickford, AJ and Nicholls, RJ eds (2012) *A Fast Track Analysis of strategies for infrastructure provision in Great Britain: Technical report.* Environmental Change Institute, University of Oxford, Oxford.

Hall, J.W., Henriques, J.J., Hickford, A.J. and Nicholls, R.J. (2013) Systems-of-systems analysis of national infrastructure, *Engineering Sustainability*, ICE, 166(5): 249–257.

Hall, J.W., Henriques, J.J., Hickford, A.J., Nicholls, R.J., Baruah, P., Birkin, M., Chaudry, M., Curtis, T.P. Eyre, N., Jones, C., Kilsby, C.G., Leathard, A., Lorenz, A., Malleson, N., McLeod, F., Powrie, W., Preston, J., Rai,, Street, R., Stringfellow, A., Thoung, C., Tyler, P., Velykiene, R., Watson, G. and Watson, W.J. (2014). Methodology for rapid assessment of long-term, cross-sectoral strategies for infrastructure systems, *Journal of Infrastructure Systems*, ASCE, in press.

House of Lords (2008). *The EU's Target for Renewable Energy: 20% by 2020.* House of Lords. House of Lords EU Select Committee, London.

Janssen, M (1998) *Modelling Global Change: The Art of Integrated Assessment Modelling.* Edward Elgar, London.

Lempert, RJ, Popper, SW and Bankes, SC (2003) *Shaping the Next One Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis*. RAND, Santa Monica, CA.

Milly, PCD, Betancourt, J, Falkenmark, M, Hirsch, RM, Kundzewicz, ZW, Lettenmaier, DP and Stouffer, RJ (2008) Stationarity Is Dead: Whither Water Management? *Science* 319(5863): 573-574.

OECD (2006). *Infrastructure to 2030: Telecom, Land Transport, Water and Electricy.* Organisation for Economic Cooperation and Development, Paris.

SSE (2011). *Memorandum submitted by Scottish and Southern Energy.* Commons Select Committee Energy and Climate Change. House of Commons, London.

The Economist (2011). America's transport infrastructure: Life in the slow lane. *The Economist*, London.

ULI and Ernst & Young (2011). *Infrastructure 2010 - investment imperative.* Urban Land Institute (ULI), Washington DC.

WEF (2011). *The global competitiveness report 2011-2012.* World Economic Forum, Geneva.