Centre for Digital Built Britain (CDBB) research network on Planning Complex Infrastructure under Uncertainty.

Final Report

Executive summary

This report presents the conclusions of a research scoping network supported by the Centre for Digital Built Britain. The main source of information is a pair of workshops bringing together a range of research disciplines and practitioners, with information gathered being synthesised by an interdisciplinary core network team of researchers in mathematical sciences, engineering and social sciences. This has been supplemented with a survey to gather wider views, and knowledge of the core team gathered through other events and projects. Alongside this main report, an annex on good practice in research software development is also available, written by the Head of Research Engineering at the Alan Turing Institute.

The full report that follows contains the full conclusions on research requirements. Wider themes cutting across multiple individual areas of research are:

1. In some research areas, full scale work can begin immediately. In others, there is detailed enabling work required, on identifying stakeholder needs and current state-of-the-art, before full scale research can commence.
2. The need for a more nuanced understanding of failure and success of projects, recognising that this is not a binary distinction, and that ex ante there is uncertainty over project costs and timelines. This can be summarised in the phrase "processes of success", recognising that any headline outcome should be seen in context of the quality of practice in planning and implementation.
3. Communication between analysts and decision makers is a key aspect of modelling for decision support. This is a two way process; analysis outputs must be presented in such a way that decision makers have a proper appreciation of what the analysis has to say about the real system under study, and conversely in order to deliver useful analysis the analysts must have a proper appreciation of the interest of decision makers.
4. There was a strong consensus that typically the budget for analysis supporting strategic planning in very large projects, i.e. the early questions of what and how big, is not commensurate with the overall value of the project. Research on quantifying ex ante the value of analysis can deliver very significant value in allocating appropriate budget to different phases of project planning.
5. There is a pressing need among stakeholders for improved quantification of uncertainty in the relationship between model outputs and predictions, and

equivalent quantities in the real world. Specific issues include unmodelled aspects in complex systems of systems; hard-to-quantify issues such as intangibles and externalities; improved capability to develop logical arguments based on scenario studies; the use of modelling to de-risk contracts; and developing more efficient and robust engineering standards and regulatory incentives, which must deliver good outcomes in a wide range of circumstances.

6. Improved data availability is key to many areas of research and practice. For instance, developing appropriate datasets as a national project is a key enabler of applicable research, and there is a need for research into what data should be gathered and reported for ex ante assessment of success of projects.
7. Care is required in design of CDBB and related funding calls, so that appropriate interdisciplinary project teams are supported to develop the new capabilities required by industry and government.

Acknowledgments

This report was prepared by the network core team of Chris Dent, Adam Anyszewski, Tom Reynolds and Gordon Masterton (University of Edinburgh); Hailiang Du and Evelyn Tehrani (Durham University); James Hetherington (Alan Turing Institute); Henry Wynn (London School of Economics); and Kat Lovell and Gordon Mackerron (Sussex University). The authors thank Ed Wheatcroft (LSE) and Charles Boulton (CDBB) for assistance in facilitating workshops, Charles Boulton and other as CDBB for valuable comments on drafts, Lynn Gibson (Durham University) for administering the network, and all the network participants for contributing their time and experience.

Conclusions from Workshop 2

1. Immediate enabling and survey work

This first section describes topics on which work is required to enable later R+D projects, and on which reports on the current state of art on these issues could be commissioned and completed at an early stage. Many of these tasks might be performed by consultants or engineering contractors, with appropriate academic support. As well as providing a starting point for good practice case studies and more extended research projects, this will also identify where there are key gaps which require research.

The network core team will survey workshop participants to identify where existing activities can cover these and other review activities. Several have already been identified from projects of the core team, for instance related reviews within the Alan Turing Institute, the Centre for Energy Systems Integration, and the Project Management Institute (PMI, supporting the Infrastructure and Projects Authority's "Project X").

1.1 Defining success and failure of projects

There was consensus that enabling work is required on definitions and understandings of success and failure before definitive plans can be produced for research across a number of areas. Issues involved in measuring success and failure include:

(i) *'On-time' and 'on-budget' are continua rather than binary yes/no concepts*. There are subtleties such as uncertainty over tasks required and use of contingency funds ex ante, and 'success' may be managing unforeseen specific tasks well even if this increases budget above the central estimate.

(ii) *There are different timescales on which aspects of performance can be measured*, for instance on-time and on-budget are known before ex post assessment of performance against purpose. Definitions of success and failure can also shift over time, for instance due to changes in political climate. Longitudinal assessment is thus required, and appropriate points for assessing success may arise at different times for different elements of performance.

(iii) *Objectives may be multidimensional, with some aspects hard to quantify*, for instance externalities or intangibles.

(iv) *What data recording and reporting can support ex post performance assessment?* Can a data collection standard be introduced for infrastructure projects, and is there data which should be made widely available to enable assessment and improvements. Are there obstacles or norms to greater transparency and sharing of data?

(v) *What role can non-conformance reports play*, both in assessing particular projects and in learning lessons for the future? As well as more general use, this might be of help in assessing performance where project specifications change.

(vi) *There is a need to incorporate social science (including humanities) research* around issues such as understanding 'value', capturing change in value/s, multiplicity of voices (success for whom?), and critical assessments of data and models. There are different potential relationships available between *social science* research and that of *science, mathematics and engineering,* and scope to consider these relationships creatively in developing interdisciplinary work; there is value in social science research not only to support and/or challenge work in technical subjects but also sometimes to lead or shape the challenges addressed and approaches taken.

(vii) *The use of success criteria and metrics both in ex post assessment against a single realisation of planning background, and ex ante planning under uncertainty*. On the latter, there is an active debate as to what decision criteria might be used, for instance contrasting minimax criteria with a Bayesian decision analysis picture. On the former, how can the effectiveness of decision processes be assessed, the lack of counterfactual, and the challenge of archiving data and/or models used for decision support?

(viii) *Different perspectives from which a project might be assessed*, e.g. of government, parliament, users, general public, contractors, north vs south etc., and different aspects of environmental, social, economic or engineering performance. The use of metrics, including how externalities are treated may implicitly define what constitutes 'success' or 'value'. For instance, if contribution to UK economic growth is seen as a key outcome metric, this may unduly favour projects in some parts of the country. For instance, if contribution to creating country-wide balance of growth opportunity is the key outcome metric, this would favour projects in less buoyant economic zones.

(ix) *Assessing the performance of projects as part of a wider system of systems*. This involves a boundary critique of models, which recognises that the boundaries of what is modelled are artificial and that the system modelled is interlinked with other entities.

The new thinking required in this area can be summed up in the phrase "processes of success", recognising that success is not a binary flag which can be evaluated at a discrete point in time, and that the reality of infrastructure projects often dictates that success is measured at multiple junctures and over multiple criteria. Project performance involves balancing and prioritising points of attainment, and a key element in project success is about how the project is planned and reacts to events over time. This in turn requires means of communicating this nuanced reality to stakeholders including government, the media and the general public.

1.2 Decision making

Another key initial priority is to understand the decision-making environment, as analysis should be aligned to purpose, i.e. be directed towards actual decision and actual policy. This should include (i) a taxonomy of the decisions involved in projects (ii) the time line (iii) the stakeholders (iv) the policy environment (v) audit of what decision-makers “actually need” (vi) special priorities: “what keeps decision-makers awake at night” (vii) the decision makers appreciation of uncertainty and its influence on the decisions.

A common theme running through many aspects of this report is communication to stakeholders. This is often seen as a one-way process, i.e. analysts communicating modelling results to decision makers and others. However, a key part of any research into how modelling sits within decision processes should also consider carefully how analysts can gain a proper understanding of the decision maker’s actual needs and questions

1.3 Other enabling work

Glossary of definitions and concepts. There is value in a glossary of definitions for relevant concepts in infrastructure planning, and some discussion over whether a glossary or a concise discussion of issues is required. For instance, there is no agreement over specific meanings of ‘risk’, ‘resilience’ and ‘uncertainty’, and thus a discussion of relevant issues involved in using these terms seems appropriate.

Communication of uncertainty. The importance of effectively communicating uncertainty during a project lifetime was raised frequently in discussions – whether this be from policy makers to the general public, analysts to decision-makers, or by project managers to stakeholders. It was noted that this can make the difference between a project being perceived as a success or failure. Examples were identified of useful glossaries or tools for communication which have been developed in different sectors to communication issues such as risk. A project could be undertaken to scope what tools exist for clear communication and visualisation of uncertainty within sectors such as infrastructure, health care, and climate change. Where necessary work could be undertaken to develop appropriate tools for the context of planning infrastructure under uncertainty.

Key examples of best practice. At the second workshop, interest was expressed in a Performance Chart or premier league table of infrastructure projects. The government Aqua Book was suggested as a starting point in defining what constitutes best practice in analysis.

Communicating quality and strength of evidence. In subsequent discussion among the core team, there was also discussion over a ‘star rating’ system for quality of analysis and strength of evidence, following that used by David Spiegelhalter[1], in turn based on the Cochrane Collaboration's assessments of the state of knowledge in effectiveness of medical treatments. A project on developing this in the specific context of infrastructure analysis, along with some commentary on what is necessary to place a study at a given star level, could be an effective way of communicating to decision makers and project leaders a better understanding of the maturity levels of the various models used in the system representation at any time. Discussion also highlighted importance of recognising and incorporating the various issues raised by measures of success, as described above.

[1] See for example slides 34-35 at http://ccu.soton.ac.uk/presentations/spiegelhalter.pdf

2. Projects which can be specified immediately

In the following areas, a full-scale project could be designed at an early stage, without needing to wait for the results of the enabling work described previously.

2.1 Value of analysis

There is very considerable benefit in development of methods for estimating the value of additional analysis at different stages of a project, to enable better allocation of overall project budget and time. There was a strong consensus that typically the budget for analysis supporting strategic planning in very large projects, i.e. the early questions of what and how big, is not commensurate with the overall value of the project. Communication to other stakeholders of the value of further analysis is also important, given that additional work will probably bring immediate costs or delay, but may deliver additional value or save time later on. Work in this area could allow more efficient sizing and allocation of detailed engineering design budget, though there was less concern here that budgets are typically inadequate.

2.2 Decision making in systems of systems.

Many infrastructure systems involve a hierarchy of systems (e.g. energy networks) or parallel systems (e.g, national road/rail/airports). Research is required in how integrated decision making across such systems of systems is carried out, and on how different projects interact and shape each other, to inform how planning can take place with appropriate coordination between projects and infrastructures. This would link to proposed early work on measures of success, and build on existing analysis methods used in government and industry.

Some issues here are of technical modelling, including the boundaries of models and how modelling only part of the overall system of systems introduces modelling uncertainty; and in complex systems identifying a sweet spot balancing detail of system modelling with uncertainty analysis linking to the real world. It is however also vital to understand the context of different levels and positions within a network of governance and decisions, each level having different decision makers who are facing different pressures and have different measures of success. Further it is important to acknowledge and improve understanding of changes in hierarchy, boundaries, scales and extent of reach of control over time and with shifts in priorities and power structures.

This links to another very general issue, namely analysis to support decisions against very complex planning backgrounds, where it is not possible to build a model which approaches the complexity of the real situation. In such circumstances, it is particularly important to co-design the system modelling and uncertainty analysis to maximise learning about the real world system.

2.3 Considering the hard-to-quantify

Better methods are required for measuring (by quantifying or otherwise considering in logically consistent ways combining different types of information or data) hard-to-quantify-or-model aspects of costs and benefits, for instance intangibles, externalities and soft factors. This is a contentious issue in many large infrastructure projects. A general issue cutting across much of this is the lack of counterfactuals – as discussed above, ex ante decisions are taken under uncertainty about planning background, but ex post there is only one realisation of the background.

Different perspectives might be applied on how these issues can be considered in analysis. For instance, in quantitative analysis these might be represented as uncertainties in a cost-benefit analysis, though it may prove more natural to use multi criteria decision analysis approaches which recognise that not all issues can brought together as a single bottom line in a direct monetary CBA.

2.4 Data for assessment of success and failure

There is a desire for research into data that might be used to assess, and allow comparisons of, success or failure of infrastructure development, including how this might be represented in a standardised summary 'dashboard'.

Much of this cannot be fully specified until enabling work described above is complete. However, one clearly defined aspect where a project might be specified immediately is in identifying where circumstances have changed to a sufficient extent that decisions need to be revisited. This might apply at all stages of a project, for instance in the construction phase there is large expense in any re-design so there is high value in better ways of taking decisions on when the stage has been reached that a pause in construction is required.

2.5 Uncertainty in analysis

There was consensus at the workshops that this is such a broad cross-cutting area, which is not yet well understood, that it should be continued as a "long term" research area for the duration of the research agenda. Important sub-areas were identified: (i) the changing and dynamic nature of uncertainty; (ii) that uncertainty is wider than propagating parametric uncertainty through the model; (iii) propagation of uncertainty between models, and how uncertainties my compound in a system of multiple models; (iv) visualization and communication methods to support decision making; (v) calibration and history matching of models. The discussants were aware of the different methodological schools but also that there was no panacea method, the key being to identify what data and information are available and to let that question-driven approach determine the mode of analysis.

There are well-established general methodologies for considering uncertainty in modelling and other analysis, however these will need specialising to the particular circumstances of infrastructure analysis, and even at a basic methodology research level there are still open questions. However another key area is identifying how to make advanced analysis methods more widely available to analysts in the field, where these might mean a significant change from current skills and practices.

Many of these research needs under uncertainty analysis and elsewhere might be summarised as “analysis for decision making in the real world”, and research and practice should be designed with this in mind. It is important to guard against matters such as collecting data for the sake of having a large dataset, or confusing optimality in the model world with a good decision in the real world – the real goal being to identify decisions which one has logical reason to believe are good ones in the real word.

2.6 Case Studies

At all stages of this research agenda it is important to provide case studies with full collaboration with the project on which the case study is based.

Once enabling work on defining success criteria is complete, this might start with a small number of studies which could be used to inform work on decision-making. There was a consensus in the workshop that “lower hanging fruit” should be identified, for instance retrospective case studies of existing projects, but also that more complex or challenging case studies should proceed where this is necessary to demonstrate particular research questions. Opportunities should be grasped if/when available, for instance current initiatives such as Crossrail and HS2.

2.7 Data

There was extensive discussion of data at the second workshop. At the heart was the tension between quality (or “fidelity”) and quantity. There may be huge quantities of data (such as from sensors), but it may not be collected with particular decision-making aims in mind. There may be selection bias, because the data (sample, training set) may not be representative of the population of interest. On the other hand, collecting data carefully for a particular purpose may be expensive. Different types of data were identified including (i) meta data generated from modelling/simulation itself and (ii) data from formal or informal elicitation of expert judgment (with necessary consideration of cognitive bias).

This can be summarized by the need to understand and handle the “diversity of data”, and to understand better how data can be collected most effectively to support the overall goal of decision making in the real world.

2.8 Contract design

Identifying the time line is important in infrastructure development, and tendering and contracts were identified as areas where modelling can help and where different genres of modelling (e.g. engineering and economic) need to be linked. There is an important difference between capital (CAPEX) investment and operations (OPEX) with different types of risk and uncertainty. CAPEX and OPEX could be combined into "TOTEX", indicating a preference for integrated modelling. There are also different styles of modelling from detailed physical/engineering modelling to more spreadsheet style.

Project development has phases: feasibility studies, planning/design, business cases, tendering/bidding, construction, operation. Some Key Performance Indicators (KPIs) which are used in the inputs and outputs to models will appear in contracts, leading to "model-based contract design". Ideally this will lead to better contract monitoring, flexibility, and coherent and fair handling of contingencies as scenarios develop and regulations change.

2.9 Scenarios

Scenarios are widely used in infrastructure studies in industry and policy; one important role they play is as a way of exploring different possible futures and communicating this widely. Work with scenarios is often important for incorporating qualitative elements into modelling analyses, and for enabling/guiding critical thinking on the structures and simplifications used in a model and on the implications of those decisions.

However, there is a need for work on using scenario studies both rigorously and critically in decision support. Scenarios can be developed for different purposes and can take many different forms; approaches to scenario studies are shaped by both the research questions involved and the intended contribution of scenarios in the context of the broader study. Whether they are predictive, explorative or normative[2,3] scenarios can have key parts to play in research addressing uncertainty. One important application of scenarios, of particular relevance in this context, is in linking qualitative and quantitative approaches and examining critically the conceptual approach to this connection is crucial for generating rigorous research. Scenarios can contribute to understanding phenomena and connections to their context, as well as to enabling deeper engagement with issues and analysis, including as a tool for communicating outcomes of modelling analyses or for influencing stakeholder actions.

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[2] E.g. Börjeson, L., Höjer, M., Dreborg, K. H., Ekvall, T., & Finnveden, G. (2006). Scenario types and techniques: towards a user's guide. Futures, 38(7), 723-739.

[3] 'Normative' is used to capture scenario studies intended to change/influence people's thinking or behaviours. One example is where scenarios are developed to respond to a question of how a target or situation could be reached.

Issues include choice of scenarios in the context of the question being addressed, typically sparse coverage of the uncertain space by scenarios, and clear communication of the messages which should be drawn from scenario studies, and the use of scenario studies in decision support. There is scope for research on exploring an uncertain space using scenarios in an efficient way, for instance using surrogate models. The key overall requirement is for scenario studies to have a firm logical basis, and for good scientific method to be followed both in generating scenarios and in linking those scenarios to modelling analyses.

2.10 Regulatory incentives and engineering recommendations

Government, regulators or professional bodies often provide frameworks, for instance regulatory incentives or engineering recommendations, within which other entities do detailed planning and design. These need to strike an appropriate balance between efficiency through standardisation, and not oversimplifying the framework provided. There are opportunities for innovation in how to do this, for instance in how to provide software tools which allow a wide range of people to do a good job efficiently, while retaining a strong logical or scientific underpinning.

There are certainly ongoing research needs in the use of data for comparison of performance of regulated entities. One key piece of context here is that while ‘regulation by comparison’ of utilities in different regions seems attractive, the circumstances of different companies will be quite different and so determining the appropriate baseline for success for different companies is non-trivial. There are also ongoing opportunities for innovation in efficient design of data reporting for regulatory compliance, i.e. in ensuring that the necessary information is available to the regulator with a minimum of administrative burden, and that the regulator is equipped to interpret the data.

Engineering recommendations are inevitably quite context-specific, however there may be opportunities for projects to demonstrate ways of thinking in how new modelling techniques may successfully be used widely in planning, or how a degree of simplicity in practical planning processes can be maintained in a complex environment. A good example of the latter challenge is the P2 standard for capacity of electricity distribution networks where an existing standard, with a starting point of demand being met by incoming circuits from higher level, must be adapted to consider a much more complex situation with a wide variety of local resources.

3. Design of CDBB projects and funding calls

A common theme throughout this report is the need to assemble effective interdisciplinary teams, both in research and in wider practice. This is particularly important for CDBB in planning research projects, as there is a well-known tendency for multidisciplinary projects based across multiple departments or institutions to silo into monodisciplinary activity. Careful design of calls and projects, with this in mind, is thus a key enabler of productive work.

One challenge in assembly of projects is balancing the need to have application experience within the project, with the need to include relevant specialists who may not be so well known in the community. Inviting full proposals which would be funded as-is often results in projects staffed by those already deeply engaged in the application area, without bringing in new perspectives from other disciplines. Alternative models include inviting expressions of interest to join a project team, which will then develop the full proposal.

There may be considerable benefit to CDBB in collaborating with other national initiatives. Some, such as the 'Evidence based decision making for UK landscapes' initiative between NERC, DEFRA and the Isaac Newton Institute[4], are truly inclusive national initiatives. In other cases, however, the benefits of collaboration with such national initiatives must be balanced with the question of whether an initiative has the best interdisciplinary team for a given area of research. A related point is the need for research to be question-driven rather than methodology-driven, as large initiatives sometimes develop around emerging areas of methodology which may or may not be appropriate approaches for specific practical questions.

[4] See http://www.turing-gateway.cam.ac.uk/event/tgmw60 for further details

Appendix: List of network participants

First Name	Surname	Organisation
Simone	Abram	Durham University
James	Angus	Network Rail
Adam	Anyszewski	Edinburgh University
Filip	Babovic	Edinburgh University
Chris	Bagley	KTN
Pete	Barbrook-Johnson	University of Surrey
Stuart	Barr	Newcastle University
Burcak	Basbug Erkan	Coventry
Jacki	Bell	Durham Energy Institute
Ronan	Bolton	Edinburgh University
Charles	Boulton	CDBB, Cambridge Uni
Richard	Bradley	London School of Economics
Dominic	Calleja	Liverpool University
Chris	Dent	Edinburgh University
Hailiang	Du	Durham University
Michael	Goldstein	Durham University
Weisi	Guo	Warwick University
Matt	Hemsley	National Audit Office
James	Hetherington	Turing Institute
Bill	Hewlett	Costain
Matthew	Hindle	Energy Networks
Adam	Hutchinson	Ofgem
Kat	Lovell	SPRU, University of Sussex
Iain	MacLeod	IESIS
Sebastian	Maier	Imperial College London
Sebastian	Maier	Imperial
Gordon	Masterton	Edinburgh University
Martin	Mayfield	Sheffield University
Will	McDowall	UCL
Gordon	McKerron	SPRU, University of Sussex
Hugh	McMichael	Jacobs

John	Miles	Cambridge University
Andrew	Mortimer	Scottish Government
Mike	Mosely	i3P & KTN
Giannis	Moutsinas	University of Warwick
David	Owens	Costain
Nazmiye	Ozkan	Cranfield University
Tom	Reynolds	Edinburgh University
Joe	Roussos	London School of Economics
Julie	Sigles	Centre for Digital Built Britain
Antti	Silvast	Durham Energy Institute
Ritchie	Somerville	University of Edinburgh
Neil	Strachan	UCL
Jonathan	Sweeney	Ofgem
Evelyn	Tehrani	Durham Energy Institute
William	Usher	University of Oxford
Liz	Varga	Cranfield University
Lynne	Ward	Scottish Futures Trust
Alec	Waterhouse	BEIS
Jim	Watson	UCL
Ed	Wheatcroft	London School of Economics
Elliott	White	National Audit Office
Mark	Winskel	University of Edinburgh
Andrew	Wright	Cognitive Energy & Durham Energy Institute
Henry	Wynn	London School of Economics