Institution: Queen Mary University of London (QMUL)

Unit of Assessment: B10 Mathematical Sciences

Title of case study: Informing policy and mitigating risk – modelling infrastructure networks

1. Summary of the impact

Researchers at Queen Mary have applied mathematical modelling techniques to understand how and when problems may arise in complex man-made infrastructure networks including electricity, gas, global shipping and haulage networks. Many of these networks have points of vulnerability where a local issue such as an earthquake, a terrorist attack or even a simple engineering problem can bring down widespread areas of the network. Our research and the associated modelling techniques have impacted on organisations including the UK Treasury Office and the European Commission's Joint Research Centres at both Petten and Ispra, where it has been used to inform UK and European policy guidelines and legislation for infrastructure projects.

2. Underpinning research

Our research in the study of infrastructure networks has focused on:

- Building new datasets, particularly of European electricity and gas network data, overlaying these networks to determine important common nodes, and offering a range of new insights using mathematical measures of robustness that are based on network topology; and
- Applying mathematical analysis to networks using real-world data and understanding the problems and opportunities this raises.

Our expertise in this area was demonstrated by the development of an EU-wide series of collaborations on the subject of network vulnerability. The MANMADE project (2007-09) [6], which was EU sponsored, addressed the diagnosis of vulnerability in networks, emergent phenomena and volatility in man-made networks. The grant resulted from the collaboration between Arrowsmith and the European Commission Joint Research Centre, Ispra (JRC) and grew to include the National Emergency Supply Agency (NESA) in Finland and academic institutions across Europe, including the prestigious Collegium Budapest. This collaboration supported the analysis of real networks from both the mathematical and engineering perspectives. Industrial, government, European Commission and commercial stakeholders have contributed real data from continental, country and city-wide networks. An indicator of our success came towards the end of the MANMADE project when we were awarded an EPSRC grant on Resilience, Adaptability and Volatility of complex Energy Networks (RAVEN) [5]. The thrust and novelty of the project is that the investigation of the mathematical models and methods are data rather than theory driven [5].

Work by Carvalho, Arrowsmith and others at Queen Mary [1, 2] has uncovered insights into network robustness according to various criteria of importance. The extensive data mining that we have undertaken has, for example, allowed us to:

a) consider error-tolerance of gas transmission networks and network redundancy in greater detail than ever before at the European scale;
b) investigate the probability distribution of the impact on society as a result of disruptions to electricity and gas supply across Europe after an earthquake;
c) consider the critical infrastructure aspects of road networks in major cities and attempt to identify the critical building blocks, the so-called motifs, in these networks; and
d) identify load- and fault-tolerant backbones of the trans-European gas pipeline network by combining topological data with information on pipe diameters and inter-country flows.

This research was carried out between 2009 and 2012 and was led by Carvalho (postdoctoral research assistant of MANMADE and RAVEN, supported partially by ImpactQM) and Arrowsmith (Principal Investigator of MANMADE and RAVEN, Head of School, 2003-11).

The research establishes that overloading transmission lines in transport or energy networks can trigger a cascade of failures resulting in a critical breakdown. To address this we have developed models that allow us to make predictions about robustness that are of significant use to network designers. We have developed network algorithms that produce graphs which are acutely prone to cascade breakdown [3, 4]. By characterising these graphs we can determine the extent to which real networks differ from these extreme constructs. This research has resulted in models that allow us to investigate the connectivity and dynamics that result from these graph-building scenarios, which in turn allows us to propose counter-measures which can be employed to prevent cascade failure. This research was carried out between 2007 and 2009 and was led by Arrowsmith (see above) and Mondragon (co-investigator of MANMADE and RAVEN, senior lecturer in electronic engineering).

3. References to the research

1. R. Carvalho, L. Buzna, F. Bono, E. Gutiérrez, W. Just, D.K. Arrowsmith, 'Robustness of Trans-European Gas Networks', *Phys. Rev. E,* 016106 (2009) (doi:10.1103/PhysRevE.80.016106)
2. R. Carvalho, L. Buzna, W. Just, D. Helbing, and D. K. Arrowsmith, 'Fair sharing of resources in a supply network with constraints', *Phys. Rev. E* 85, 046101 (2012)
3. M. Woolf, Z. Huang, and R.J. Mondragon, 'Building catastrophes: networks designed to fail by avalanche-like breakdown', *New Journal of Physics*, 9, 174 (2007) (doi:10.1088/1367-2630/9/6/174)
4. R.J. Mondragon, 'Topological modelling of large networks', *Phil. Trans. R. Soc.* A 366 (2008) (doi:10.1098/rsta.2008.0008)
5. Arrowsmith, *Resilience, Adaptability and Volatility of complex Energy Networks* (RAVEN), EPSRC EP/H04812X/1, awarded March 2010, grant value £350k
6. http://manmade.maths.qmul.ac.uk/ Arrowsmith, *Diagnosing vulnerability, emergent phenomena, and volatility in manmade networks*, FP6-STREP (2007-2009)

4. Details of the impact

The Joint Research Centre (JRC) is the scientific arm of the European Commission and provides advice to the Commission to inform policy-making. In collaboration with the JRC, the research conducted at Queen Mary has had impact in a number of ways. Firstly, through collaboration with JRC our research has influenced European security policy. Secondly, with JRC and the Directorate General Taxation and Customs Union our research has informed security performance standards in the container shipping industry. Thirdly, our collaboration with JRC and relationships with E.On and the National Emergency Supply Agency of Finland (NESA) has informed the security of electricity and gas networks. And fourthly, through collaboration with HM Treasury our research has informed the delivery of the High Speed 2 rail network in the UK to identify opportunities for a shared corridor. The following section explains each of these impact areas.

Influencing security policy

Our research and the associated modelling techniques [1, 2, 3, 4] have been adopted by the JRC who, in turn, have impact on European legislation for infrastructure projects. A key mission of the JRC is to provide research that supports EC policymakers in their efforts to ensure global security and the protection of European citizens from accidents, deliberate attacks, fraud and other illegal activity. In 1996, Gutiérrez joined Arrowsmith's group as a PhD student and together they published research on structural engineering. Gutiérrez joined the European Commission as a researcher in the JRC where later, in collaboration with Arrowsmith, he provided research expertise in the fields of gas and electricity supply security, building upon the methods described above in Section 2.

The data-mining exercise mentioned in Section 2 allowed us to identify load- and fault-tolerant backbones of the trans-European gas pipeline network by combining topological data with information on inter-country flows [1]. This has made it possible to estimate the global load of the European gas network and its tolerance to failures by applying two complementary methods generalised from measures of betweenness centrality and the maximum flow. We found that the gas pipeline network has grown to satisfy a dual purpose. On one hand, the major pipelines are crossed by a large number of direct connections thereby increasing the efficiency of the network; on the other hand, a non-operational pipeline causes only a minimal impact on network capacity, implying that the network is error tolerant. Our findings conclude that the trans-European gas pipeline network is robust – it is tolerant to failures of high load links. The data for this activity has been made available by the Head of Unit, Energy Security, EC Joint Research Centre at Petten, and Queen Mary conducted the mining and analysis exercise.

The collaboration between JRC and our researchers has contributed to the ongoing evaluation of technologies and the improvement of security standards which have an impact on EU regulations as confirmed by Gutiérrez, now a researcher at the JRC [8]: *"I would like to record the significance of the collaboration between the European Laboratory for Structural Assessment of the European Commission's Joint Research Centre (JRC), Ispra, and the School of Mathematical Sciences of Queen Mary, University of London, most notably with Prof. D.K. Arrowsmith. This collaboration has enabled the JRC to have an impact on the development of a framework for standardisation, regulation and legislation with regards to supply chain container management and security. The scientific input and the unique expertise of SMS/QMUL have been a key ingredient for its collaboration with the JRC, whose role is to provide scientific and technical support to European Commission services by delivering guidelines with a view to promote standards and legislation".*

Addressing security performance standards in the container shipping industry

Arrowsmith and Gutiérrez have also collaborated on research into the robustness of containerised transport networks and the ability of sensors to provide appropriate indicators of secured goods. There were over 400 million container movements in 2010 and containerised transport is particularly at risk of being targeted for the smuggling of people or goods, as indicated in the "*EC Technical Report, An overview of research programmes and prospective technology in the development of more secure supply chains: The Case of Shipping Containers*" [11]. The scope of this report, a joint activity of our researchers, JRC, and The Directorate General Taxation and Customs Union covers "*on the one hand the two primary technological considerations (materials technology and production, ad-hoc sensor networks deployment) and, on the other, the economic and trade statistics backdrop of the container industry. By considering these aspects – in conjunction with the technological developments and policies in container security of the EU's major trading partners – it is intended to set the backdrop to the potential innovative technologies in the area of tamper-proof intermodal containers. The aim is to provide support to European Commission services in their policies of motivating the development, capability testing and evaluation of technologies that could meet the security performance standards in the container shipping industry, and in matters relating to meeting the EU's international cooperation agreements on supply chain security"* [11]. Arrowsmith and Gutiérrez's collaborative research in MANMADE and RAVEN [5,6] led to an invitation to address security performance standards in the container shipping industry [12]. The project research has been applied in matters relating to meeting the EU's international cooperation agreements on supply chain security.

Ranking and the impact on security of gas networks

In 2012 Arrowsmith, Carvalho and Gutiérrez founded a research group named Real World Networks (RWnets). This group produced an energy network analysis that ranked the security of gas networks in Europe. This research led to a novel method of ranking countries in terms of the vulnerability of their infrastructure to degradation, natural disaster or deliberate attack. Furthermore, as a result of the development of expertise in the analysis of real networks within MANMADE [6], which was further developed by EPSRC funding in RAVEN [5], we now have a memorandum of understanding with the EC Joint Research Centre, Petten, which has enabled the release of key energy network data to develop novel ideas of fairness of flow indicators [2] (January 2012, data via the Head of Unit for Energy Security, EC Joint Research Centre, Petten). Much of this research is to address issues of the Grand Challenge energy scenarios that Research Councils UK is now supporting, such as the supply of energy becoming increasingly pan-European with the potential for political involvement in the transport of energy across the continent.

The research group which was set up at Queen Mary as part of the MANMADE project [6] collaborated with the energy supplier E.ON in Hungary [9] to develop a dynamic power grid model with a view to understanding likely cascade scenarios at a national level, and with the National Emergency Supply Agency of Finland (NESA) [7] who attended all six management meetings over the three years of the project to monitor the outcome of MANMADE, for them to feedback on national energy security.

Evidence of impact on UK infrastructure development: High Speed 2

Our research resulted in an approach from HM Treasury [10] to offer advice and expertise on one of the largest infrastructure projects in Europe. Specifically, the Treasury's approach was stimulated by interest in our investigation of the European gas network [1], which led to our involvement with HS2. Our research outputs have been discussed by the HS2 team, as described by the Interdependencies Lead within the Enterprise and Growth Group at HM Treasury [13]: "*Your report mapping HS2 route against electricity and gas network density has been read with interest here and I have used the results with DfT and the HS2 delivery team to explain how we can go about analysing potential opportunities for shared corridor.... In particular, we are working with the HS2 team to make a case for a fibre backbone down the HS2 route".* This indicates impact in the decision making process on future high-profile infrastructure projects.

5. Sources to corroborate the impact

7. Senior Researcher, National Emergency Supply Agency (NESA). [Impact of the research performed in the EU-STREP Manmade for a key aim of NESA, the security of the Scandinavian infrastructure network].

8. Senior Scientific Officer, EC Joint Research Centre, Ispra, Italy. [Impact on the development of a framework for standardisation, regulation and legislation with regards to supply chain container management and security].

9. Commercial Advisor, Infrastructure UK, HM Treasury. [Impact of the research on vulnerability of networks done within Manmade for infrastructure security (gas) and planned transport network projects (HS2)]

10. An overview of research programmes and prospective technology in the development of more secure supply chains: The Case of Shipping Containers Report EUR 25298 (EN 2012) JRC Scientific and Policy Reports, E. Gutierrez (DG-JRC), W. van Heeswijk (DG-TAXUD), D.K. Arrowsmith (Queen Mary, University of London), EUR 25298 EN, ISBN 978-92-79-24168-0 (pdf),ISBN 978-92-79-24167-3 (print).

11. Policy Officer, Supply Chain Security and Technology expert, European Commission. [Impact of the research on European Commission services in their policies for the development, capability testing and evaluation of technologies to meet the security performance standards in the container shipping industry].

12. Interdependencies Lead, Enterprise and Growth Group, HM Treasury. [Impact of the research on the HS2 project, in particular how to analyse potential opportunities for shared corridor].