Spatially modelling dependent infrastructure networks

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Summary

The resilience of infrastructure networks to different types of perturbation is of significant interest due to the importance of these systems for the efficient functioning of modern society. Significant failures such as power blackouts and their subsequent knock-on effects on other infrastructures are particularly important to understand. We present a spatially explicit method for representing infrastructure spatial dependencies and modelling of failure impacts using a PotsgreSQL-PostGIS database coupled with spatial network failure models. The utility of the methodology is shown by simulating how the London underground may respond to different failure types on the South East electricity transmission grid.

Keywords: Dependency, resilience, critical infrastructures, spatial networks, spatial database

1. Introduction

Critical infrastructures (CI) facilitate active economies and underpin the quality of life in modern nations. Failures or disturbances to these CI, such as the Italian and North American electricity blackouts of 2003 (Andersson *et al.*, 2005), can lead to far reaching societal and economic consequences. Such failures affect not only a single CI, but instead failures propagate to other infrastructure networks exacerbating the effects. For example, failure of electricity transmission systems affect multiple CI, including communications (the internet) and transport systems, and in the case of the 2003 blackout in USA and Canada it is was estimated to have had an economic cost of 4-10 billion dollars (U.S.-Canada Power System Outage Task Force, 2004).

Understanding the relationships between interdependent infrastructure systems is vital to ensure the repercussions of failure in one network does not adversely affect the multiple systems which may be dependent upon it. Dependencies between CI can take multiple forms (Rinaldi *et al.*, 2001), from physical connections to cyber dependencies and geographic dependencies, all of which can result in failures propagating between infrastructure systems. An ever increasing number of CI exhibit dependencies, and thus the analysis of these systems should account for this (Dueñas-Osorio *et al.*, 2007) to improve our ability to understand the consequences of failures in CI.

In this paper we introduce a spatial analysis of the relationship between two CI, the National Grid and the London tube network using a spatial-topological based analysis approach to highlight the potential vulnerability of the tube system to electricity substation failures. This is facilitated using a PostgreSQL PostGIS enabled database within a python driven framework.

2. Method

Interdependent spatial networks were constructed using a dedicated postgreSQL PostGIS enabled interdependent network database schema model (Barr *et al.*, 2013). National Grid shapefiles (National

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Grid, 2014) were processed using a suite of software tools for spatio-topological network construction (Barr *et al.*, 2013) to generate a power network for the South East of England comprising of 709 nodes and 877 edges. Data from Transport for London (TFL) was employed to build a representation of the tube network (Transport for London, 2014) that consists of 436 nodes and 466 edges. To build the relationship between the two networks (Figure 1) we make a number of assumptions; (i) each tube station is powered by its geographically closest electricity substation, (ii) there are no other sources of electricity for each station, and (iii) the substations at the edge of power network are the sources of power for the South East area. Within the interdependent network database schema the dependency relationships between the electricity and tube networks are stored in a separate interdependency table using node id's to record the substation that each tube station is dependent on.

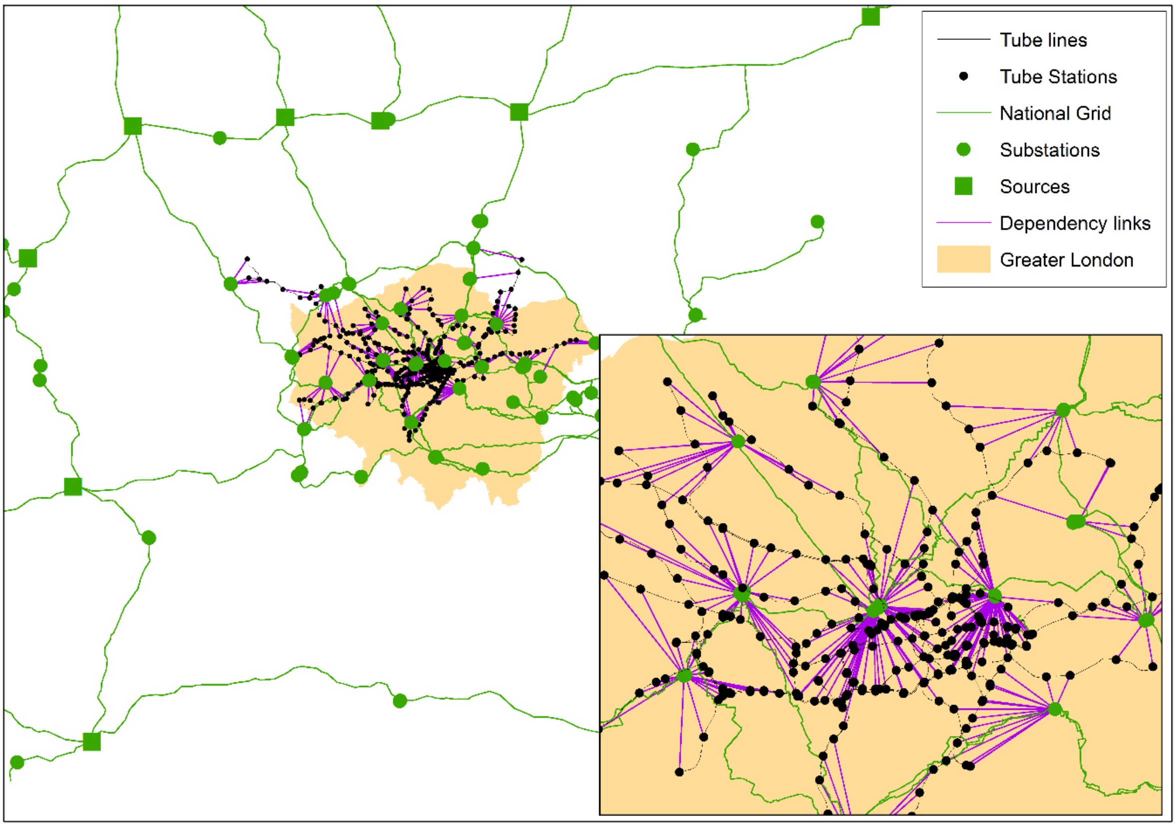

Figure 1: The electricity grid for South East England and the London tube network. Inset: Central London showing spatial dependency edges (mappings) between electricity substations and tube stations.

In order to perform interdependent failure analysis networks are retrieved from the database forming NetworkX instances (NetworkX, 2014) and the particular failure model of choice initiated: either (i) random, (ii) degree (a measure of the most connected nodes) or (iii) betweenness (an estimate of the load on each component) (Boccaletti *et al.*, 2006) **(**Figure 2). Each failure model involves removing a selected/targeted substation every iteration, checking to ensure remaining substations are still connected to a 'source' node (i.e., that the electricity network is still functional), and then via the dependency list identifying those tube stations that will fail as a result of a dependency to the selected/targeted substation. The failed station nodes are removed along with their coincident edges (tube lines). Performance metrics are then computed, and along with the current instance (state) of both networks and their dependencies, written back to the database. The process is repeated until no nodes/edges are left in one network.

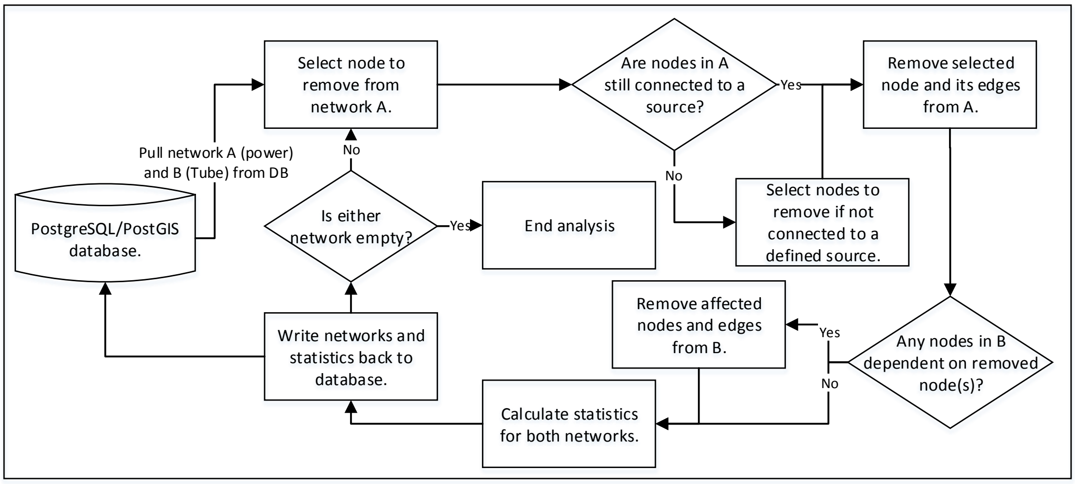

Figure 2: Flow diagram of interdependent failure model.

3. Results

The results show that the degree and betweenness failure models have a greater impact on the tube network (Figure 3) with all tube stations becoming disconnected earlier (17 and 10 substations removed respectively) compared to the random model (70 substations removed before complete failure). Not only does the betweenness model lead to quicker total failure but that the effects of the failures in this model are far more dramatic at early stages of failure, as shown by the fact that the largest connected functioning component of the tube network decreases significantly quicker for the betweenness model than for the random (Figure 3).

The spatial pattern of failures for the three failure models shows that both the degree and betweenness methods have a greater impact spatially in the centre of London, whereas the random failure model does not target a specific spatial area thus allowing travel across the network to remain possible for longer (Figure 4). The sensitivity of the tube network to the betweenness failure type is shown in Figure 5 with 61 tube stations failing after only four iterations and 319 by the sixth.

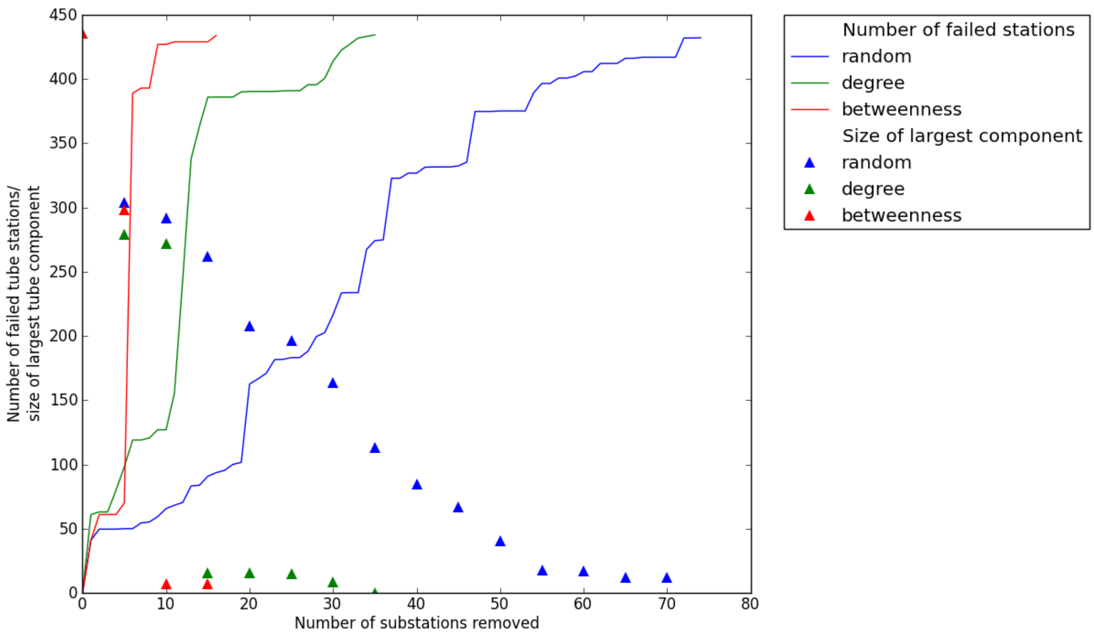

Figure 3: Change in the number of failed tube stations and the size of the largest group of connected tube stations as the number of failed substations increase.

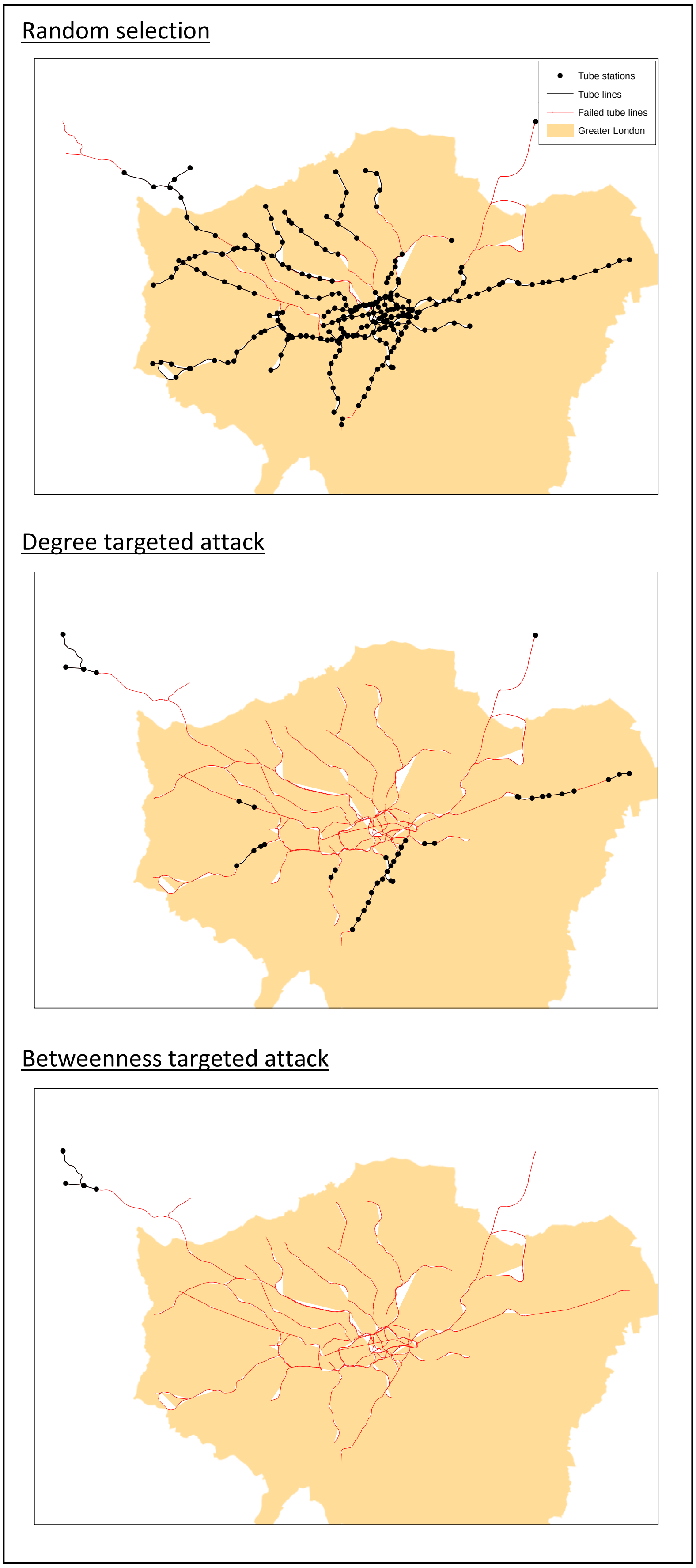

Figure 4: The state of the tube network after fifteen iterations for a single run for each failure model.

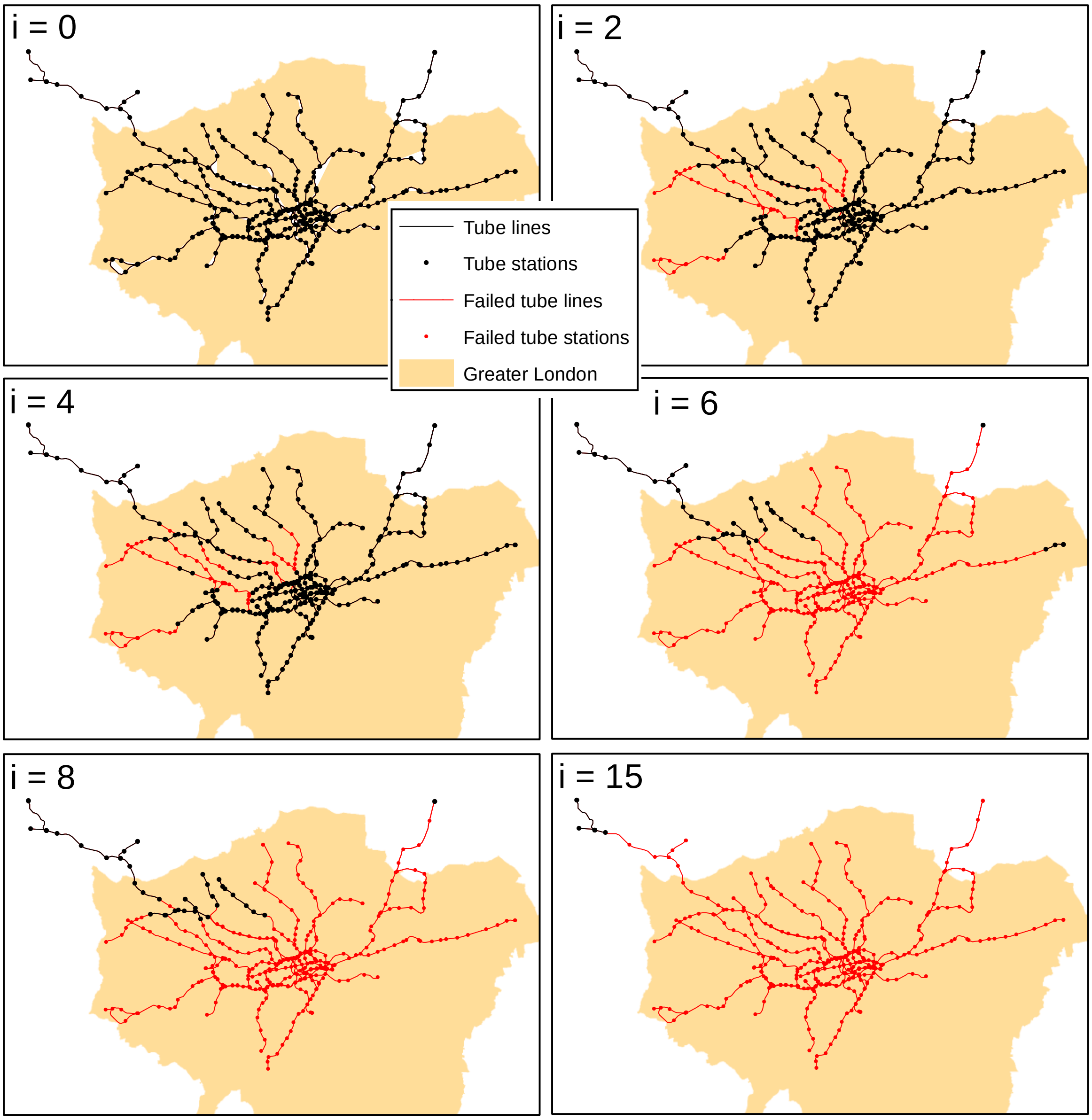

Figure 5: Evolution of the tube network failure when the power network is exposed to the betweenness failure model.

4. Conclusion

This paper has presented a software framework that couples a new open-source database schema representation of interdependent spatial networks with iterative network failure models. The resulting software not only allows for several different types of network failure to be run, but the use of a database management system allows a persistent record of the failure dynamics at each iteration to be recorded and analysed further. In the case of this study, this allows a user to not only understand the global characteristics of the failures, but also critically to understand the evolving spatial pattern of failure and how this differs between the three models investigated. The results for the electricity and tube networks show that potentially dependent systems are very vulnerable to failures on the most highly connected nodes but robust to spatially random failures in the supplying network. Future work will extend this spatio-topological analysis to develop models with a stronger physical-basis.

5. Biography

Mr Craig Robson received a B.Sc. (Hons) degree in Geographic Information Science from Newcastle University in 2011. He is currently studying for a Ph.D. in spatial infrastructure network modelling at Newcastle University.

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Bibliography

Andersson, G., Donalek, P., Farmer, R., Hatziargyriou, N., Kamwa, I., Kundur, P., Martins, N., Paserba, J., Pourbeik, P., Sanchez-Gasca, J., Schulz, R., Stankovic, A., Taylor, C. and Vittal, V. (2005) 'Causes of the 2003 major grid blackouts in North America and Europe, and recommended means to improve system dynamic performance', *Power Systems, IEEE Transactions on*, 20, pp. 1922-1928.

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.

Boccaletti, S., Latora, V., Moreno, Y., Chavez, M. and Hwang, D.U. (2006) 'Complex networks: Structure and dynamics', *Physics Reports*, 424, pp. 175-308.

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.

National Grid (2014) *National Grid - Services - Shape-Files*. Available at: http://www2.nationalgrid.com/uk/services/land-and-development/planning-authority/shape-files/ (Accessed: 24/10).

NetworkX (2014) *NetworkX: Overview*. Available at: https://networkx.github.io/. (Accessed: 24/10).

Rinaldi, S.M., Peerenboom, J. and Kelly, T. (2001) 'Identifying, understnading and analysing Critical Infrastructure Interdependencies', *IEEE Control Systems Magazine*, 21, pp. 11-25.

Transport for London (2014) *Transport for London*. Available at: https://www.tfl.gov.uk/ (Accessed: 28/10).

U.S.-Canada Power System Outage Task Force (2004) *Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations*.