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CASE STUDY REPORT

CASE STUDY 07.A: RESILIENCE OF INTERDEPENDENT URBAN INFRASTRUCTURE SYSTEMS (LONDON)

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Interdependent Urban Infrastructure Systems: How can the public transportation network in London be made more resilient and robust to flooding?

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The functioning of large and populated cities is highly dependent on the operation and efficiency of local public transportation. Acute shocks and chronic stresses can have serious impacts on transportation networks when affecting streets and transport links. The aim of this paper is to suggest potential mechanisms to enhance the resilience of London's transportation network (bus, metro and train) to flood events. Firstly, the key flood threats to London's transport network are introduced, before the authors debate the concepts of resilience and robustness in relation to this scenario and propose appropriate definitions for this case, associating resilience to temporary measures, and robustness to permanent and long-term measures allowing the system to function even if a few links are removed. The addition of extra bus lines is proposed to make London's transport both more resilient and robust, according to outlined definitions. A model is offered to assess and analyze the benefits of additions of such extra lines to the London public transportation network.

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I. INTRODUCTION

Public transportation systems are a vital component of any major city. By moving goods and people around the city, the public transport system is responsible for the majority of commutes occurred within the city. With approximately 8,6 million people [1], London is one of the largest capitals in the world. The public transport accounts for 33 % of all daily trips made in the city [2]. Transport for London has recorded nearly 3 billion passenger journeys per year in 2015 [3],including buses, London Underground, Docklands Light Railway and London Overground.

The expansion of urban centres, the subsequent modification of the environment and the effects of climate change on rain patterns have increased the risks and occurrence of flooding phenomena [4] which has an impact on public transport system. The flooding phenomena in London can be divided in two types: fluvial flood caused the elevation of the Thames produced by tidal movements, and pluvial flood caused by rain knowns as flash flood. Both phenomena are considered to be risks to the functioning of the public transport system, and can create shocks or disruptions altering the status of the system. This can cause a large-scale impact to the users and on the economy of the city due to delays. Whilst flood risk can never be completely eradicated, its impacts can be mitigated. Well-designed transportation systems are an essential factor in the economic welfare of major cities. Planning and designing the transport system requires a quantitative understanding of traffic patterns and relies on the ability to predict the effects of disruptions to such patterns, both planned and unplanned [5].

The determination of conditions under which complex networks are stable is an important challenge. In critical infrastructure networks, meeting the most important (or vulnerable) elements is crucial for providing more efficient and robust systems. In this context, robustness is understood as the ability of the system to absorb disturbance to its nodes (stops) or links (service lines) and continue to operate under the same conditions found in a normal situation, that is, continue connecting users to their destinations [6].

Robustness vs. Resilience

The concepts of resilience and robustness share similarities, but there can be subtle differences between them. Resilience is most associated with adaptation, the ability to self recover from large-scale disturbances, returning to its original state or to adjust to a new state [7]. It was Holling's 1973 seminal work on resilience that stressed the importance of a system's ability to maintain its structure under duress and defined resilience as *"a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables"* [8]. However, in academic works there are two distinct interpretations of how resilience relates to system state and disturbance: the engineering and ecological resilience approaches. Engineering resilience focuses on time spent to return to equilibrium after a disturbance, whereas ecological resilience refers to amount of stress or disturbance a system can withstand or absorb before altering state. The engineering resilience focuses on ensuring functional efficiency whereas ecological resilience is based on maintaining existence of function. On the other hand, robustness refers to the ability to absorb shocks and maintain continuous operating despite disruptions. Therefore a system is robust when it is able to continue functioning despite external shocks and changes to the original system. One may also think about robustness as a property of resilience, in the sense that, when a system has to recover it implies that the robustness has failed on a shorter time scale [9].

In any complex system, the structure that is seen depends on the level that one is observing. The debate on required characteristics for a transport system to be resilient and robust is still on-going; however when the authors, look at it being compounded by all of its sub systems, including personal staff, resilience properties are identified like self healing for example, where transport personnel act immediately to restore the system to its original state in instances of failures or shock events. In a public transport network, resilience can be interpreted as emergency measures, such as the existence of maintenance staff and a series of contingency plans, including abandoning subway tunnels and activation of multiple extra bus service lines, based on demand, in case of flooding. Robustness would be associated to permanent changes in the network, such as the existence of permanent redundant routes, what would allow the system to keep functioning without the removed links.

II. MODEL

Models are one of the main instruments of modern science, with dozens of variations created to investigate different phenomena in nature and provide a simplified mathematical representation of a system of interest [10]. One of the main aspects in the definition of a model is the selection of variables and system's characteristics to be exploited, with the most important agents and variables identified in relation to the phenomenon under observation.

To investigate the identified problem, a hybrid model is proposed, merging different approaches to capture the properties that are being investigated (see Fig. 1). Transportation systems can be represented as a network, where the stations, terminals and stops can be interpreted as nodes and their lines and routes as links. The following diagram shows an abstract model combining a network flow model and a genetic algorithm that consumes input data and returns outputs to improve the system capabilities. This process works as a continuum flow, where outputs can be reintroduced to the system, updating its status and providing a method instead of a statical solution.

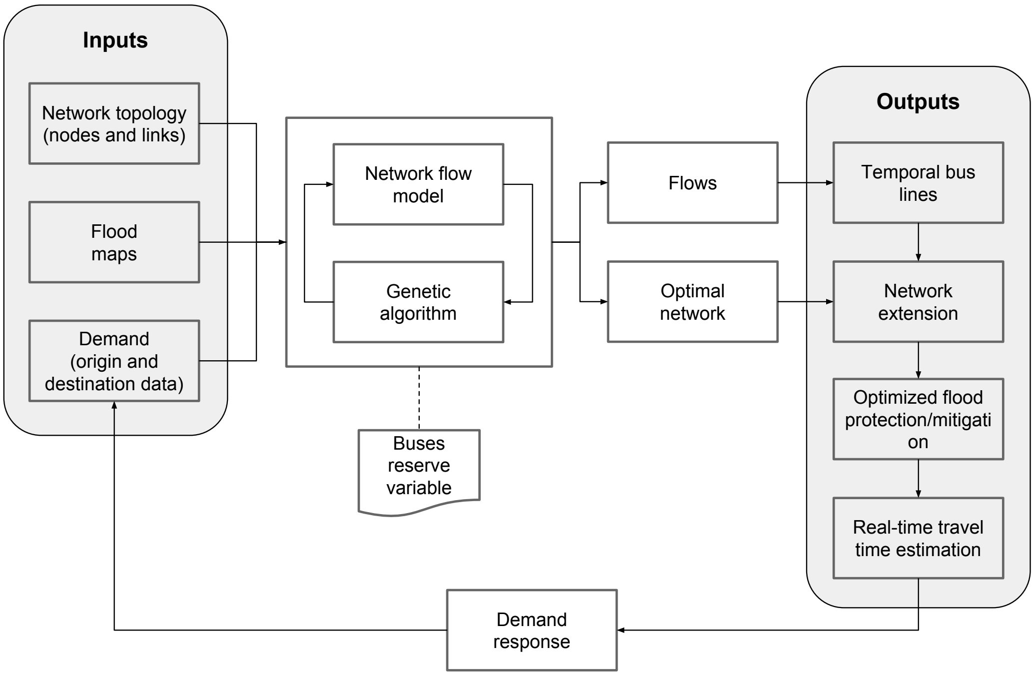

FIG. 1: Hybrid model that uses a network flow and a genetic algorithm to propose new lines to the transport system. The results are used again as inputs, providing a continuous framework to evaluate the transport in long and real-time.

The diagram shows a data-driven model, that is, input data is used to tune the behavior during simulations. The current system structure compounded by its stops and lines is used as the network topology input, with flood maps showing the areas with higher flood risk and origin-destination survey for transport demand. With this empirical data, the network flow model can calculate the most demanded lines, the stops with higher connectivity and proximity of stations to flood-risk areas. In the next step, the genetic algorithm uses this model to propose additional lines and paths that could improve the robustness of the network, avoiding risk areas. A variable with the number of buses is included to help planning agencies get more realistic results based on their budget.

After some interactions, the model returns the flows of the network with a proposal of new lines to be added temporarily. According to our definition, this measure would make the network more resilient. Also, based on passengers usage, or even on the decrease of the average time of travel per passenger, they can become permanent, which would contribute to make the network more robust. With this new topology, the flooding areas can be avoided or at least have alternative routes proposed in the case of interruptions. These outputs can be used again as inputs to the model as a monitoring framework, using real-time data, allowing the system to learn and adapt to any kind of interruption, not only floods.

Data and methods

One of the biggest challenges of modelling real systems is to acquire data and process it to obtain useful information. This data is required to drive the modelling process and to validate it against reality, comparing simulated results with empirical observations. The network topology can be easily obtained from traffic agencies, requiring some adjustments to correct data gaps and create the graph. The network connectivity can be built based on bus stops and subway lines that are serviced by at least one line. The sequence of two stops attended by a line characterize the link between them, as can be seen in Fig. 2.

In the same way, flood risk maps can be obtained from meteorological agencies or estimated based on rain and terrain elevation. In fact, there are terrain models that can simulate how rain water could behave based on surface topology [11], but more attention is required in the case of cities as they posses water flow systems for this situations. Another way is to track statistics data from past incidents and map where they are frequently located.

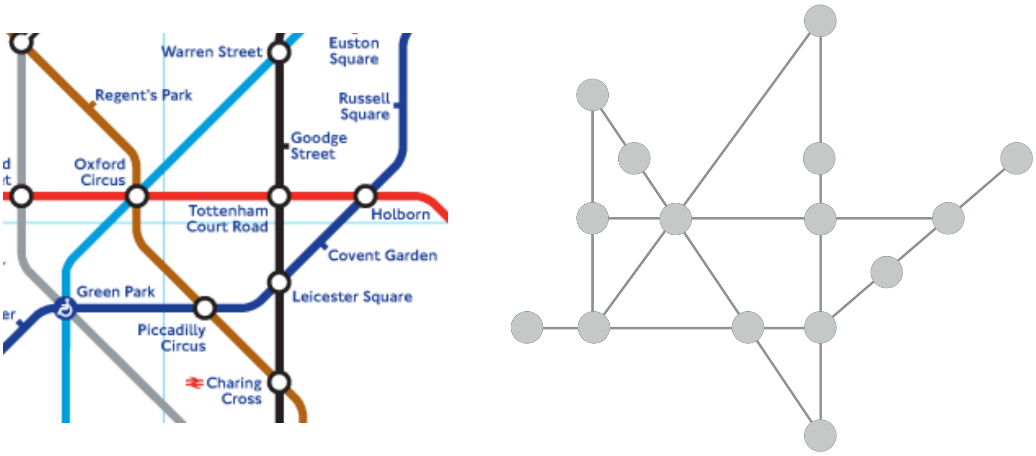

FIG. 2: Part of London tube network represented as a network (graph). Service lines are interpreted as edges and stations as vertex. Source: Transport for London `https://tfl.gov.uk/maps/track/tube`.

Origin and destination surveys are commonly carried out by traffic agencies and historic data can be obtained, however data often has large decade-long time intervals. In best situations, ticketing data can be extracted from the system's billing, granting a richer and more precise picture of traveller's behavior. With this ticketing information, the location where the passenger boarded can be obtained based on the GPS of buses, or in the case of subway, the location of the station of first use. Analysing this data for a period (week for example), the origin and destination of a passenger can be inferred based on frequencies and periods that the system is used.

III. CONCLUSIONS

Cities are made up of systems, including ecosystems, utilities, economies and transportation systems to form complex systems. Each part of this system and it's subsystems are reliant on other parts. This is the case of London's transportation network, which is highly interconnected. Whilst flood risk is a significant concern to London, the impacts of flood events on the transportation system can be mitigated and reduced. The authors suggest the use of a hybrid network flow and genetic algorithm model to assess the risk of flooding at station level, and suggest alternative routes to avoid disturbance and maintain functioning of the system as a whole. Interpretations of resilience within complex adaptive systems see it as the ability of system to withstand, recover from and reorganise after a crisis event, with function maintained but system structure potentially altered. Resilience is then associated with temporary measures to recover from interrupted links in the short-term scale, whereas robustness is associated with permanent, long-term changes in the network, allowing it to keep functioning even when some links are removed. It is discussed in the study here, where the transportation system of London's future resilience may be due to the flexibility of being able to add or alter lines in the case of a flood incident, while its robustness may be due to the existence of redundant routes.

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[1] Population Estimates for UK, England and Wales, Scotland and Northern Ireland, Office for National Statistics. Visited 23 June 2016.

[2] Travel in London Key trends and developments. Report number 1, Transport for London (2009).

[3] Record passenger numbers on London's transport network, Transport for London (2015).

[4] R. Ugarelli, J.P. Leitão, M.dC. Almeida, and S. Bruaset, Overview of Climate Change

Effects Which May Impact the Urban Water Cycle. Visited 24 June 2015.

[5] J.R. Banavar, A. Maritan, and A. Rinaldo, *Size and form in efficient transportation Networks*, Nature **399**, 130-132 (1999).

[6] E. Rodríguez-Núñez and J.C. García-Palomares, *Measuring the vulnerability of public transport networks*, Journal of transport geography **35**, 50-63 (2014).

[7] C. Folke, *Resilience: The emergence of a perspective for social–ecological systems analyses*, Global environmental change **16**, 253-267 (2006).

[8] C.S. Holling, *Resilience and Stability of Ecological Systems*, Annual Review of Ecology and Systematics, **4**, 1-23 (1973).

[9] S.C. Bankes, *Robustness, Adaptivity, and Resiliency Analysis*, in AAAI fall symposium: complex adaptive systems, **10**, 2-7 (2010).

[10] R. Frigg and S. Hartmann, *Models in Science*, in The Stanford Encyclopedia of Philosophy, edited by E.N. Zalta (2012).

[11] Koussis, Antonis D., et al., *Flood forecasts for urban basin with integrated hydro-meteorological model*, in Journal of Hydrologic Engineering, **8.1**, 1-11 (2003).